Performance Analysis Of Optimised Wireless Sensor Network In Indoor Environment

Thesis

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Certificate from the Supervisor

This is to certify that the thesis entitled "**Performance Analysis of Optimised Wireless Sensor Network in Indoor Environment**" submitted by Shri **Arnab Ghosh**, who got his name registered on **26th September, 2014** for the award of Ph.D. (Engineering) Degree of Jadavpur University is absolutely based upon his own work under the supervision of **Prof. Niladri Chakraborty**, Professor, Department of Power Engineering, Jadavpur University and that neither his thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

……………………………………………………………………………………

Signature of the supervisor and date with office seal

Dedicated

to

Ma, Baba, Mamam

Ranga Masi and Ranga Meso

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ABSTRACT

The advent of the wireless sensor networks has helped to eliminate the problems of monitoring through the wiring infrastructures subjected to external damages and excessive cost to cover large areas. The low cost, low power and simpler architectures related to wireless network design have made it quite acceptable as the monitoring tool in varied fields of applications nowadays. The bidirectional communication facility provided by the wireless network infrastructure helps to transmit the control signals through the return path thus forming a major component of the controlling framework. The ease of utilization of the wireless networks has made it suitable for supervising the performance of the renewable sources like solar and wind that are installed in some remote areas. The advancement in today's world requires real time data monitoring from all the installed sensors of a certain application simultaneously. It therefore needs a communication architecture that enables quick data delivery. Digital data communication through radio frequency (RF) channels helps to provide this facility of speedy data delivery in the wireless sensor networks. The collected data from the different sensors in the application area helps to recreate the model of the application in the control station and abnormality in the processes can therefore be easily detected. However, the wireless sensor network is subjected to chances of data loss and unreliable performance due to several factors. The data loss surveyed based on the type of network architectures and network characteristics suggest that interference, signal attenuation and signal crossover has been the main sources that has resulted in data loss in the wireless network. Energy depletion at the nodes is one of the other important factors that resulted in node deaths leading to loss of the entire data collected by that particular node. Energy requirements at the node during data communication, data delivery success ratio and transmission delays thus become the determining parameters about the reliability of the network. Optimal positioning of the routers and choice of routing topologies thereby plays an important role in the wireless network design. This work has therefore focused on efficient selection of cluster heads and placement of the nodes to enhance the reliability and lifetime of the network.

To identify the effects of interference on the monitoring architecture designed by the wireless network, two nodes were chosen to collect the data from two different sources and the data was transmitted through the same routing pathway. The studies related to the error in the data monitored were studied due to signal crossover in the network. This necessitated the optimal choice of the number of routers in the network and their placement in the chosen area of application. This has been attempted here in this work based on Cascaded Cuckoo Search Algorithm (C-CSA) approach which has focused on signal attenuation minimization during data transmission through design of a novel mathematical function. The other parameters such as the transmission energy for each packet, signal to noise ratio and packet error ratio related to the signal attenuation in the network have been evaluated for the designed network. The statistical analysis of the obtained results over 50 independent trial runs helps to establish the precision of the proposed algorithm. The signal attenuation was found to be largely reduced and the SNR of the network was found to be 37.59dB which is quite good for a

communicating network. The comparisons of the results obtained through this algorithm with other pre-existing algorithms establish the fact that better packet delivery ratio and reduced energy consumption during data transmission has been achieved through this approach. Hardware implementation involving physical utilization of wireless nodes to test the packet delivery ratio in the Power Engineering Department of Jadavpur University Saltlake Campus, Kolkata (22.5733^{0}N, 88.4137^{0}E) helped to verify the results obtained through simulations. The packet error ratio has been obtained to be an average of 4% for the entire network which is quite low considering the number of walls, metallic structures and other wireless networks present in the network. A newly designed parameter named as "Router Placement Efficiency" is also tested and compared with existing works that helps to determine the amount of signal crossover and network coverage related to the proposed design. Cost benefit analysis based on cuckoo search algorithm for wireless network design of different sizes through battery based nodes has also been performed to identify the best topology suited for the network architecture. The results suggest that for smaller application area of 100×100m^2 and involving only 20 or 30 sensors star topology is suitable. With increase in network area and number of deployed sensors, the mesh topology was found to be suitable both in terms of economic and performance benefits. Two existing routing protocols namely Open Shortest Path First (OSPF) protocol and Level Based Routing (LBR) protocol have been also utilized in this work to identify the routing pathways chosen through these two protocols. A comparison of the results suggests that OSPF protocol was suitable for quick data delivery while LBR protocol helped in energy efficient data transfer.

In order to overcome the problem of unbalanced energy consumption in the nodes due to data traffic overhead, a novel joint clustering and routing protocol named as Residual Energy based Distributed Clustering and Routing (REDCR) protocol has been proposed in this work. This protocol helped to balance the data traffic load amongst the nodes in the network thus preventing early node deaths and reduction in network lifetime. This designed protocol utilized LEACH protocol to select cluster heads by rotation at every round of data transmission based on the residual energy of the nodes through modification of an existing equation. Multi-hop communication through efficient placement of the cluster heads in the network in the next part of the algorithm was achieved by the help of Cuckoo Search Algorithm. A novel multi-dimensional objective function designed especially for this work helps to find the positions of the cluster heads. The network performance related to network lifetime, energy conserved and amount of data transmitted was studied and compared with existing clustering algorithms. The network stability in terms of first node death and the network scalability based on 80% node death has been studied through this proposed algorithm. The proposed REDCR protocol has shown protocol significant improvements on an average of 15%, 25%, 30%, 33% and 60% for network throughput, network scalability, network stability, residual energy conservation and network lifetime respectively. The performance of this hybrid approach was also tested for different wireless networks by pre setting the number of maximum cluster heads in the network. The proposed approach showed an improvement of 60% for network lifetime when 300 nodes with 30 cluster heads were chosen in a certain application area which decreased to about 35% when considering dense network architectures. The performance of the designed wireless networks through this proposed algorithm was also performed for different positions of the base station to identify the best position related to the most efficient performance of the network. Optimal choice and positioning of the cluster heads proved beneficial in terms of enhancement of network lifetime proving this approach to be more acceptable one in near future.

The design of reliable communication architecture through wireless sensor network has been later utilized in a problem to co-ordinate the shifting of the appliances based on time of day tariff structure for low demand prosumers. The data related to the operational details of the different appliances are carried over to the Energy management Unit (EMU) where the scheduling of the appliances is performed. This scheduling strategy is a novel one which has been designed based on Cuckoo Search algorithm. The new energy management strategy shifts the operation hours of the appliances not only based on the tariff structure but also takes care of the customer's comfort hours and priority. The control signals from the EMU are transmitted back to the appliances to delay their operation by the help of the same communication framework developed by the WSN. The cost benefits related to the appliance shifting suggested a cost saving of Rs 8.86 for each household after satisfying the comfort of the customers. Added cost benefits can be attained through the proposed rooftop solar installation at each household. Considering an area consisting of 50 bungalows with almost same load consumption pattern, grid connected solar rooftop panels are suggested to be installed in this work. The design scheme of the society suggests accumulation of the power generated from each household in a central power distribution unit which feeds back this total accumulated power into the traditional grid. Based on available rooftop area of each household, solar rooftop panels of capacity 2kW are suggested to be installed in each household. The simulations performed based on current tariff structure suggest selling of the generated 100kW power from the rooftop solar panels along with the applied energy management scheme has helped to yield a profit of $18034.013 and a payback period of 4.45 years. Efficient performance monitoring of the solar panels through the designed wireless sensor network and the decreasing trend of solar prices would help in potentially increasing the profits for the prosumers.

The proposed solar energy integrated demand side management scheme has helped to predict future smart grid networks for monitoring of load data from wide areas such as university campuses. A future smart grid network for Jadavpur University Saltlake Campus, Kolkata has been identified to monitor the load from different buildings. Appropriate positioning of the ZigBee based wireless nodes in the proposed architecture has been also suggested to form a bidirectional and reliable communication architecture. Solar and wind power systems installations monitored by the wireless network has been suggested to support the lighting load of the buildings during times of excess demand. The different soft computation techniques undertaken in this work would therefore help in making the wireless sensor networks an efficient tool for data monitoring in the near future. The enhancement of network lifetime and reduction of the packet error ratio has helped to overcome the major possible areas of distress related to wireless networks. Higher resolution kits and better management of the energy consumption would help to design more efficient wireless networks for loss less monitoring in the near future.

LIST OF ABBREVIATIONS

Abbreviations Used	Full Form
WSN	Wireless Sensor Network
DAS	Data Acquisition System
DCS	Distributed Control System
SCADA	Supervisory Control and Data Acquisition system
PLC	Programmable Logic Controller
RTU	Remote Terminal Unit
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
SNR	Signal to Noise Ratio
PER	Packet Error Ratio
RSSI	Received Signal Strength Indicator
EMU	Energy Management Unit
DSM	Demand Side Management
WSHAN	Wireless Sensor Home Area Network
CSA	Cuckoo Search Algorithm
C-CSA	Cascaded Cuckoo Search Algorithm
CA	Cultural Algorithm
GA	Genetic Algorithm
LBR	Level Based Routing
OSPF	Open Shortest Path First
REDCR	Residual Energy based Distributed Clustering and Routing
RPE	Router Placement Efficiency
RF	Radio Frequency
AODV	Ad-hoc On Demand Vector
MAC	Medium Access Control
LEACH	Low Energy Adaptive Clustering Hierarchy
LEACH-C	Centralized Low Energy Adaptive Clustering Hierarchy
E-OEERP	Enhanced Optimized Energy Efficient Routing Protocol
CESC	Calcutta Electric Supply Corporation
GUI	Graphical User Interface
HEFSPM	Hyper-geometric Energy Factor based Semi-Markov Prediction Mechanism
CHSCDP	Cluster Head Selection approach for Collaborative Data Processing
HEED	Hybrid Energy-Efficient Distributed clustering
EEMLR	Energy Efficient Maximum Lifetime Routing
EPCT	Energy Proficient Clustering Technique
DBMCR	Distance-Based Multi Hop Clustering and Routing
MCR	Multi Hop Clustering and Routing
SEP	Stable Election Protocol
LDC	Least Distance Clustering
PSO-ECHS	Particle Swarm Optimization Based Energy Efficient Cluster Head Selection
ToD	Time of Day

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Chapter 1

Wireless Sensor Network in Data Monitoring Applications

In order to keep up with the pace of today's world, real time data monitoring from applications in the varied fields has become important. This necessitates usage of proper monitoring architectures that help in error free data collection. The communication frameworks that aid in data transmission should ensure reliable data delivery in order to ensure that no data is lost during transmission. When considering real time data monitoring, the data is essentially collected at almost every second and thereby missing of any important data may lead to fatal effects. For example, during monitoring of the substation data, if any data is lost it may result improper closure of the breaker leading to dangerous results. Thereby, an outline of the different monitoring techniques utilized till date is needed to understand the advantages and disadvantages of technique. This gives an idea regarding the importance and suitability of wireless sensor networks in different monitoring applications. The different wireless technologies have also been overviewed to find out the most suitable technology for indoor applications monitoring. The performance of the chosen communication architecture depends quite a lot on the placement of the nodes throughout the application area and the energy management of the nodes while data transmission. The bidirectional data transmission capability of the communication architecture can be utilized in home energy management schemes to transmit the control units from the energy management unit to the utilities. This chapter helps to establish the main objectives of the work related to implementation of the wireless networks. The novelties and contribution exclusive to this research work has also been enlisted afterwards to underline the importance of this research work and its appropriateness in today's applications.

1.1 Different Monitoring Systems associated with Data Measurement

The proper functioning of any process or appliance can be estimated by continuous monitoring of the operational data from the site of application. The sources of data losses and the abnormalities in working help the operator to know about the type and area of the fault occurred during its operation. Various industries have adopted different techniques such as Data Acquisition System (DAS), Distributed Control System (DCS), SCADA or Supervisory Control and Data Acquisition system till date for data monitoring [1]. These monitoring systems needs a detailed learning to identify the disadvantages related with the selected systems that has resulted in the wireless sensor based networks to come up as the best suitable alternative for time critical applications.

1.1.1 Data Acquisition System

The first accepted tool by the industries for data collection was the Data Acquisition System (DAS) that involves a separate instrumentation technique to collect data from various parts of the application area. Proper wiring systems are involved to fetch the data to the control station where the data is being analysed using dedicated peripherals [1]. But, this wiring system of the entire site of application to obtain the data becomes complex and hazardous when the area becomes wider. This system of monitoring is applicable in areas where the spread of the application is less such as parameter checking of some appliances, environmental monitoring of some rooms or a certain zone, soil condition monitoring, etc. Distributed control system (DCS) came into the forefront to overcome the wiring related drawbacks of DAS as they employed PLCs to monitor the parameters.

1.1.2 Distributed Control System

Process oriented plants such as power station, bottling plants, chemical plants, and paper processing plant involved Distributed Control System (DCS). Here the control system utilized field bus and local wiring network to collect the field data and directly connect with the DCS [2]. Programmable Logic Controllers (PLCs) helped to broadcast the data towards the control station set up by the DCS to have a visual overview of the processes in the plant. But, DCS is not suitable for remote location data collection from areas situated at large distances from the control station. The entire process of collection of the data from these locations becomes very complex and costly. This necessitated the introduction of SCADA system that helps to monitor all the parameters related to the application simultaneously at the control station.

1.1.3 SCADA System

The Remote Terminal Units (RTUs) form the skeleton of Supervisory Control and Data Acquisition (SCADA) system to measure the process related parameters even from remote locations. RTUs are placed at the different fields of operation to gather the remote data and transmit them to the control station. The operators stationed at the control station therefore can extract a detailed knowledge regarding the processes [3]. The primary necessity of any monitoring system is the quality of data sent which is a major issue for SCADA systems at conditions when all the field connections have failed. A database of previously collected data is maintained by the SCADA control station which necessitates having enhanced security system. This is essential for SCADA systems since it has potentially slow and unreliable connections. Traditionally, the closed and controlled industrial environments utilize SCADA. So, alternatives are needed to be thought of to replace the SCADA systems for decentralized power systems [3]. Moreover, utilization of such high cost systems in small indoor environments is not suggested due to increase in installation costs for such small scale applications. But, still several problems are linked with these existing monitoring methods which prompted the use of Wireless Sensor Networks (WSN).

1.1.4 Problems Associated with Monitoring Techniques

Manual measurement of data is most reliable and is less expensive when applied on a smaller area. However, the limited range of data measurement, the time consumption of the processes and increased risks of tripping of the sensors are some of the disadvantages associated with manual measurement technique [1]. Implementation of wiring systems to the remote areas becomes difficult for monitoring the different conditions of the area related to climate, electricity and other structural health monitoring.

Continuous supply of power to remote areas such as forest areas and hilly terrains through the conventional power generation system is not always cost effective since connection to these areas to the grid is difficult. This has resulted in power generation from non conventional energy resources like solar, wind or hydro and biomass especially for rural areas. The reliability and feasibility associated with the wiring systems for collection of the data is poor. The complexities associated with the wiring connections used in DCS system is also reduced using the wireless sensor network. SCADA systems initially were developed as centralized monitoring system which performed the communication through the help of Wide Area Networks (WANs). The centralized architecture of SCADA system enables data storage and control only at the central location of the system. This architecture makes the whole system non flexible, expensive and having low data rate [3]. These problems of SCADA can be fairly overcome using wireless sensor network [4].

The existing online monitoring techniques mentioned earlier are therefore slowly being replaced by wireless sensor networks in all spheres of monitoring applications. WSN has provided easier solutions to process oriented data monitoring, control and data processing for varied fields of application. WSN has been found to be mostly useful in remote data monitoring from sensors placed at large distances. This has made wireless sensor networks the most preferred online monitoring technique owing to its various advantages. The merit of WSN lies in the fact that it can be used in any experimental environment to monitor the process data. The non centralized WSN architecture requires several sensor nodes to be distributed throughout the entire network to make up the monitoring architecture. Local sensor nodes collect data from the individual process parameters allowing a multiple number of parameters to be monitored simultaneously. The high data rate of WSN and low cost of the system architecture ideal for real time data monitoring tools. The control station associated with the wireless network helps to maintain a uninterrupted track of the process data from the very beginning. The flexibility in WSN architectures is therefore being favoured to be utilised in future smart grid applications.

1.2 Overview of Wireless Sensor Networks

Tiny sensors are associated with measurement of various parameters such as current, voltage, temperature, pressure, humidity, etc throughout the application area [4]. Multiple wireless nodes named as tags or end devices get distributed over the entire area to collect data from these sensors and transmit the data to the control station. Multi-hop data transmission technique is utilized to transmit these collected sensor values to the control station via a set of wireless nodes called as routers [4]. The monitored data is finally stored in the control station for processing and visualization of the detailed process parameters by the help of the wireless node termed as gateway. These wireless nodes together make up a monitoring and communicating architecture termed as Wireless Sensor Network. These wireless networks enable data to be monitored from remote locations where human intervention to study the environmental situation is impossible [5]. The advancement in Very Large Scale Integration (VLSI) technology has helped to make large progresses in the development of the modern wireless nodes.

Three basic components namely a sensing sub-system, a processing interface, a storage component and a wireless transmission module are integrated to form a small device known as the wireless sensor node [6]. The microcontroller forms the heart of the node which is interfaced with other smaller size semiconductors, radio transceivers and other associated components on a single board to fabricate a complete sensor node [7]. All the involved sensor nodes perform in a cooperative manner to perform the roles of cooperative data acquisition, processing and data communications in the wireless sensor network. The data transmission pathway from the source to the sink node is determined by calculating the shortest path determined by suitable routing algorithms. These local sensor nodes are capable of processing small amount of data in their allocated memory. The data monitored by the nodes helps to recreate the entire network design along with the collected data at the control station. The flexibility of using the network in various fields has brought wireless networks into the forefront as the monitoring tool. Smart grid networks would use smart sensors and wireless sensor network as the medium of data collection and transmission respectively for real time data delivery in future time critical applications.

1.3 Fields of Application of WSN

The low cost, low power and self organizing nodes enable them to be used in variety of applications. Environmental monitoring is one of the major fields of application of Wireless sensor networks [8]. Meteorological and geographical research, planetary exploration and flood detection are some of the important aspects covered under environmental monitoring [5]. Detection of small animals and insects, tracking of birds are some other forms of environmental monitoring performed by WSN [9]. Monitoring of indoor living environments [10], habitats [11], greenhouse monitoring [12] and forest monitoring [13] are also different aspects that come under environmental monitoring. Detection of Weather and monitoring of unusual climatic conditions are some other important roles performed by WSN [14]. In military applications, tracking of enemy, positioning of the target, condition of equipment monitoring and surveillance of battle lines are some other important applications of WSN [15]. Sensor nodes are placed to collect information about enemy position, enemy equipments and for battle field assessment very easily and accurately. Wireless sensor networks have been also used recently to check the soil composition and quality of different agricultural lands [16]. The humidity monitoring of the agricultural soil is also an application of wireless networks [17]. Animal tracking and health condition monitoring of the animals are recently being done by help of WSN [18].

Wireless sensor networks have been used in several process related industries. For instance, WSN has been utilized in chemical industries to find out the chemical concentrations in various processes [19]. Factory automation and operation control of different valves and sensors can be also done using WSN. The safety limit of working in the industry can be determined using the utilization of wireless network to protect the workers from any sort of danger [20]. Applications related to civil and construction engineering also utilized WSN to test the quality and strength of the structures developed by them [21]. Power industries have utilized WSN to monitor the power generation and transmission systems. Fault location detection in transmission systems is another additional application of WSN [22]. Recently, "stick on" sensors are being used in power grids for smart monitoring of power flow amongst the grid and the home area network. Traffic monitoring [23], health condition monitoring of people [24], space explorations [25], smart home applications along with utilization of robotic units [26] have all used WSN nowadays as the preferred tool. The wireless communication technology to be chosen depends on the type of application where WSN is being implemented and thereby needs a detailed study.

1.4 Various Wireless Communication Technologies

A variety of wireless communication technologies have been utilized in various types of applications. Based on the data collection and communication methodology, they can be further sub divided into several categories such as satellite communication, WiMAX, Wi-Fi, Bluetooth and ZigBee technology.

1.4.1 Satellite Communication

The most primitive type of wireless communication technology is Satellite Communication. This type of communication helps people to remain connected virtually to anywhere and anytime in the world. The most common example for this communication is mobile phones. Even the orbiting satellites sent to space by several organisations send the information collected by help of radio signals via satellite communication [27]. Several other powerful broadcasting devices such as portable modems and satellite phones have come into existence that use this mode of wireless communication but they are highly expensive [27]. Satellite communications are therefore not suitable small area monitoring systems.

1.4.2 Worldwide Interoperability for Microwave Access (WiMAX)

The fast web surfing facility has become a necessity to the human beings nowadays. WiMAX is an example of such wireless broadband system which provides data delivery rate of about 30 megabits per second [28]. Several customers get connected with the same internet cloud and thereby the speed of data transfer provided by the server gets slower than hard wired broadband systems. However, the installation cost gets reduced if a very wide area is being considered where wiring becomes costly. WiMAX is one of the versions of 4G network in phones [28]. A typical representation of a WiMAX broadband system with various electronic devices connected to a common server cloud has been shown in Figure 1.1. But these wireless technologies are not suitable for home environment monitoring since other devices available tries to become a part of this network resulting in higher amount of interference.

Figure 1.1 Representation of a WiMAX broadband system [29]

1.4.3 Wireless Fidelity (Wi-Fi)

One of the most common technologies utilised nowadays for low power wireless communication is Wireless Fidelity (Wi-Fi). This feature of communications has been recently used in electronic devices like laptops, smart phones, local area networks etc. The wireless router acts as the communication hub which sets up the Wi-Fi network in the desired area [30]. The range of Wi-Fi is less than WiMAX or Satellite Communications due to low power of transmissions. A local area network is set up by the help of the wireless router and all the users within the proximity of the range of the router can connect with the network easily. The convenience in access of the routers, ease of set up of a local network and portability of the routers are the main advantages of the Wi-Fi network. This network is very common in setting up a communication infrastructure in offices and universities as it provides the ability to increase the number of clients [30]. But the Wi-Fi networks are highly prone to interference effects which often hamper the data rate of the networking. The implementation cost of the Wi-Fi networks is high since the router deployed at every level adds to the cost of the network. Moreover, security threat is a major factor that affects this wireless networking technology, thereby needing security password for each client.

1.4.4 Bluetooth

The wireless technology most suitable for short range communications is the Bluetooth technology. Bluetooth is used to connect different electronic devices with each other to transfer and share data [31]. Mobile phones, Bluetooth earpieces and speakers, wireless mouse, keyboards use Bluetooth technology to get connected with each other. Two devices supported with this technology are connected by the pairing process through their respective identity addresses. This eliminates the interference effect and enhances security of the system. The power consumed by the Bluetooth devices is also low since it consumes power only during data transfer and data sharing. However, the transmission range of the Bluetooth devices is limited to 15 feet to 50 feet which does not allow this technology to be used in large infrastructures.

1.4.5 ZigBee

Keeping the adversities of the other wireless technologies in mind, it has been found that the modern ZigBee based wireless communication technology fulfils the need of low cost, low power wireless sensor networks. Power required for the installation of ZigBee nodes is almost 1mW or even less and the small sized routers enable easy network set up [32]. The range of transmission of the network is high compared to the Bluetooth technology which is achieved by direct sequence spread spectrum (DSSS) [32]. ZigBee is formalized by IEEE 802.15.4 radio standard which is suitable for low range, low power data communication. The interference effect associated with the Wi-Fi technology is highly reduced in case of ZigBee technologies which makes it suitable to be used within homes, buildings and industries. The advantages of ZigBee network related to low cost architecture and high performance delivery has made its usage helpful in home automation, smart lighting, war fields and intruder warning traffic management [33]. Figure 1.2 depicts a typical ZigBee module.

Figure 1.2 A typical ZigBee module [33]

The rapid development of ZigBee technology as the wireless communication standard and its cost effectiveness has made it suitable to be selected as the communication technology in this work. To ensure the most reliable performance of the designed network and to enhance the network lifetime, the deployment of the ZigBee based wireless nodes needs special attention.

1.5 Need of Node Placement in Wireless Sensor Network

A typical wireless network application involves a large number of sensors which communicates between each other and with the base station to share the data. Therefore, proper communication link establishment is necessary to ensure reliable data transmission during the entire duration of monitoring process. Proper node deployment strategy helps to develop good coverage and strong network connectivity. The nodes placed in the network are assigned special functions depending on their position of the network. Failure of any one of the nodes therefore affects the performance of WSN [34]. The design cost of the network architecture is also dependent on the node positioning in the network. The reduction of energy consumption during data transmission in the designed wireless network is the main aim of node placement. The low energy consumption of the network ensures the signal attenuation is reduced and the lifetime of the network is enhanced. As the distance of transmission increases between two nodes, the power decay in the network also increases. So, proper node deployment ensures that power decay is minimized. The signal attenuation associated with the interference caused by the obstacles and signal crossover due to presence of other wireless technologies is somewhat reduced. This helps to maintain the signal to noise ratio (SNR) of the network and reduce the packet losses. The base station positioning is one of the other aspects that need to be taken care while designing of the network architecture.

Sometimes, the wireless network needs to be deployed in very hostile environments where strategic positioning may not be possible. The node deployment strategy in those environments should ensure robustness of the WSN against node failure, fault and external attack on it. Implementation of WSN in vast fields of monitoring need to ensure proper node deployment at right positions to maintain the communication links over such large distances. Computational geometry [35] and optimization techniques [36] are some of the important methods undertaken to ensure efficient node deployment. Since it is a very complicated task to fulfil all the requirements of node deployment, hence the role of optimization techniques become more significant in this case. Maximizing the coverage area, minimizing power consumption, reducing the cost of network architecture, establishing connectivity and providing reliability are some of the primary parameters that determine the wireless network performance [37]. Apart from these, the node deployment strategy is also dependent on several other factors such as the hardware and the software used, instalment cost of the various components, size of the area of application and the environment where the wireless network is being implemented. One of the other important objectives of node deployment strategy is energy management during data transmission in the network which needs a special mention.

1.6 Energy Management during Data Transmission in WSN

Energy management of the network is a major issue concerning the wireless sensor networks. Resource limitation and limited power supply based on battery supply energy is a key drawback of ZigBee based wireless nodes. The nodes near the base station are provided with the responsibility to collect data from all the nodes and store it in the base station. These nodes therefore have to handle a large amount of data often resulting in excess energy consumption of these nodes. Therefore, rotation of role of the nodes near the base station is necessary to avoid the problem of unequal energy consumption in the network [38]. Multi-hop data transmission and broadcasting data transmission pattern of WSN are the other factors that results in unequal data consumption in the network. This uneven energy depletion occurrence in the sensor nodes has been termed as Hotspot issue. This problem gets more prominent when the number of sensor nodes in the network increases [38]. Formation of culture mesh and election of cluster head also play a major role in gathering of data and its transmission in energy efficient manner. The adopted clustering amongst the nodes is a proven effective approach to extend the lifetime of the wireless sensor network with lowered energy consumption. The sensor nodes in the network are generally powered by the on-board batteries to supply energy required during data transmission. But, dissipation of the maximum available energy of the nodes needs battery replacement and often this replacement of the batteries becomes difficult based on the area of application [7]. This limitation of inconsistent power supply to the nodes has promoted selection of energy-aware protocols. A better utilization of the power supplied to the sensor nodes would enable longer run time of the network. Proper selection of the number and position of the cluster heads would help to diminish their hasty energy depletion pattern and thereby boost the usable time of the network. The efficient performance related to energy efficiency and network lifetime is highly dependent on the extent of control provided by the designed topology of the network.

1.7 Necessity of Topology Control in WSN

The topology control in the wireless network primarily determines the performance efficiency of the wireless network. The protocols involved with topology control emphasizes on the connectivity of the node to provide a perfect idea about perfectness of monitoring of the sensors used in the application [39]. The wireless networks involve dense deployment of nodes which are susceptible to failures and interference as these are battery based nodes which mainly depend on broadcast communications for transmission of data [40]. The links are often out of order due to different reasons such as power exhaustion of the nodes, node failure or dynamic variation in node positions. The choice of network topology is dependent on application type and the node to node communication links that are needed to be established. Excess sensor node implementation results in overcrowding of the network leading to need of choice of topology while same is the case due to use of lesser nodes resulting in communication breakdown [41]. Topology control has immense impacts on efficient energy utilization and life span of the sensor nodes used in the wireless network.

1.7.1 Energy Efficiency Enhancement through Topology Control in WSN

The modern day wireless network has aimed to bridge the gap between the increasing demands for deployment of wireless nodes with the limited energy supply for the battery based sensor nodes [42]. Recent protocols have recently aimed at different topology control techniques to enhance energy efficiency and related network performance of WSN. A recent topology control technique named as Smart Boundary Yao Gabriel Graph (SBYaoGG) algorithm was designed for energy efficient communication based on low interference in the wireless network [41]. In another work, Quorum based load sharing control protocol (QLSCP) proved suitable for harsh environments. This protocol helps in choosing appropriate communication pathway amongst the nodes by calculating the location of the sensors [43]. This approach of topology design control maintained the communication links amongst the deployed sensor nodes with highest energy efficiency. In a later work, the topology control methodology focussed on the graph theory for controlling all the sensor nodes from the central base station. The power consumption cost was somewhat reduced through this approach, however was ineffective when the topology was destroyed [44]. The topology control methodology also focussed on increasing the lifetime of the deployed sensor nodes in the designed wireless network.

1.7.2 Increment of Lifetime of Sensor Nodes by Topology Control

The energy storage capacity of the associated batteries of the sensor nodes determine the lifetime of the sensor nodes. The designed topology control algorithms thereby aimed at increasing the battery lifetime these WSN nodes by designing of multipath architecture to communicate with the sensor nodes. The energy efficient data transmission in the network by load balancing amongst the nodes helps to increase the lifetime of the kits. An earlier work focussed on designing a distributed algorithm to ensure maximum transmission coverage with minimum node deployment in the network [45]. Minimum energy usage at the lowest level of the network was determined while communicating from sensor node to the base station thus enhancing the battery life. A recent topology control helped to design a optimal network strategy based on some mathematical calculations for wireless sensor networks for presence of several obstacles [46]. The wireless sensor network was divided into several sub networks by the algorithm during presence of obstacles. Performance improvement of each of the sub networks through the topology control algorithms sums up to boost the lifetime of WSN. Recent works done on modelling of routing algorithms based on IEEE 802.15.4 protocol for low power and lossy networks (RPL) helped to eliminate the problems of network breakdown due to single node failure [47]. The energy efficient wireless network designed through this topology control methodology can have many applications. It can further be utilized for demand side management [48] in home environments which is coming up very fast in developing economics.

1.8 Demand Side Management through WSN

The communication infrastructure in the residential energy management system must focus on establishment of proper links to monitor the loads of the different appliances installed. Proper communication links needs to be established between the smart devices and the energy management unit (EMU) to control the operation of the appliances. When considering demand side management for large residential conclaves, a central control unit is set up in the complex which connects to all the individual home networks along with the utilities associated with each household [48]. Wireless sensor network has come up recently the ideal technology which helps to fulfil all these requirements for demand side management system. The wireless network enables bidirectional data flow in the network which helps in controlled and reliable operation of the different appliances necessary for proper home area energy management [49]. WSN performs the dual nature of monitoring the data and sending the control signals from the EMU to schedule the appliances. A wireless sensor home area network (WSHAN) was considered in a later work which utilized ZigBee protocol for message exchange among the different entities involved with residential energy management [50]. In recent days, small scale solar and wind installations are being made to support the excess demand from the customers. In order to monitor the proper functioning of all the individual parts of these solar and wind installations, multiple sensors are being utilized which efficiently communicate to the control station by a WSN. Several approaches including optimization based on meta-heuristic algorithms are performed in the wireless controlled EMU to provide a co-ordinated working of the appliances and scheduling of the renewable energy sources. Energy efficient, cost effective and reliable wireless sensor networks thereby form an integral part in today's demand side management schemes.

1.9 Objective of the Work

The primary objective of this work is to analyse the performance of the wireless network in indoor network environment. This work can be separated into three sections. In the first part, the reliability of the wireless network in indoor network environment has been studied. The wireless network implemented in the indoor environment is subject to probability of data loss due to existence of metallic structures, thick walls and glass structures. This results in interference in the network which increases the signal attenuation and thereby the Signal to Noise Ratio (SNR) of the communicating medium is affected. This work aims to improve the reliability of the network by proper placement of optimal routers in the intermediate position by help of suitable soft computing algorithm. A new algorithm named as Cascaded Cuckoo Search Algorithm (C-CSA) has been utilized in this work to optimally place the intermediate routers with the main aim of reducing the signal attenuation. Signal attenuation occurs due to excess node deployment resulting in signal crossovers in the network or due to lesser router placements which results in out-of- range sensors. This necessitates the choice of optimal number of routers and its efficient placement in the network. The different network parameters related to signal attenuation, energy consumption, SNR and Packet Error Ratio has been studied. Optimal number of router selection ensures that excess routers are not employed leading to signal crossover and also that routers are not too less resulting in communication breakdown. The estimation of energy consumption helps to estimate for how long the network can remain active. The SNR of the network helps to understand how good the communication architecture and whether the effects of noise in the communication channel are too much dominant. The evaluation of the parameter Packet Error Ratio helps to understand what percentage of packets delivered does not reach the control station. Ideally this factor must be zero to ensure all the data reaches the control station. The results related to the node placement obtained by C-CSA have been compared with the results obtained by other routing algorithms; objective being the checking of C-CSA performance over other**.** Different routing protocols to determine the data transmission pathway through the implemented wireless nodes has been studied and their performance has been compared. The study of the routing pathways developed through the different routing protocols helps to choose the ideal protocol suitable for a particular type of application. The routing protocols are chosen based on the priority of the clients between quick real time data delivery and utilization of lesser nodes in the network. A new routing protocol named as Level Based Routing (LBR) protocol has been proposed and the results have been compared with OSPF protocol through hardware implementation while collecting data from different energy sources. The efficiency of the router placement has been tested and compared with other soft computation techniques to establish the superiority of the proposed methodology. A cost based analysis of router placement in wide area based wireless networks has also been done to identify the most cost efficient design of wireless networks according to the type of application.

In the second part of the work, it has been aimed to improve the network lifetime. This has been achieved by delaying the round of first node death and increasing the residual energy of the nodes. The network stability and scalability of the network was in turn improved through this approach. The new algorithm termed as Residual Energy based Distributed Clustering and Routing (REDCR) protocol jointly focuses on the objective of clustering and optimally placing the routers in the network. This approach attained equal distribution of the energy consumption amongst the implemented nodes. The rotation of the role of cluster heads in the network has prevented any overloading of any of the nodes during the rounds of data transmission. The efficient improvement in the lifetime of the network helps to reduce the number of replacements of the batteries hence increasing the total savings while maintaining the network quality. The performance of this algorithm has been examined with reference to other clustering and routing algorithms to establish the efficiency of the algorithm.

An application specific work of wireless network in home energy management system has been depicted as the third part of this research work. A wireless network controlled demand side management scheme for home area networks based on Cuckoo Search algorithm has been proposed in this part to control the scheduling of the appliances. The appliance shifting from peak price hours to low price hours would aid in reducing the cost of electricity usage for the households. A design based on installation of roof top solar panels is proposed for low demand prosumers so that it reaps economic benefits over the year. This proposed design helps to project a future design of a smart grid network for large scale applications such as energy monitoring in university campus or residential conclaves based on efficient wireless node deployment.

1.10 Novelties and Contribution of the Work

This work has been divided into several parts related to reliability improvement, lifetime enhancement and application of WSN in home energy management. Several novel ideas have been promoted thereby in this work related to these topics. A new data transmission approach based on Level based Routing (LBR) protocol has been suggested and its working has been tested in a small network deployment in comparison to existing routing protocols. The novel objective function designed in this work aimed to optimize the number of nodes deployed in the network of pre-fixed area by a novel approach termed as Cascaded Cuckoo Search Algorithm. The designed objective function focuses on minimizing the signal attenuation with consideration of the effect of walls and other electromagnetic waves in the network. The study of packet delivery ratio for reduced signal attenuation through software and hardware implementation has been performed. A novel parameter termed as Router Placement Efficiency (RPE) proposed and maximized through router placement in a 2-D network by designing the mathematical formulation based on minimum signal overlaps and keeping minimum number of sensors (ideally zero) out of the coverage area. The optimization is done through CS and modified CA algorithm and the results have been compared with a previous work using GA algorithm. A new work based on determination of the architectural cost of the network has been studied for two design schemes implementing star and mesh topology.

In order to improve the lifetime of the network, a new mathematical formulation has been suggested for selection of cluster heads in every round of data transmission based on the individual energy of the nodes after each round of data transmission. A novel hybrid approach using LEACH and Cuckoo Search Algorithm named Residual Energy based Distributed Clustering and Routing (REDCR) algorithm has been utilised to solve a mathematical problem of cluster head placemen. The designed mathematical formulation is based on residual energy of the nodes; inter nodal distances and the maximum network coverage. This new approach aims to improve the lifetime and throughput of the network with reduced energy consumption. Performance study based on variation in cluster heads in terms of network lifetime and energy consumption through modified approach of CS-LEACH Algorithm has also been done.

Wireless Network controlled solar integrated novel home energy management scheme has been proposed here to study the cost benefits achieved by the low demand prosumers. The wireless controlled energy management unit focuses on scheduling of the high power appliances to reduce the electricity energy usage cost. The appliance shifting is based on the comfort hours of operation of various household appliances and the time of the day tariff structure. To achieve more cost benefits, the design proposes installation of solar roof top panels of appropriate sizes with low payback periods. This new proposed scheme helps to design future smart grid architecture for energy management in a university campus through proper node placement and efficient communication architecture.

The novelties related to the work have been highlighted below:

I. Development of C-CSA algorithm to simultaneously optimize the number of routers and signal attenuation.
II. Design of novel mathematical formulation for signal attenuation minimization in the network.
III. New parameter “Router Placement Efficiency” has been proposed to test network coverage and number of signal overlaps.
IV. Cost benefits for wireless network design for wide area implementation tested through newly designed objective function.
V. A novel algorithm, REDCR, jointly attained the objective of clustering and routing.
VI. Novel mathematical function designed to choose the cluster heads in the network by random rotation through LEACH protocol.
VII. A new design scheme for low demand prosumers has been proposed which involves installation of rooftop solar panels and appliance operation control through wireless sensor network.
VIII. A novel Cuckoo Search algorithm based home energy management scheme is planned which shifts appliance operation based on tariff structure satisfying the customer’s comfort requirements to earn economic benefits.

1.11 Organization of the Thesis

This thesis has been divided into nine chapters to provide a detailed representation of the work performed during the entire course. Chapter One introduces the readers to the importance of wireless sensor network in recent monitoring applications. It discusses about the necessity of the proper node placement in the wireless network and its application in recent home energy management applications. The objective of the work, novelties and contributions are also enumerated here.

Chapter Two provides a detailed literature survey on the sources of data loss in the wireless network. A brief discussion about the previous works done to identify the data loss in various architectures and the main parameters determining the packet losses in the network has been presented. A review on the works done related to reliability and lifetime improvement of the network has also been offered.

A detailed presentation about the node placements in the network and the main objectives of node placement in the network has been discussed in Chapter Three. The node deployment strategies and the different routing protocols involved in determining the data transmission through the implemented nodes has also been offered. The application of soft computing techniques in node placement problems and the implementation of WSN in renewable energy based monitoring have also been analysed.

Chapter Four introduces the modern day home energy demand side management schemes where WSN can be implemented as the controlling unit. The time of day tariff infrastructure and the importance of appliance scheduling to achieve economic benefits have been discussed in this chapter as well.

The mathematical formulations designed to solve the various problems related to lifetime enhancement, reliability improvement and energy management in home environment are presented in Chapter Five. The novel mathematical propositions of this work have been discussed in detail in this chapter.

Chapter Six talks about the various solution methodologies implemented during this work. The novel Cascaded Cuckoo Search algorithm utilized in this work for node placement in the wireless network has been discussed here. Efficiency related to node placement and cost benefits by router placement has also been studied. The novel REDCR algorithm designed for lifetime enhancement of the network has been introduced in this section. The working of the cuckoo search based home energy management scheme has also been detailed in this chapter.

The hardware kits and other instruments implemented during the course of the work have been presented in Chapter Seven. The input conditions considered for simulation purpose is also given in this chapter.

Chapter Eight represents the results section related to the various works performed during the entire study. The results are related to reliability improvement, lifetime enhancement and cost benefits related to home energy management scheme. Several case studies and comparisons with previous works in literature have been performed and the detailed analysis of these results has been presented in this chapter. A future smart grid design scheme for university campus has also been promoted at the end of this chapter.

Chapter Nine concludes the entire work showing the superiority and methodologies of the proposed work related to wireless networks. Some future scopes related to the presented work have also been put forward at the end of this chapter.

In order to fulfil the objectives of reliability improvement of the wireless network, the sources of data loss in the network need to be identified. The various reasons that may lead to data loss, the network characteristics based on the data loss and the determining parameters that define data loss need to be evaluated. The sources of node failures due to energy extinction may lead to node deaths that result in entire data loss monitored by that node. Therefore, extension of the lifetime of the nodes has been considered through conservation of residual energy of the nodes. The different works found in literature based on the sources of data loss, its effect on the network performance and the possible control measures related to the wireless network design undertaken till date have been surveyed in details in the next chapter.

Chapter 2

State of Art Related to Wireless Sensor Network Performance

Establishment of reliable wireless communication links in complex environments is one of the important steps that make sure minimization of data loss to enhance the wireless network performance [51]. The nodes in the wireless sensor network are spatially distributed across the entire network with the aim to collect the data from the various sensors distributed throughout the network. A transmitting node often does not find any neighbour node in its transmission range making communication in such scenario susceptible to breakdown and the monitored data being lost. These sensor nodes receive energy mainly from batteries and often the battery gets exhausted hampering the network lifetime and network reliability. The nodes are of limited resources and they are often unable to process the received data when there is a data overhead. The network lifetime of WSN is dependent upon the topology of the network, the data handling capacity of the sensor nodes, energy consumption during transmission in the nodes and the routing protocols applied. Designing of energy efficient routing algorithms for WSNs can thereby ensure an architecture that gives best results for the total energy usage in the network, reliability in communication and reduced cost of the network set up. Other than these, data lost from the unattended nodes or due to other adversaries in hostile environment also affects the reliability of the network. The present day industrial plants, machineries and other data centres may utilize the sensing and remote monitoring features of the wireless networks to deliver sensed information [52]. This needs a designing of a reliable architecture to ensure no important data loss while data is being transmitted to the control station. Image and video transmissions through wireless networks also become a challenging task since these types of transmissions are constrained by both reliability and real time application requirements [53]. Resource constraints of the nodes, ever dynamic topology according to applications, interference prone environment, node attacks, Quality of Service (QoS) and the data transmission time are also the responsible factors affecting the reliability of the network [54]. These factors and their effects leading to data loss therefore require a thorough understanding. The determining parameters that detect data to be lost in the network need to be closely monitored. The different wireless application specific architectures and the nature of the communication network also need a detailed consideration to understand the chances of data loss. To reinforce the acceptability of WSNs as a dependable technology in wide area applications such as residential conclaves, university campuses, hospitals and industrial domains, the works available in literature about ensuring reliability of the network are essential to be understood along with the available security models.

2.1 Effect of Variant Sources Leading to Data Loss

Wireless nodes communicate data in the application area based on radio frequency (RF) signals mostly at a frequency band of 2.4GHz. But these RF signals based data transmission are subjected to signal interference owing to existence of different metallic structures, obstructions and other radio signals in the area. Thereby, signal interference is one of the primary sources that results in data loss. The wireless node and the chances of its failure are mostly responsible for the data loss in the network. The presence of dynamic topology and continuous node reorganization in the network may lead to signal attenuation and communication link failure which may result in data loss during transmission. Introduction of malicious nodes and other node attacks also hampers packet transmission in the network.

2.1.1 Data Loss due to Interference

Interference is defined as anything which alters, modifies or disrupts any message signal that is being transmitted. In case of wireless sensor networks, all the nodes transmit data through RF signals and several radio waves are present in the same area. Often these RF signals, come in the pathway of another RF signal resulting in interference. Increase in the quantity of nodes in a certain network and co-existence of two wireless networks are the main contributors to the interference caused in the network.

2.1.1.1 Interference due to Increase in Number of Nodes

With the increase in number of wireless devices in the network, the short range and high data rate communications often results in sharing of the same frequency band causing amplification in interference of the network [55]. The performance of the devices is degraded to a certain extent due to these signal crossovers. However, this interference in the wireless network is unavoidable thereby decreasing the throughput of the entire network. An experimental work had been performed to calculate the network throughput in a strongly interfering network where data transmission takes place through multi-hop technique [56]. In this experiment, two separate system models were chosen and it was assumed that whenever there is a slight collision due to time and frequency, overlap between packet deliveries occur and the entire data is lost. The time duration for packet delivery from two different sources was chosen to be different, unlike in other works, but the packet transmission occurs through the same frequency channel [56]. It was observed that after the active time interval, there was an overlap of data whenever packets were sent from different nodes simultaneously. It was considered that a lower limit on the throughput was the limiting factor in cases where the co-channel interference (CCI) did occur [56].

It has been proved through various experimental set up that multi-hop data transfer through a large number of nodes causes more interference when the data transmission takes place through same frequency channel even with variable beaconing interval. Interference can also occur when two different wireless networks existing in the same region have different frequency channels of operation.

2.1.1.2 Co-existence of Two or More Wireless Networks and Related Result

Wi-Fi, ZigBee, Bluetooth are some very common low-power wireless technologies that are being used nowadays for measurement purposes in different environments which enables digital data communication in smart environment. These networks have varied data rates and different frequency channel of operation. But the bandwidth of operation of a certain wireless technology may include the frequency band of operation of another technology leading to signal crossovers.

2.1.1.2.1 Interference among Different Wireless Technologies

The most widespread wireless local area network (WLANs) was developed using Wi-Fi because it provided good data transmission rates and was easily used for connecting the measurement devices due to its plug-and-use capabilities [57]. But it has been observed Wi-Fi is the potentially most interfering source for modern instrumentation with other wireless technologies having the Wi-Fi band of operation between their bandwidth and operating frequencies [58]. The study of disturbance effects during measurement at different measurement stations and in the spectrum analysers or digital oscilloscopes due to Wi-Fi implementation needed an analysis [59]. It was analyzed that the performance of high-dynamic-range instruments like traditional spectrum analyzers showed high performance decay. The results of the performed experiment proved that the Wi-Fi transmitter had significant disturbance effect when the other source was situated at a distance less than about 5m and for signals below −60dBm [58].Works on design of network based on co-existence of Wi-Fi and other Heterogeneous small cell networks were also performed [60]. With an increase in demand of data communication, small network architecture and hybrid network architecture were given importance to increase the throughput of a network. Unlicensed 2.4 GHz and 5 GHz frequency band spectrum were the most commonly used frequency bands used for designing these heterogeneous networks. It is worth noting that technical issues such as efficient spectrum sharing and interference mitigation related to the coexistence of Wi-Fi and other heterogeneous cellular networks were not considered properly when they worked in unlicensed spectrum [61]. Figure 2.1 represents the inability of data transmission to certain nodes when there is co-existence of two wireless networks in the same region. The wireless sensor nodes *N1* to *N6* are spread between two wireless network areas, out of which *N3* is common to both the networks. This node faces interference due to transmission of data through two frequency channels and hence the data perceived by this node is often lost.

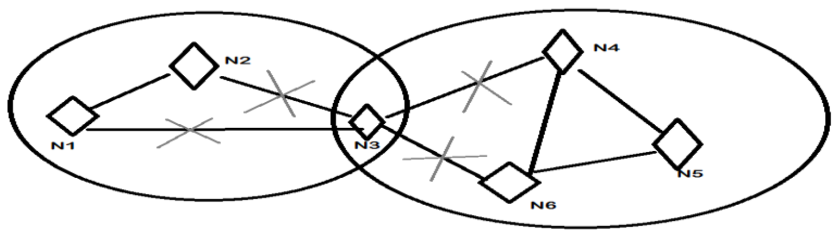


Figure 2.1 Interference due to existence of multiple networks

Experimental works have shown that set up of a wireless network based on simultaneous presence of two wireless sensor technologies gave rise to interference related data loss.

ZigBee, on the other hand, was the most suitable wireless sensor technology adopted recently for low data rate applications. Therefore, a study of the network involving the Wi-Fi technology and the ZigBee technology is a necessity.

2.1.1.2.2 Interference due to Co-existence of ZigBee and other WLANs

The low cost, low power, lesser data rate and lower complexity features of the ZigBee module promotes the design of wireless mesh network suitable for real time system monitoring, load-demand control and automations of the equipment suitable for smart grid applications. But unfortunately, communication through the ZigBee modules resulted in overlap with other wireless local area network (WLAN) channels resulting in severe degradation of the performance of the network. ZigBee modules were placed in the wireless network based on the guidelines under the interference of WLAN [62]. Two factors namely "Safe Distance" and "Safe offset Frequency" played major role while placing multiple receivers by theoretical analysis, software simulation or empirical measurements. The necessity was visible to eliminate interference as the transmissions occurred between different wireless technologies operating in different frequency bands. A modified frequency agility-based interference avoidance algorithm was designed which helped the idle nodes to switch to 'sleep' modes to avoid interference from other WLANs having lesser latency and low energy consumption [63]. With increasing traffic, ZigBee based networks needed to be arranged at some distance away from Wi-Fi or at more offset frequency to avoid interference. The experimental results suggested that 8m was the safe distance between ZigBee and Wi-Fi while 8MHz was the safe frequency for even a small distance as low as 2m [62]. It provided better interference immunity than both ZigBee and Wi-Fi 2.4 GHz communication protocol and hence adaptable for interference-free environment in smart grids. This method provided information about optimal position of wireless transceivers within power substations to reduce data packet loss during transmission due to interference [64].

Extensive research have still not been able to exactly specify deployment guidelines as to how far away the ZigBee should be placed from the Wi-Fi access point and over which frequency should it operate so that there is no interference. Nowadays, researchers have focused on choosing the wireless technology based on the area of application where it is being used. The problem of data loss due to signal crossover persists in critical areas of application where high quality of data transfer is required.

2.1.1.3 Interference due to Signal Crossover

Some modern applications require video transfer associated with minimum data rate requirements so that the quality of video received by the end user is of satisfactory quality. A modified framework of WSN had been tried elsewhere in order to fix the problem of data loss due to interference by maximizing the throughput of the system [65]. The network designed was subjected to constraints imposed due to self-interference, interference due to cross over of signals between two different networks existing in the area and minimum data rate. The difference of these wireless networks with wired networks is that the volume of data transferred at any instant is large for wireless networks although the quality of service may be reduced if a particular node co-exists in two different network areas [66].The QoS of the network may be enhanced to support data flow in the network even when the bandwidth of transmission was shared between the different networks [65]. The QoS needed to ensure the constraint of self-interference, where the packets of data flow interfere with other packets being transmitted in the same application area along a multi-hop arrangement while designing the framework [65]. To maximize the data flow under these constraints, the framework selectively eliminates some of the sources and the data were redistributed among different sources to meet QoS requirements. The proposed framework readily leaded to a simple and effective admission control mechanism [65]. The large separation between the receiver nodes leaded to different path delays comparable with the rate of transmission thus leading to elimination of interference [67]. The scenario of overcoming the effects of strong interference in case of multiple receivers may be other option. A group of receivers helps in significantly increasing the resistance to jamming and helped to cancel out the interference leading to only a 0.5 dB loss.

All these causes of interference may be interrelated resulting in decrease in efficiency of the system. Research works have still not been able to completely eradicate this effect while projects have been designed and tried to reduce this effect. The wireless sensor nodes and their placements attribute to an important source of data loss in the network.

2.1.2 Wireless Nodes based Data Loss

The low cost low power nodes employed in the wireless network provided a lot of advantages but they also may turn out to be a major cause of data loss due to their poor power back up and limited memory space. Failure of the nodes and the lack of adaptability with the ever changing dynamic architecture resulted in data loss from the wireless nodes.

2.1.2.1 Effect of Reduced Transmission Range and Signal Attenuation at Nodes

Limited memory of the sensor nodes, reduced transmission range and node failures due to poor power back-up had resulted in break of data flow in the wireless sensor networks. A sensor node employing ZigBee module as the wireless transceiver could transmit data within a range of 30m in indoor environment while 100m in outdoor region [68]. Although newly designed ZigBee-Pro modules increased the indoor transmission range to 100m and outdoor range to 1.5km in line of sight conditions, intermediate nodes are employed to relay the data in the network for reliable transmission from the source to the sink. Multipath arrangement of the network by organization of the nodes also increased the reliability of the system because even if one of the relay nodes fails, data is still transmitted through the other available nodes hence improving the efficiency of the system. This was observed by Dohler et.al in their work related to reliability of the system [69]. Signal attenuation is one of the factors which also affect communication within the wireless sensor networks. This is why cooperative communication is given more importance in recent years to combat chances of data loss and increase throughput of the system [70]. A failsafe wireless sensor network was developed in this endeavour to support cooperative communication which ensured successful reception of data at the sink from various sensor nodes situated at variable distances from the sink node. This model prototype is suitable for WSN applications in hazardous and harsh environments like underground coal mines, nuclear plants, and oil refineries etc., where successful reception of data is mandatory. The obtained results showed the advantages of cooperative communication ensuring reliability and timely deliverance of monitored data in the network, lacking in traditional networks [68].

Cooperative communication of data may help in making a failsafe network and prevent data loss due to signal attenuation. However the nodes sometimes are not adaptable to the change in topology of the network resulting in data loss.

2.1.2.2 Node Reorganization according to Topology Change

In static applications such as for the coal mines, under water applications or for military applications, the wireless nodes needs to be kept fixed in application areas to maintain proper connections. But in dynamic applications the connections may break due to mobility of the nodes and reorganization of the routers. In order to locate the devices displaced from their original position, the route reconstruction method was employed so that the data is not lost due to the mobility of these nodes. The conventional method to cancel out the effects of topology change is to reconstruct the routing mechanism, but it results in consumption of a large amount of resources [71]. If the node mobility patterns were regular, then the reconstructions required were less and ensured that the data transmission from the mobile nodes was efficient. It had been observed that cluster tree network performs better than a mesh network even when the routers and the sensor nodes are mobile [72]. The tree construction framework for deployment of ZigBee devices provided a lower power consumption technique than the conventional reconstruction methods [72]. The modern day wireless sensor networks are "self healing" which enables the nodes to rearrange themselves to the suitable topology according to requirement of the network. It aids the network by using limited bandwidth and enhances the efficiency of transmission by providing proper connection from the end devices to the gateway. This technique considers regularity in the mobility pattern of the nodes while reconstructing the topology. Later, a tree topology in ZigBee based wireless network which took care of the mobility issue of the nodes was therefore constructed to understand the situation [71]. This approach deployed routers in specific positions and constructed a tree topology that ensured that the mobile nodes would only move along the path with highest probability of data forwarding. The results showed this framework could help to achieve higher data delivery ratio and longer path range with lesser data overhead than other existing techniques when there was irregular movement of sensor nodes within the network [72].

Node reorganization often becomes necessary in the wireless network when new sensors are introduced in the monitoring area. Addition of higher number of nodes needs a topology change to accommodate maximized data monitoring. In order to overcome the problem of topology change in the wireless network, mobile nodes were designed to adapt with the changes during network reorganization and can also be utilized for mobile applications.

2.1.2.3 Effect of Mobility of Nodes

The ZigBee specifications mentioned elsewhere promoted to find out a procedure to find out the mobile node, when a central server cannot get linked to a certain sensor data [33]. The control station broadcasted the messages to all the available nodes in the network to find out the displaced end device. But, this method was not economic in terms of resources to be utilized and unsuitable when there was multiple instance of node movement [73]. This was not all acceptable in applications like health monitoring where the sensors sent alarm signals to the hospital attendants in case of emergencies [74]. In case, the data delivery stops due to excess mobility of the wireless nodes the alert message was not sent and it resulted in fatal issues. Thus adequate support must be provided to mobility issues while designing a ZigBee network. Designing a wireless network applicable for static applications becomes a challenging task with multiple mobile nodes. It is seen that the employed wireless nodes are often to be blamed for the data loss in the network. But, proper functioning of the wireless nodes are also dependent on the communication links between the nodes, failure of which would result in loss of contact with a particular node.

2.1.3 Data Loss due to Communication Links

Wireless communications in a certain network from one node to another take place through a certain designated frequency band. Radio Frequency signals transmitted from one node to its neighbours helps in communication of data in the forward direction. It is necessary to ensure existence of communication links between the nodes in case of networks applied in wide areas and the sensitive application areas where time to time data monitoring is required.

2.1.3.1 Link Failures between Nodes

Wireless links for communication between sensor nodes is an important factor that influences efficient performance of the Wireless Sensor Networks [74]. During transmission of data in WSNs, every routing protocol is designed in a way that the data transmission between nodes occurs through the shortest available path between the sensor node and the gateway. During a link failure the shortest available path is broken and data transmitted through a longer path resulting in transmission delay and increased energy consumption. To overcome such cases a time dependent model was introduced to overcome the link failures due to limited power supply, excess power consumption of sensor nodes and external conditions like background noise or interference [51]. This model had been put to test using different routing protocols to study the reliability of transmission and investigate the minimum energy consumption model. To ensure communication link assurance along with reduced energy consumption, different link models have been designed by different researchers [75, 76]. Three kinds of situations were conceived in an attempt where the communication link from the server to the client was modelled based on different conditions [75]. In the first case, the link of the source node with the destination node was decreased as the distance between them increased. This is known as the "gradual cover model". This indicated that the source node is mobile in operation and maintains a constant link with the destination node. The second model, known as the "cooperative cover model", was designed keeping in mind that all the source nodes transmitted data to the same destination node which accumulated data as the cluster head. In the third model termed as “the variable covering radius model”, the user could design the network according to his wish. The range of transmission between the client and the server involved intermediate routers which increased the reliability of transmission, however increased the cost of the model comparatively. In another instance, a novel approach was undertaken in order to increase the overall coverage of the network and also to overcome the deficiencies of remote location problems [76]. This approach was designed based on an application of WSN where several sensor nodes were assigned to the application with multiple data handling capacity and was titled as “Covering with Variable Capacities” problem [76].

This problem of communication link especially needs to be addressed when the wireless networks are employed in the critical areas where the wiring connection is not enough to reach all the sections of the application. Proper communication links ensure proper data delivery through a shortest path; it helps to minimize both data delivery time and energy consumption of the network with increased reliability.

2.1.3.2 Link Problems in Wide Area Monitoring

Temporary link failures may occur in the wireless sensor network in such wide area deployments due to conditions like blocking in the path of transmission by external objects such as metallic structures and trees, environmental conditions, noise in the communication channel, interference during RF transmission, inactive node due to power supply failure [77]. On the other hand, higher node deployment in order to cover the entire area looked to be a simple solution, but it resulted in increase of deployment and maintenance costs and also increased interference in the network [78]. Therefore, researchers looked at provisions for dynamic topology change of the wireless networks with time as both the sensor nodes and the wireless links are failure-prone [78]. Introduction of some mobile nodes helped in overcoming the deficiencies of deployment in large areas and link failures. In case of topology change, re-locatable nodes could be moved to different positions to improve the network connectivity [79]. The mobile nodes selected in the network could be functioned to perform all the functions of data collection, data transmission and destination node as required by the system application. In case of static application areas such as coal mines, oil rigs, power plants, the task of estimating the uncovered areas becomes easier [80]. The mobile nodes are employed in such a way that they move towards the uncovered zone with higher priority and act both as sources and relays maintaining the reliability in data monitoring. This helped to increase the area of monitoring of WSNs in static infrastructures by use of mobile nodes. Whenever the mobile peer was within the transmission range of sink node or the gateway, it transferred its own data as well as the data from other nodes which it has collected [80]. This ensured that a continuous link is maintained between the sink node and all the other nodes deployed in the network.

To ensure continuous communication in such wide and critical areas of application, mobile nodes were employed to maintain the communication links, but excess mobility terminates the links and may result in increased energy consumption. Keeping the communication links in good frame may also sometimes result in communication of a certain node with a malicious node in the network. These external nodes attack often prevent data transmission to the actual sink station, thus making the study of data loss due to these node attacks a real necessity.

2.1.4 Consequences of External Node Attacks

Security issues have been one of the major areas of concern in case of critical applications of wireless sensor network. The unattended nodes and the broadcasting of messages amongst the nodes in the network make the nodes susceptible to attack from external sources. The protocols and the routing algorithms along with the hardware of the system are affected by this kind of node attack and it results in corruption and loss of data from the network [81]. The vulnerability of the security system forced the researchers to look at the kinds of attack that pose threat to the wireless sensor networks.

2.1.4.1 Data Loss due to Sybil Attacks in case of Static Networks

Sybil attacks were recognized as the most serious threat for WSN. In case of Sybil attack, the malicious node places many forged corrupt nodes thus misleading the sink node to believe them as several legitimate neighbours [81]. To do so, the attacking network physically captures one node of the network, extract its features and then the same node is reproduced in large quantity. These replica nodes are then placed strategically at various positions in the network thus hampering WSN applications [82]. This attack is of utter importance since to prevent these kinds of attacks specialized hardware is not employed. The nodes being randomly deployed for wide range of covering following the IEEE 802.15.4 protocol, need an efficient system which can detect and tackle the Sybil attacks. Similar types of nodes which are of malicious nature exist in the same network area, resulting in malfunction of most of the network operations such as data aggregation in cluster heads, proper routing following a definite routing algorithm and loss of gathered data. RADS (Rule based anomaly detection system) was planned elsewhere in order to scrutinize the Sybil attacks in IEEE 802.15.4 based wireless networks since the nodes in such cases are randomly deployed throughout the entire network [83]. Using this system, each node periodically monitored the distance of the source node with each neighbour node and sends an alarm if a forged node is detected within the same distance. A standard Path based Denial-of-service (PDoS) attack can be attributed somewhat similar to a Sybil attack. During this attack, the clustering head node in a certain network is made inactive initially and then all the intermediate nodes and the sink node are flooded with data packets all along the routing path [84]. These result in excess and continuous data handling by the cluster head resulting in excess power consumption of the node ultimately making it inactive as observed by Li et.al. In case of mobile networks though, the Sybil attacks are not prevalent but the nodes are still subjected to attacks of other kinds for specialized mobile ad-hoc networks.

2.1.4.2 Node Attacks in case of Mobile Ad-hoc Networks

The most common attack amongst the node attacks in case of Mobile Ad-hoc Networks (MANETs) is the flooding attack [85]. In case of flooding attack, the bandwidth of the network, as well the computational capacity and battery power of the wireless nodes are consumed readily leading to disruption in the routing operation. The MANETs use Ad-hoc

On Demand Distance Vector (AODV) protocol for data routing where nodes send request signals to the destination node for data to be routed. In case a malicious node enters the network, it generates large number of request signals to a certain destination node which are non-existent in the network [85]. When it does not receive any response, it floods the whole network with these request signals leading to consumption of battery power and network bandwidth. Excess flooding may lead to denial-of-service and hence the entire wireless network fails to work. Blackhole attacks are utilized by attackers to gather information from a certain wireless network [86]. In this attack, a malicious attacker node sends fake routing information to the source node as a signal that it is available for routing data. The node appears to be a fresh node that can be utilized for routing purposes, and hence causes the source node to select this node as the routing node. As a result the data is either misused or the link between the source and the sink in the wireless network is discarded [86]. Topology changes are very frequent in case of MANETs due to presence of the mobile nodes. As the existing topology often changes, a malicious node may record a valid control message of a correct node and resends them later when the topology has changed. This kind of attack is known as Replay attack which disturbs the routing operation in a MANET [87]. The most severe of the node attacks in case of MANETs is the wormhole attack [88]. In this type of attack, a pair of malicious nodes acts together. They record packet from a certain network and send them to another network by help of some high speed operation. It is a very modern and sophisticated kind of attack that can be launched against all types of communication and hence data transmission needs high degree of confidentiality [88].

After the main sources of data loss have been identified, it is necessary for the researchers to have an idea about the main defining parameters of a network that helps to identify if the packets are lost in the network. These parameters are interrelated with each other and they help the researcher to find out the most important source associated with the loss.

2.2 Defining Parameters of Data Loss in the Wireless Network

The measurement of the number of packets delivered, energy consumption due to data overhead and the transmission delay in the network indicates the loss of packets during transmission in the wireless network. The limited capacities of the nodes result in data overhead in the particular network. Transmission delay is introduced in the network due to computational burdens in the employed node when there is data overhead. This leads to some packets which cannot be measured giving rise to reduced packet delivery ratio. This makes the management of load at every node to prevent data loss due to overhead.

2.2.1 Data Loss due to Data Overhead

Multiple data coagulation at a single wireless node simultaneously would result in data overhead at the particular node due to its limitation in memory space and computational ability [89]. The data reaching the wireless nodes before the beaconing interval are also sometimes discarded when the nodes are engaged in performing the computation related to the previously received data. Introduction of corrupted data in the network due to malicious nodes or other node attacks leads to unwanted data overhead leading to extra energy consumption to overcome the problem.

2.2.1.1 Data Overhead due to Limited Node Resources

A trade off in the network design related to memory space and security implementations needs to be done in order to design low cost and low power wireless nodes. The wireless networks being implemented in areas with high concentration of data has to adopt the process of clustering to reduce the number of nodes employed in the network. Directed Diffusion was one of the earliest schemes to be implemented which stored all the collected data in the sink node or the base station and the data processing was done in the control station [90]. This was assumed for this approach that the base station was well connected with all the deployed sensor nodes in the network. As the data analysis was done in the external storage unit, the chances of data overhead in the network could be reduced. Geographic Hash Tables approach looked upon storing the data within the local nodes in the wireless network temporarily and was forwarded to the base station only after completion of the previous processing task [89]. This however required large memory space of the batteries leading to increase in wireless node build up cost. Non uniform distribution of the sensor nodes throughout the networks often results in excess energy consumption of a particular node that has been assigned the role to collect that from a cluster of higher number of sensors. Thereby, data centric storage mechanism helped to set a datum of the perimeter for a particular node upto which it can easily collect data [89]. This approach looked to improve the uniformity in handling of the data for each node and thereby increase the overall lifetime of the network. The present security mechanisms that have been existent do not handle suitable data aggregation schemes in energy efficient manner. These security protocols incur data communication overheads and also increases the complexity of computation [4]. The nodes are given the responsibility to encrypt or decrypt the messages at every level of communication which adds to the overburdening of the sensor nodes often leaving out some important messages. End to end encryption scheme is also not desirable since the intermediate nodes fail to obtain the aggregated results in such scenario [91].

The presence of corrupted data also adds to the computational burden and communication overhead at the link and node level. Monitoring of these unwanted corrupted data may result in fatal conditions of the application being monitored since this overburden often leads to discard of the important data.

2.2.1.2 Data Corruption Leading to Data Overhead

The Transmission Control Protocols (TCP) that determine the communication in the network can only estimate the data packet loss due to congestion, however it does not detect the presence of corrupted data in the network [92]. Data packets are exchanged between the source to the sink via a queue of routers responsible to aggregate the data. When all the routers in the transmission pathway have been employed due to excessive data flow, the important data packets lost are termed as congestion loss. In this condition, the routers drop the incoming data packets whenever they are pre occupied with other data processing. The presence of noise in the transmission channels and the malicious nodes introduced in the network can introduce some unwanted data during data transmission even if there is no congestion and is termed as the non-congestion loss [93]. TCP in wireless links cannot distinguish between the congestion and non-congestion loss. Whenever, a loss in data packet is identified by the network, the data transmission rate is instantly reduced considering that the data has been lost due to congestion. In order to overcome this problem, a variation of the transmission protocol termed as VS-TCP (Variable Segment size Transmission Control Protocol) was proposed by Park et.al that aimed at controlling the non-congestion losses [94]. This allows dynamic packet sizing in order to improve the throughput of the system. Whenever the data packets were frequently lost or corrupted data packets were receive, the protocol helped to shorten the packet sizes during retransmission to overcome the problem of congestion and probability of data corruption in the network. During less communication overheads in the transmission channel, the packet sizes were accordingly increased to transmit a bulk amount of the data at the same time [95].

The time interval between receipts of two data packets depends upon the beaconing interval of the nodes and remains fixed throughout the process of transmission. Any increase in this time interval can be attributed to the checking of missing data packet in the sequence and accordingly retransmitting it. This is termed as transmission delay which helps to identify the data loss in some form while transmission in the network and needs proper control during multimedia transmission through scheduling algorithms.

2.2.2 Transmission Delay related data loss

The transmission duration and the interval between two data packets are highly dependent on the amount of data being sent in the network. The delay in transmission time indicates that some data in the process has been lost and the receipt of acknowledgement signals have been hampered thereby delaying the transmission of the next set of data. The transmission delay in the network can be calculated by knowing the beacon interval and the effect on multimedia transmission.

2.2.2.1 Unbalanced Beacon Interval for Transmission Delay

The data transmission through multi hop transmission has been found to be the solution in today's world to transmit data with decreases transmission power and increased data rate. But transmission delays are sure to happen in such scenario when the beacon interval becomes different in case of different paths depending on the beacon interval of the nodes [96]. Wireless coded networks design was one of the alternatives that did not require fixed data rate of transmission. In such networks, the data transmission rate depended on the current stand of the nodes in that transmission channel which was unfavourable since the intermediate nodes did not enough information to recover the lost data packets. In order to overcome this problem, a feedback channel was designed related to the multi hop network that helped the nodes to identify if the data packets were lost from the information received at the control station [96]. But the latency in transmission should be as low as possible in case of real time applications in order to maintain uniform data rate through all transmission channels. The path loss in the transmitting channels often becomes asymmetric since the control station may eliminate one of the transmitting agents from the communication channel to decrease the transmission delay. Therefore, scheduled packet transmission information must be stored in the control station for monitoring applications spanning over longer periods or else only the instantaneous value is stored to avoid any delay. The reliability in packet loss can be enhanced by generation of acknowledgement (ACK) signal from the receiver node. If this signal is not received at the source node, the data packet is considered to be lost and resent through the transmission channel [95]. The acknowledgement signals are especially an efficient solution for data transmission over long distances. The time interval between sending of a data packet and receipt of the ACK signal at the node is termed as the waiting period. But this generation of ACK signals and retransmission of lost packets creates further delay. This is particularly significant for applications responsible for monitoring a large set of data associated with the application. Therefore, modified protocols were designed that aimed at generating the ACK signal only after receiving certain amount of data packet [97]. This reduced the amount of ACK signals and increased the space for accommodating more data packets to be handled by the memory space associated with the wireless nodes. But the major disadvantage with this approach was that often a certain packet missing amongst the entire set remained undetected.

Various experimental methods and modern protocols have recently become decisive on increasing the reliability of the network based on transmission delay and quality of data being sent in the network. These experiments have been applied to both static and dynamic applications to understand the effect of transmission delays in these wireless deployments [98]. In short transmissions, the data was subjected to congestion which required excess transmission delay for smooth accumulation of data from the sensor nodes. On the other hand, to improve real time sensing requirements, the transmission delay needs to be small for long range transmissions [98]. A new data transmission protocol based on two phases namely the data reception phase and the data forwarding phase was designed for delay tolerant networks [99]. The state of mobile receiver nodes was initially analyzed before requesting next set of data during the data reception phase. On receiving the handshaking signals, the data forwarding was initiated from the source node. Although this method ensured low energy and reliable data delivery, but a trade-off was required with the transmission delay in the network due to exchange of the handshaking signals. The transmission delay shows its maximum detrimental effects in case of multimedia transmission where the data is divided and needed to be transmitted through multiple communication channels simultaneously at same rate.

2.2.2.2 Transmission Delay in Multimedia Transmissions

The modern day success of wireless networks has prompted utilization of this technology in multimedia data transmission in electronic classrooms and for video conferences where the applications are time specific [100]. These applications require larger bandwidth for data transmission and the transmission delay in all the communicating channels should be as low as possible. The multimedia is disintegrated into several small data packets sent simultaneously to multiple receivers at the same time at equal intervals. Therefore, efficient broadcasting algorithms need to be employed to remove the chances of interference that may result due to transmission of data from multiple channels at dame frequency band. The fragmented data packets from the source node should reach the receiver node at the same instant where these packets are reconstruct the original multimedia [100]. Concurrent multipath transfer (CMT) technology is one of the upcoming technologies that enable multimedia transmission by maintaining QoS of the network for video transmissions [101]. Stream control transmission protocol (SCTP) enable utilization of mobile nodes to transmit data through the mobile nodes but the different bandwidths of communication channels and the different beacon rates of these nodes resulted in disordered receipt of the fragmented data packets [99]. Thereby, SCTP was combined with CMT in order to take care of the fault tolerance and reduced transmission delay in the communicating channels of the network. Processing delay and transmission delay were identified as the two important delays in the wireless networks which were inter-related to each other and to the memory size of the wireless nodes thereby affecting the throughput of the network. When the memory size of the nodes was small, the processing of the data took longer duration whereas for large memory size, the nodes could handle a large volume of data but that introduced transmission delay in the network. This has prompted the researchers to design delay constrained routing tree algorithms where the whole video transmission scheme was divided into three steps [102]. First the whole period of video content was fragmented into short and equal time frames which were assigned the function of data transmission. These local sensor nodes were updated about the position of the relay nodes to find out the nearest node in the next step. A scheduling algorithm designed at the base station helped to collect the data from these relay nodes based on priority thereby maximizing the throughput of the network with minimum delay [102].

Optimization of the transmission power, reduced transmission delay and adaptation to the pre specified data rate helps to propose an efficient wireless network design. However, the number of data packets received successfully at the control station needs to be monitored efficiently to understand the effect of data overhead and transmission delay in the network.

2.2.3 Data Loss based on Data Delivery Success Rate

Data delivery success ratio helps to give an idea about the number of data packets lost amongst the set of data sent from the source node. For wide area monitoring applications, poor data delivery ratio has significant effects on network throughput and transmission delays are introduced. The message delivery success rate is mainly dependent on two factors namely performance of the individual nodes and the quality of transmission pathway through which the data is sent. These two factors determine the chances and reason of data packet loss in the network and thereby a learning of their effects is necessary.

2.2.3.1 Data Delivery based on Individual Node Performance

Various studies on the performance related to the wireless networks have showed that data packets can also be lost in bursts even for non-interfering networks [103]. An experiment performed to evaluate the packet delivery assumed that packet transmission occurs at same transmission rate from all the nodes and can be lost randomly at any node. This could be attributed mainly to the performance of the wireless node. Node failures would mean both the original data and the retransmitted data are simultaneously lost making it difficult to comprehend the amount of data loss [104]. Previous experiments related to WSN have proved that mobile nodes help to reduce the burning up of energy in the network but increased the transmission delay. A modified ring topology based routing was proposed by

Shih et.al to avoid the transmission delay and the performance related to packet delivery rate showed that data delivery success rate improved from 77.06% in conventional routing to 85.67% using this approach [71]. However, the success rate of message delivery for any wireless network cannot attain 100% since all the deployed nodes in the network are always not in range with the sink node. Later works focused on developing routing algorithms based on different rates of communication channels to utilize the intermediate nodes for improving the throughput of the system during multimedia data delivery. The results of the algorithm showed that when the number of nodes in the network was high, low data rate provided better results in terms of data delivery success ratio [105]. A comprehensive analysis showed that data can also be lost due to unavailability of the wireless nodes due to two conditions. Firstly, when the wireless node was in Power Saving mode, the device remained inactive and was found unavailable in the network. Secondly, if the processor associated with the wireless node was already engaged with processing tasks, the node did not accept new set of data leading to data loss [103]. The results showed that, unavailability of the devices can result upto 100% of data loss in the network which was highly observed for nodes with limited memory and battery power supply leading to inactive nodes.

Proper functioning of the nodes also did not ensure 100% data delivery since the conditions of the transmission channels was found to be the more critical factor that largely affected the data delivery between the deployed nodes in the network.

2.2.3.2 Network Throughput based on Data Transmission

The data loss that may occur due to the problems in the employed Transmission Control Protocol (TCP) is estimated based on the information like transmission error pattern and power of the transmission signal [94]. Figure 2.2 represents a scenario for unscheduled data transmission and drop in data packets while transmission resulting in missing information at the control station.

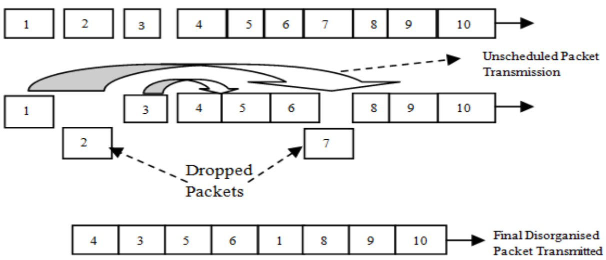


Figure 2.2 Example for packet drop while transmission of data [76]

To improve the network throughput in high traffic based wireless network, a new concept of Admission Control was introduced that made uplink and downlink communication feasible in ZigBee networks [71]. During the uplink communications, the data packets were sent from the tag to the co-coordinator to store and process the data. The acknowledgment about the reception of data packet was done through a return path signal from the co-coordinator to the source nodes in the network and was termed downlink communication [71]. The data rate of the network and higher data transmission can be achieved with deployment of intermediate routers to forward the data packets and a trade-off becomes necessary with the transmission delay and interference in the network [101]. Mathematical analysis about accurate data monitoring has shown that shorter measurement periods has provided better results related to received packet rate in different application environments [105]. The existing data transfer protocols focused on local area networks whose buffer sizes exceeded the bandwidth delay product of the network. Bandwidth delay product helped to determine the amount of data required to be transmitted in the network [106]. It was observed that the existing TCP did not consider transmission of data through the wireless links having higher propagation delay. It was also observed that when several nodes were connected via the same link, the throughput of the network decreased with increase in propagation delay in the communicating channel.

The low memory capacities of the wireless nodes have proved to create data overhead in the network that creates computational complexities in the network. The transmission delay also affects the throughput of the network. These resource constraints necessitated the choice of an appropriate architectural design with minimum impact on performance. Therefore, the basis of data loss related to the WSN architecture requires a detailed overview.

2.3 WSN Architecture related Data Losses

The placement of the wireless nodes in an implemented wireless network is of utmost importance that affects the performance of the network. The chances of data loss related to the wireless network can also be due to improper choice of network architecture. Thereby the various WSN architectures classified as distributed network, large and dense network, indoor network and industrial hybrid networks and their related data loss has been surveyed to draw the attention of researchers to this less attended field.

2.3.1 Data Loss in WSN Architecture for Distributed Networks

In case of distributed networks, localization of the nodes to cover up the entire area is the primary challenge to monitor the data from the entire network. The data collected from the sensor nodes can only be properly utilized if the position of the sensor nodes is correctly known. DV-Hop Localization was designed in earlier work that aimed at localizing the sensor at locations for minimum power consumption and with minimum memory requirements for minimized data loss [107]. For this approach, the anchor nodes were placed along the perimeter of the some circles and semi circles that represented each cluster. The anchor nodes broadcasted the message to all other nodes and the distance of the anchor node from the source sensor nodes was estimated. The distance between the source and the sink node was calculated by multiplying the total hops with average hop distance from the source node [107]. This approach was particularly suitable for WSN applications in military surveillance, environmental monitoring and tracking applications. The international borders of the countries are quite long nowadays and ensuring security of borders through WSN implementation over such extent becomes difficult [108]. Maintaining communication links with the control station becomes necessary for such applications and it is a difficult task considering the dispersed arrangement of nodes over the entire area. Self-organizing sensor node architectures were preferred in such scenario in order to reduce the number of deployed nodes and maintain the security system of the wireless architecture. A novel cross layer routing protocol known as Levels Division Graph (LDG) addressed the problem of reliable communication for long distance data transfer in wireless networks [108]. This designed protocol aimed at allocating the nodes at different segments of the network to meet the communication requirements. This approach helped to determine the shortest path link with the main control station. The designed protocol showed significant improvement in performance related to Dynamic Source Routing (DSR) in terms of average end-to-end delays, packet delivery ratio and throughput of the network [108]. Modernization in the wireless node architecture through implementation of ATMEGA128L microcontroller and CC2420 transceiver module was conceived in an experiment for drought monitoring in tea plantation area [109]. Performance comparison based on diamond shaped node deployment and random deployment showed that reliable and continuous transmission was achieved through the first deployment. The introduction of new nodes through this deployment did not affect the routing performance of the network, but the data loss in the network was increased with increase in time interval. It was observed that the packet loss rate was much less in case of diamond shaped node deployment and this gradually decreased with increase in time interval [109]. Addition of nodes helped to increase the network lifetime, since the extra nodes help to replace the dormant nodes with the newly added active nodes. However, its effect on the network topology formation time, stabilization time and reconstruction time was not considered for this problem. It can be well assumed that with increase in network size, the topology time is bound to increase. Failure of a base station or an intermediate node leads to reconstruction of the topology which leads to loss of a large set of data.

The researchers have recently focussed on designing control strategies to minimize data loss in these distributed networks. The chances of data loss in case of large and dense network architecture are characteristically different to the distributed network architecture and needs special attention.

2.3.2 Data Failures in WSN Architecture for Large and Dense Networks

The modern day applications involve a large number of sensors densely allocated over the entire area which participate in object detection and tracking. Employing such large number of sensors leads to excess energy exhaustion during message exchange amongst the nodes leading to shortened lifetime of the network. The presence of dead nodes in the network leads to failure in data transmission. Park et.al used the switching methodology to exchange the sleep and wake up modes of the nodes in order to address the energy issue while object tracking [110]. This approach helped to take care that the sensor nodes around the object being monitored only remained active during monitoring while the other nodes were in sleep node. The changing conditions of the object related to topological conditions were well detected by the nodes in close periphery and accordingly the other nodes worked in a collaborated manner. Two architectures based on planar architecture and multi-tier architecture was studied for data transport in dense networks [111]. The visual study of the data in Tiny OS Simulator (TOSSIM) software depicted that multi-tier architecture provided better results related to large and dense networks as data was transferred through clustering technique. The cluster heads were functioned only to transmit the data via themselves in order to reduce the complexity of operations using lesser number of nodes while all the other cluster members remained in ‘sleep’ mode thus conserving the energy. This protocol guaranteed a unique and unused time slot for communication for each of the cluster head in the network [111]. A free time slot for each cluster head ensured that the data collision is minimal in the network. This ensured a better load balancing during data transmission of data from cluster members to the cluster heads and then to the base station. Often the imbalance of loads created amongst the deployed nodes in the network lead to loss of data in burst. Therefore, for large and dense WSN architecture administration of the designed network becomes important. Combined monitoring and visualization software named Sensor Explorer was proposed to visualize the entire network deployment in 3D plot in the control station and examine the pathways of transmission [112]. Visualization of the network are gave the observers an idea about the data traffic in the network and the sources of data loss related to node deaths in the network. The problem of identifying the faulty nodes in such dense deployments was somewhat eradicated through this approach.

Several protocols have been looked upon by researchers to eradicate the problem of energy consumption and data collision in case of large and dense networks. However, data transmission was very much prone to external attacks and interferences due to presence of other RF signals present in the indoor environment. This necessitated the study of data loss in different proposed WSN architectures for indoor networks.

2.3.3 Data Errors in WSN Architecture for Indoor Networks

Smart home developments through implementation of wireless networks have become the order of the data due to its ease of implementation and low cost architecture. But the data transmission in the indoor networks often suffers from signal attenuation and the transmission range of the nodes is largely reduced due to the metallic structures and walls present in the indoor network. Patwariet.al found out that the power decay in the wireless network is proportional to d^2, where d is the distance between the signal and receiver [113]. Multipath data transmission and shadowing were found to be the two major sources of dependence to measure the signal strength and packet delivery in case of indoor environments. The signals with different amplitude and phases arriving at the receiver node are added up constructively or destructively as a function of frequency. Often through this approach the higher frequency waves overshadow the lower frequency waves leading to data loss from the lower frequency channel [113]. The received power of these communication bands is the algebraic sum of the powers for each multipath signal [113]. The data overhead and presence of obstacles resulted in the consumption of extra power of the sensor node. Data loss in the area can also due to signal crossover between different RF signals in the network. The dynamic network topologies of the wireless network are also unwanted in case of indoor networks that may cause a group of nodes to malfunction within the network. A newly designed parameter named Received Signal Strength Indicator (RSSI) helped to identify the position of unknown node with respect to fixed nodes in such dynamic topologies to overcome the problem of signal attenuation due to distance of communication [114]. But due to some added factors like interference and presence of other obstacles often the original position of the node is not identified leading to loss of data from these nodes. The RSSI values associated with the different nodes was estimated based on the pattern of data transmission and transmission interval [114].

The extent of application of the wireless networks has made it suitable for monitoring in industrial applications. With the aging of the traditional industrial systems, low cost intelligent automation systems are being looked upon to improve the efficiency of the monitoring systems and thereby increase the productivity from these industries.

2.3.4 Data Loss in WSN for Industrial Monitoring Networks

The coordinated functioning of the wireless nodes helped to create self-organizing architectures for intelligent processing in industrial monitoring and control applications. In this regard, Gungoret.al presented the challenges of wireless network design related to hardware development, system architecture and network protocols [115]. The communication standards related to data transmission in the hostile industrial environment are the main contributors that determine loss less industrial automation applications [115]. In order to reduce the energy dissipation of the network, hybrid system architectures involving both wired and wireless networks were utilized in industrial systems [116]. It is a well-known fact that manual wiring system have always proved to be more reliable than the digital based monitoring systems. In the hybrid set up, the wired connections was preferred for communication between the sensor nodes close to each other while the wireless communications was preferred between the dispersed sensor nodes. The number of hops between the nodes was reduced thereby reducing energy dissipation in the network. The reduced energy consumption helped to maintain the uniformity in energy usage of the nodes while the chances of data loss reduced. The industries are subject to highly acoustic and corrosive environments which affect the functioning of the nodes related to signal attenuation. The nodes are placed in covered boxes to avoid data loss due to signal attenuation. This covered set up also helps to protect the nodes from dirt, dust and other conditions that challenge the performance of the network [116]. The WSN has been used along with SCADA architecture elsewhere for condition monitoring of wind power plants [117]. The ability of WSN to be placed dispersedly was utilized to place the nodes at remote positions of the wind power plant to monitor the wind speed, wind direction and control the working of the wind generator. The controlling function of the wind power system was facilitated using the Remote Terminal Units (RTUs) which was centrally controlled by the SCADA system. As battery replacement was difficult in such applications, the batteries were recharged by help of the energy drawn from wind power generator [117]. This ensured that the lifetime of the designed architecture is enhanced and chances of data loss due to inactive nodes are decreased ensuring safety of the industry. This led to the hybridization approach in industrial monitoring applications to ensure an error less architecture.

The reliability of the data being sent from the source to the base station is highly dependent on the network characteristics based on amount of congestion, extent of lifetime and effects of jamming during data transmission. The data loss related to these conditions in the communication architecture therefore calls for detailed learning.

2.4 Network Characteristics based on Data Loss

Reliable data transfer from the source node to the sink node is highly responsible for defining the characteristics of the network through which the data is sent at that instant. Data congestion in the network, reduced lifetime of nodes and jamming effects define the characteristics of the network occurring due to data losses.

2.4.1 Data Congested Network

Data Congestion is one of the most significant challenges in case of wireless sensor network. This problem in wireless sensor network is generally due to the constraints in resources and the number of nodes that are deployed in the network. The amount of data congestion in a wireless network is generally attributed to the factors like data packet collision, rate of data transmission, many nodes transmitting to one single node and varied transmission time.

2.4.1.1 Data Congestion due to Limited Network Resource

In WSNs, the sensor nodes are characterized with limited storage and limited bandwidth leading to chances of data congestion in the network [4, 7]. The congested network results to packet losses from the source to the sink thereby reducing the Quality of Service (QoS) in the network performance [118]. Different routers having different buffer sizes and communicating using different frequency bandwidths for varied applications can be present in the same wireless sensor network area. When the different network resources do not meet the essential traffic demands for data flow, packet losses occur in the network [119]. If the nodes are not properly allocated in the network, the performance and quality of service of the network may deteriorate rapidly due to dropped packets and data congestion. The bandwidth of the network, transmission delay and the rate of data packet loss are the main factors that determine congestion in the network.

Different applications require different bandwidth for data transmission; several applications are delay sensitive while some applications are hampered by loss of data packets. Therefore, a study of data loss due to congestion during multiple data transmission is also an important area of observation.

2.4.1.2 Multiple Data Transmission leading to Data Congestion

The bandwidth requirement for wireless transmission varies significantly for applications involving file and data transfer to files involving video transmission [120]. ZigBee suits the low bandwidth requirements for applications related to power system data monitoring due to its low bandwidth while Wi-Fi and Bluetooth having higher bandwidth is utilized for transmission of video files. Whenever there is a variation in the estimated arrival time of the packets, it is termed as “jitter”. Loss of packets and transmission delay during transmission of real time application data in a data congested network largely affects the monitoring and control of the system [120]. In wireless ad-hoc networks, nodes are arranged throughout the network in distributed manner and data transmission is based on the broadcast scheme [121]. This transmission of data can be done in two ways. In the first process, one stand alone node is chosen which transmits the same information to all the nodes available in the network as quickly as possible [122]. In the other process, the different nodes act as source and destination node to transmit the data based on a certain transmission protocol. The simple method to transmit data for most of the existing algorithms is the flooding mechanism, which enables communication of data from one node to all the neighbouring nodes in the network which are in its range. But this leads to some inefficiency in the network resulting due to congestion in the network due to higher number of collisions and contentions [121]. Based on the congestion occurring during transmission of data, two types of congestion can be classified namely node level congestion and link level congestion.

2.4.1.2.1 Node Level Congestion

Node level congestion occurs in the sensor nodes closer to the sink, when several data packets simultaneously reach the sink node. Due to limited memory size, the sink is unable to process and store it in the control station at the same rate [123]. Node level congestion results in increased packet loss in the network and wastage of power of the WSN kits resulting in reduction of the lifetime of the network. The node level congestion in the wireless sensor network is shown in Figure 2.3(a) where each circle depicts a single node placed in the network. In such cases, the sink nodes receive data from other router nodes in the network along with some other sensors which remain in range of this node resulting in node level congestion.

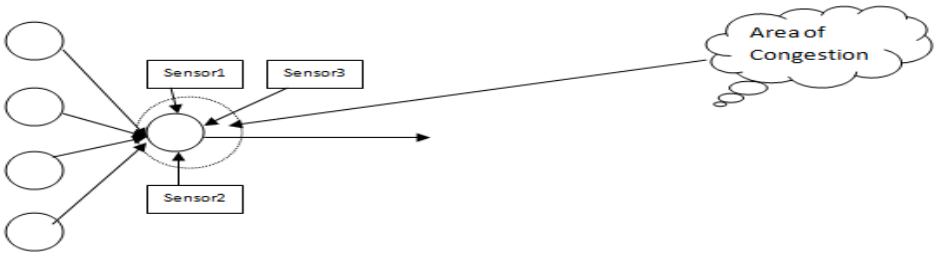


Figure 2.3(a) Node level data congestion [123]

2.4.1.2.2 Link Level Congestion

Data collision in the Link-level congestion results in reduction of data packet rate to sink node. The congestion detection phase generally occurs in the primary stage of the transmission network between the end devices and the router level [123]. Whether or not congestion has occurred in the network can be determined by some of the pre-defined techniques such as packet drop rate at the sink, packet delivery time, packet interval and the length of the queue. The measures are taken at the base station itself to prevent the collision and data congestion in the network thus enhancing throughput at the sink node [123]. The congestion in the communication links between the different nodes, depicted as circles, in the wireless sensor network is shown in Figure 2.3(b).

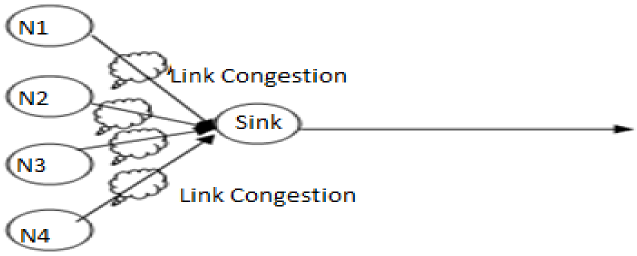


Figure 2.3(b) Link level data congestion [123]

A new control mechanism namely Receiver Assisted Congestion Control (RACC) was designed to solve the problems of data congestion and enhance reliability of the network [124]. A timer is set up at the receiver ends which takes into account the arrival time between two packets and when no data packet is received within this time period a packet drop is estimated to occur. By this mechanism, the receiver detects the packet drop earlier and sends an ACK signal to the sender, informing it about the packet drop [124]. By estimating the available bandwidth in the network, it can inform the sender about the data transmission control rate. The sender can retransmit the data packet before sending a new packet with the improved rate thus greatly reducing the waiting time for retransmission of a lost packet. This designed mechanism helps to increase the throughput of the system in case of data congested wireless sensor thus reducing data loss.

Multiple data transfer between nodes along with the resulting acknowledgment signals on receiving the data results in both way signal transmission along the same data pathway. Both ways signal transmission is also another source of data congestion since collision of the data occurs resulting in loss of a set of data.

2.4.1.3 Loss of Data due to Data Collision in the Network

When one of the routers receives data from two or more neighbour nodes simultaneously, the receiver node fails to update itself. This is because there is a collision of data received from the two neighbour nodes leading to data loss [125]. A new model named as Write-all-with-collision (WAC) model was modelled based on the features that determine broadcast communication in WSNs [126]. In this model, at each step, a single node writes it own state and the current state of the node is communicated to its neighbours. But, in case of direct transmission of data, the system model becomes inefficient and message losses needs to be considered [127]. In real world applications, message losses still occur due to presence of interference, data congestion or inactive nodes which affects network performance. Whenever there is a loss of message in a certain node, the broadcasting of the message is prevented to other nodes and hence proper evaluation of the process dependant on that data is not possible [127]. In order to overcome such problems reducing the performance, a new model based on shared memory namely "Slow is Fast" (SF) was proposed which slightly varied from WAC model [125]. In the SF shared memory model, in each step, a single node was permitted to read the state of its neighbour node and correspondingly determined its own state. Two kinds of actions namely, 'slow' and 'fast' action could be performed by this SF shared model [125]. If for a certain case, the data to be monitored changes very fast and correspondingly the state of the neighbouring nodes, then it is termed as a fast action and need to be executed immediately. On the other hand, in case of a "slow action", the node can store the action to be executed at a later stage till other functions do not intervene.

The limited resources of the wireless sensor nodes resulted in data congestion while the limited power supply reduces the lifetime of the network. This result in loss of data while getting transmitted due to node deaths thus reducing performance of the network.

2.4.2 Lifetime Reduced Network

To make the sensor nodes smaller in size and of low cost, the modern wireless nodes have been equipped with very limited power supplying sources which may supply power to the electronic components available in the node. The lifetime of the network therefore gets hampered if the data transmission process in the network is not energy efficient. The sources of excess energy consumption and its effect on the network performance therefore needs a detailed learning to implement the solutions in future to enhance network lifetime.

2.4.2.1 Reduced Lifetime due to Limited Power Supply

A small power unit is associated with each node along with a battery system to supply power to the associated components of the node [128]. The lifetime of the sensor node is entirely dependent on the power resource capacity supplied with the node. The sensor nodes lying in the remote and unattended areas may become inactive due to insufficient power supply. In order to avoid such hindrance in monitoring, the simplest way is to replace the batteries of the deployed nodes periodically. But, WSNs finds its application in areas such as dense jungles, hilly terrains where the nodes cannot be attended frequently and replacing of the batteries becomes impossible [129]. In such scenarios, some solar cells and an energy efficient routing protocol may help in extending the lifetime of the node. Applications of WSN in deep sea [130], disaster management [131] or underground monitoring [131] are few examples where battery replacement is not possible.

Failure of a sensor node has significant impact on the performance of the entire wireless sensor network. In order to reduce the battery consumption some researchers proposed a trade-off with increased battery life by reducing the features of the node so that the nodes can switch off during idle periods [132]. Often a certain sensor network is deployed at a particular application to operate for a designated time period known as the network lifetime [132]. The communication of data consumes maximum energy while data transmission takes place and hence lifetime may be reduced due to such energy consumption hampering the reliability of the network in remote applications.

2.4.2.2 Excess Energy Consumption leading to Early Node Death

A critical problem of wireless sensor networks is that the main source of excess power consumption is the inter-node communication of data. The data compression and data aggregation schemes aim at reduced data transmission over wireless channels to reduce power consumption [133]. As the resources of the sensor nodes are limited, enough energy is not available with a particular sensor node to report every received data to the base station throughout the network lifetime. In this scenario the node needs to decide which readings are to be sent to the control station. To ensure reliable transmission of all the readings from the source node to the base station by an energy conserved manner, a number of data compression and data aggregation techniques are being employed in the wireless networks.

2.4.2.2.1 Energy Issues due to Data Compression Technique

Efficient dynamic data compression and decompression facilitates fewer amounts of data to be communicated by a particular node in case of wireless sensor networks [134]. By lowering the transmission capacity, the extra garbage data transmissions were eliminated but the energy consumption of the nodes still needs to be reduced. In turn, when the transmission power is reduced, it improves the privacy of the network but often results in disruption of wireless links between some of the nodes [134]. A Linear Programming (LP) framework was introduced to study the tradeoffs between network lifetime and load balancing in security based scenarios for uniform sensor node deployments [135]. In a modified approach, the concept of tuneable compression was proposed which aimed at data compression without any data loss keeping in mind the energy availability [136]. This is done using different compression tools which focuses at compression of data at different ratios and finally selecting the best suited for reduced energy consumption. An overall energy saving is observed by considering the energy consumption for compression/ decompression with reduced data transmission to the next node.

Data aggregation schemes are applicable for multi hop networks where the data transmission takes place from the sensors to the base station by intermediate relay sensors which determine the path. The exchange of information among the different sensors in consecutive hops helps to improve the efficiency of the scheme unlike data compression technique as compression which involves utilization of high energy, transmission delay and lack of robustness.

2.4.2.2.2 Energy Management during Data Aggregation technique

The concepts of data aggregation deal with the concept where the various nodes are grouped to form different clusters. Amongst the nodes that are part of a particular cluster, one node is selected as the cluster head (CH) where the data is aggregated from all the nodes within the cluster. The CH communicates the collected data to the central control station after performing the data aggregation operation [137]. It was observed that when the data collected from the sources are correlated, Distributed Source Coding (DSC) can be utilized to reduce the rates of communication in the network [138]. DSC was designed to employ in applications where different codes for multiple sources were designed at the same time but huge amount of energy utilization was needed for data compression. This was considered for a pair of nodes to maximize the lifetime of WSN and was termed as pair wise DSC [139]. This setting of DSC for two correlated source was based on the complexity constraints, as the computational complexity and memory requirement would increase if considered for multiple number of nodes at a time. So, designing a proper rate allocated structure for a certain sensor node to ensure proper data aggregation in order to maximize the lifetime was felt necessary [138]. The results show that this algorithm enhances the network lifetime in comparison to traditional algorithms and effective utilization of the distributed source coding allows capturing of most of the available data in the network [138].

For efficient performance and enhanced lifetime of the network, energy saving is a necessity to battle the limitations of limited sensing coverage range and network connectivity. Data aggregation techniques can aim at minimizing the frequent energy drain from the sensor nodes increasing its lifetime. Mobile data collectors can also be employed to conserve energy and simultaneously energy requirement for data transmission is also reduced. But the mobile data collectors employed in time dependent applications often gives rise to jamming effects reducing reliability of the network.

2.4.3 Data loss leading to Jammed Network

In case of data transmission in time critical applications, the wireless channels get exposed to jamming attacks when the jammers broadcast radio signals to interfere with the transmission signals resulting in network unavailability for the electronic devices. This jamming attack is mostly prevalent in case of time-based applications than in case of conventional data service networks like the Wi-Fi [140]. In case of smart grids, wireless networks have been proposed to be utilized for power monitoring purposes to facilitate some smart actions like the energy management or protection of the relay [141]. For an example, it can be cited that in case of a smart grid monitoring, if a certain result is missed due to which the action on circuit breaker is delayed, it may lead to potential damages on the equipment [141]. Moreover, the obstacles in the path like the physical infrastructures often lead to failure in data delivery leading to instability in system operation. On the other hand, the shared nature of communication amongst the wireless channels loses its information during jamming attacks which severely degrades the performance of the wireless links and the reliability of monitoring through this wireless network [142]. In case of other conventional networks, the data lost due to jamming attack is evaluated based on sent/delivery ratio [142]. These estimations do not however reflect the latency in data transmission, since 100% packet delivery ratio does not ensure that all the data has reached the control station in time. Thus, estimation of jamming attacks in case of time critical applications becomes difficult. The jamming attacks can be classified into two general classes known as reactive jamming and non-reactive jamming [142]. In case of reactive jamming, the jammer remains idle when no transmission is taking place in the wireless channel, and starts to transmit radio signals when activity has started on the channel [143]. In case of non-reactive jamming though, the jamming node transmits radio jamming signals according to its wish irrespective of activity in the wireless channel. These studies reveal that jamming is the major factor in any mobile ad-hoc network which prevents proper reconstruction of the routing path. Imperfect jamming is more dangerous since it leads to damaged data delivery instead of completely blocking the communication in the network [144].The researchers have focused nowadays on designing of ideal routing protocols which could establish proper communication links between two nodes as shown in Figure 2.4 by avoiding the jammed region. Research works are still being done to design effective routing protocols to avoid the jamming effects and ensure reliable data delivery even in the jamming environment.

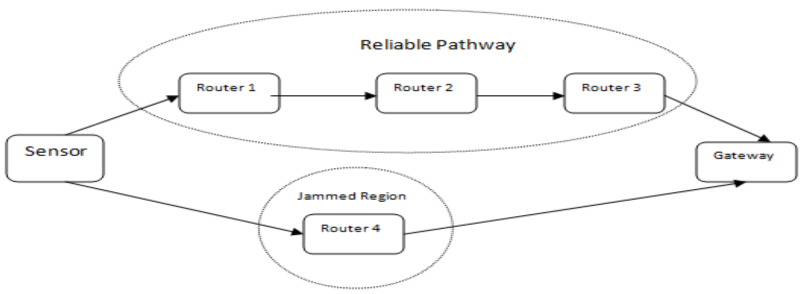


Figure 2.4 Data Transmission through a reliable path in jammed region [144]

The researchers have started focusing on reliable network architectures and designing protocols for efficient wireless network design that ensures reliable data delivery in the network. The various steps undertaken till date have been presented vividly in the next section.

2.5 Reliability Enhancement by Addressing Data Loss in Wireless Sensor Network

Research works are being done nowadays to ensure data transmission through reliable network architectures and secure encrypted algorithms in order to eliminate the chances of data loss in the network. The methods undertaken based on the designed architecture, network quality enhancement and security implementation has been surveyed efficiently to underline the importance of reliability enhancement in the modern day wireless architecture.

2.5.1 Methods to Eliminate Data Errors in Different Architectures

The first step related to reliability enhancement is taken at the base level itself while deciding the network architecture suitable for a specific application. Various control strategies have been proposed till date and further works are also underway that focus on minimizing data loss in the different kind of wireless network architectures.

2.5.1.1 Designed Control Strategies to Minimize Data Loss in Distributed Networks

With the purpose to address the problem of dispersed node deployment in distributed wireless networks, initially self-organizing architectures was thought of to avoid any complexity in network operation. The first of the works relates to creation of geometrical array of nodes often referred as “cell” to form triangle, square or pentagon architectures representing a cluster [145]. The deployed nodes were placed at the vertices of the structure and one node amongst them acted as the “anchor” that performed the job of data transmission. It was taken into consideration that all the structures had same cross sectional area to maintain the maximum area of node coverage with minimal collisions between the cells and with respect to the positions in the anchor cells [145]. The main drawback associated with the following system is the failure of a distant anchor node which would lead to loss of data until the problem is fixed at the site. VigilNet was one of the protocols proposed later that aimed at designing of self-organization technology for surveillance applications [146]. This protocol facilitated deployment of the nodes in dispersed fashion over the entire international borders and was particularly suitable when high density of nodes was needed to sent confidential data [146]. For a test case application, 70 tiny MICA2 motes were placed along 280 feet length grassy field and they communicated at 433MHz. This radio frequency bands allowed the motes to communicate amongst each other and contained detailed information about the data being monitored. In case of long range communication, when the nodes were not in line-of-sight, intermediate nodes helped to relay the information to the base station. This protocol assigned a set of nodes, termed as ‘sentries’, the function of monitoring the occurrence of an event when the set of active nodes are in sleep mode. As soon as the new event is detected, the sentries sent an alarm signal to all the other nodes in order that they work in a collaborative manner to monitor the event [146]. This approach helped to design a better energy management scheme for the deployed nodes in the network. In a later attempt, Bankovic et.al suggested self-organizing architecture for wireless mesh networks where the nodes responded only after receiving the beaconing signals [147]. Based on the importance and reputation of the system all the nodes in this architecture were provided with a reputation value. The most suspiciously behaving nodes were given low reputation values which indicated communications with this node was minimal. This approach was particularly helpful for distributed networks where effects of external agents on a particular network member are very common and these nodes were needed to be eliminated [147]. The packet arriving interval and the amount of data packets delivered were the significant parameters that were utilized to identify the unusually functioning nodes. The nodes were also provided with a history of previously known attacks and it protected the network from such attacks. Any new form of attack was thereby easily identified and the information was stored in the database of the network.

This approach was not suitable for large and dense networks since it would lead to excess communication overheads in the nodes. Thereby, the designed protocols for loss minimization in dense and large architectures need to be separately treated.

2.5.1.2 Designed Protocols for Data Loss Minimization in Large and Dense Wireless Networks

One of the first protocols designed to minimize data loss in large and dense scale networks was Embedded MONitoring (EMMON) suitable for real time systems [148]. This was first implemented in a test bed consisting of 300 sensors in Europe, the highest till date. It was seen from the performance of the protocol, that at higher levels it used Internet Protocol (IP) as the networking protocol and the gateway to establish the link between the remotely placed node and the base station. The ZigBee based nodes were arranged in a Cluster-Tree network in the user specified application area for end to end transmission in a hierarchical fashion by avoiding chances of data collision. A time bounded data flow based on Time Division scheduling helped to fix the schedule for data transmission in the network [148]. The software and hardware module integrated with the communication protocol helped to meet the application requirements for highly congested networks such as data centres, structural health monitoring systems and environmental monitoring systems etc [148]. Energy exchange in the designed architecture through EMMON protocol could take place directly between the nodes and the base station or via cooperative communication through the intermediate relay nodes. The performance of the two communication schemes was tested based on message exchange probability, throughput of the network and network lifetime through Monte Carlo simulation and the direct communication provided better results for dense networks [149]. Jackulin et.al designed Actor Directed Clustering Protocol (ADCP) to enhance lifetime of the large and dense networks architectures [150]. The traffic in the network was looked to be reduced through efficient clustering approaches. A group of sensor nodes chose the closest node as the cluster head and data transmission was continued amongst the cluster heads through minimum utilization of energy. This helped to counter the node attacks in the initial stages itself thereby reducing the complexity in the routing protocols [150]. The lifetime of the links predicted through simulation of this protocol ensured that it increased through energy savings at the processor level by 40% [150]. A protocol designed later known as Virtual Infrastructure-Based Energy efficient (VIBE) protocol aimed at multi-hop data transmission for sensor nodes distributed randomly in a given area of application [151]. The deployed sensor nodes in the area have the information about the location of all the other sensor nodes in the area and about the location of the sink. The communication session was initiated when data was collected by the individual sensor node and forwarded through clustering fashion. A two-way communication model was designed where the individual nodes could choose itself as a normal node or cluster head. The advantage of this protocol was that extended communication architecture could be created for such large areas of communication so that chances of link failure are eliminated. The nodes deployed in the region easily coped with the requirements of signal transmission and was subjected to a constrained signal transmission range [151]. This algorithm produced better energy saving results compared to other greedy forwarding algorithms.

Separate protocols that focussed on eliminating the chances of interference in the network needed to be designed for wireless network applications in wireless network. The Radio frequency identification (RFID) technology was utilized to fix the position of the routing nodes in the wireless network.

2.5.1.3 Approaches to Minimize Data Errors in Indoor Networks

By involvement of the RFID networks, the sink node of a particular group of nodes had the information of the frequency band through which data is transmitted and the location of the other nodes in the network. Separate RFID systems were attached with the sensor nodes so that the sink node is able to check, monitor and authenticate the correct tag according to the area of application to be monitored. This enables better target detection as the sensing of the real data could be done within a given cost or helps to reduce the cost related to data sensing requirements. These RFID systems in conjunction with the wireless network have been utilized in practical life to maintain stock levels in more than 104 Wal-Mart stores [152]. RFID based wireless networks were also employed for data collection in large scale industrial applications [153]. In order to ensure communication within strongly interfering networks, an algorithm based on Extended Kalman Filter (EKF) and Particle Filter (PF) was designed. The first part of the algorithm based on EKF was designed for linear systems subject to Gaussian noise. The The PF based algorithm was designed for the non-linear systems and it helped to estimate the chances of interference based on indirect approximation of noise distribution in the network. But this algorithm increased the computational complexities related to router placement in indoor networks as a large number of parameters needed to be considered.

However, this system did not consider the energy consumption resulting due to signal crossovers during data transmission in indoor networks. Lee et.al looked at providing a solution to overcome the problem of signal crossover where the tags sent special signal only to the neighbor node to activate the process of transmission. This approach showed that other communication links being inactive at this instant, the energy consumption due to crossovers could be eliminated once the nodes had information about the data communication intervals [154]. The recent works have focused on three parameters namely Time of signal Arrival

(TOA), Angle of Arrival (AOA) and Received Signal Strength Indicator (RSSI) for localization of the nodes in the indoor network [155]. The distance between the nodes is measured based on signal propagation velocity and propagation time by the factor TOA. The distance of transmission measured based on the direction of signal transmission is done by the factor AOA by help of the RF antennas connected with each sensor node. RSSI measures the signal power on reception at the receiver node and thereby calculates the distance of signal transmission [155]. This methodology of router positioning based on RSSI value was utilized in an experimental work in a photo voltaic plant where the positions of the measuring sensor nodes were decided based on the messages sent and received in the set up [156]. A dedicated sensor node was attached to each solar panel which helped to sense the power output of these panels and the data was sent to the control station. But with increase in the network area, manual configuration of the nodes became impossible and thereby self-organizing and auto configuring schemes were chosen for node deployment. This enabled the nodes to automatically choose the next neighbour and the frequency channel for data communication based on the value of RSSI for the messages being exchanged. The experimental results showed increase in complexities of computation and degradation in the algorithm performance when the number of RSSI values associated with the nodes was increased for decision making [156]. A typical indoor localization platform has been depicted in Figure 2.5 which allows measurement of several parameters from the different allocated nodes.

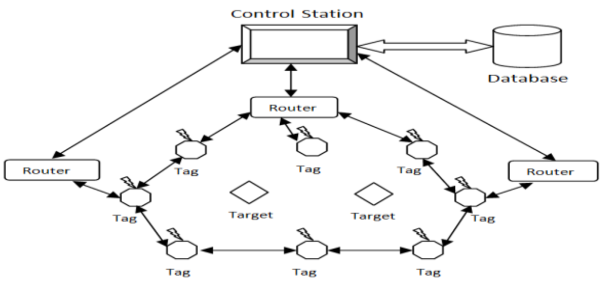


Figure 2.5 A typical indoor localization platform [152]

The upcoming industries and the smart grid networks have preferred wireless networks as the communicating medium for easy data transmission. To obtain better performance, hybrid approaches of utilizing two or more wireless modules have been performed according to the type of application.

2.5.1.4 Hybridization in WSN architecture for Efficient Monitoring

In order to ensure reliable and efficient monitoring, WSN is often used in hybridization through various means according to the need of the application. In one of the earlier applications, two sets of nodes were chosen to function differently in the same WSN deployed area. One set of node was subjected to normal mode of operation while the other set of nodes engaged themselves in encrypted data transmission to make up the hybrid architecture [157]. The encryption and decryption during data transfer increased the complexity of processing of the data and introduced transmission delays in the network. The normal nodes were associated with collection of data from the deployed sensors while the second set of node therefore operated only during hostile conditions to transmit data in form of cipher texts [157]. This system was especially suitable in smart grid applications where the data from remote side needs to be intelligently secured in the data acquisition unit. In another work involving topology control namely Adaptive Disjoint Path Vector (ADPV) algorithm, an adaptive, energy aware and fault tolerant wireless network was aimed to be designed through two set of nodes [158]. A heterogeneous wireless network was planned to be designed through regular nodes and super nodes. The regular nodes were involved with collection of data from the sensors deployed in the application environment and forward the data to the super nodes. The super nodes formed the bridge of the entire network from the regular node to the control station thus dividing the load amongst the nodes in the network. The designed algorithm divided the working into two phases namely the initialization phase and restoration phase [158]. The initialization phase initiated the data delivery process while the restoration phase invoked an alternative node to work to restore the transmission when a super node was dead [158]. This hybridized approach helped to improve the packet delivery ratio.

The different wireless technologies such as Wi-Fi, Bluetooth, ZigBee and GSM technology can be simultaneously utilized in the monitoring application to ensure high quality communication performance. ZigBee has proved the most suitable wireless module for low range and low data rate application while Wi-Fi helps to connect several devices in the local area network. Qiu et.al combined these two wireless technologies to find out that Wi-Fi affected the performance of the different frequency based instruments [159]. Thereby special rules were proposed to place ZigBee devices in the Wi-Fi based area to collect the data from these placed instruments. Thereby, selection of the combination of the communication technologies becomes vital to prevent data loss in the network. In a later work, Markov Decision Process (MDP) was utilized to design the communication architecture for industrial networks through less computational complexity and reduced signal overhead [160]. The control of the transmission power and optimizing the packet size helps to enhance the lifetime of the network through energy conservation. The reduction of bit error rate (BER) helps to improve the transmission power. For smart grid application, lower packet sizes helps to reduce the packet error ratio while higher packet sizes increases the payload-to-overhead ratio. In aim of this, a novel mixed integer programming framework was designed that optimizes the transmission power level and the data packet size [161].

Ensuring security of the designed wireless network is another important aspect that ensures that no data packet is lost through external node attacks. Encryption, ciphering and some mathematically formulated algorithms have been designed in view of this to enhance security of the system while data transmission.

2.5.2 Security Enhancement in Data Transmission

Security is a major area of concern for dense networks, since invaders might implant malicious nodes within the network to capture the network data. Research works based on address based encrypted data routing can be planned since this would ensure that the data to be transmitted reaches the correct node where it is intended to be sent.

2.5.2.1 Security Modeling using Encryption

Data encryption has become necessary in case of WSN as the sensor nodes with limited resources are often subjected to various node attacks [162]. The encryption of the data being sent prevents the adversaries to inject false data into the network. It had been observed elsewhere that the encrypted data transmission is highly energy consuming rather than the data processing capabilities of the nodes [163]. But, it must be kept in mind that the data transmission in WSN needs to get through various hazardous environments and needs enhanced security during transmission. A hop-by-hop encrypted data aggregation (EDA) scheme was proposed in order to design a less energy consumption network with enhanced security [162]. In this scheme, an intermediate sensor node acting as the cluster head or the aggregator stores all the security keys for the encrypted messages being sent from the sensor nodes. These messages are decrypted at this aggregator node, the processing of the data is performed and then the result is again transmitted in an encrypted form to the base station [162]. To reduce the total number of encryption and decryption in the network, a later work proposed the use of Homomorphic Encryption (HE) Scheme [164]. In this scheme, only the base station was able to decrypt the encrypted messages received from the different cluster heads and the various sensor nodes. This helped to somewhat improve the performance of WSN which was affected by transmission delay and energy consumption caused due to excess computations at every single node. Data aggregation at every hop has been identified as the easiest method to transmit huge amount of data for a certain application. But this technique has some constraints such as the base station cannot identify the best result based on decryption of the messages [165]. This type of scheme is also subjected to the fact that attacks at a particular cluster head may result in loss of the entire data. Avoiding the data aggregation scheme on the other hand increases the energy consumption scheme of the entire network [166]. This has promoted the researchers to design different protocols keeping the drawbacks in mind.

Several protocols have been designed by researchers to ensure secure and reliable data transmission in networks handling multiple applications and in networks subjected to several node attacks. Concealed Data Aggregation Scheme for Multiple Applications (CDAMA) was one of the protocols designed to ensure secure data transmission in wireless networks [167]. This scheme was suitable for multiple applications connected to a single base station. The base station extracted data from selected encrypted texts which were associated with a specific application thus reducing the data handling by a particular node. This helped to mitigate the attacks in case on single application environments and also reduced the damage caused due to unauthorized nodes of the network [167]. Another protocol designed for wireless networks named as Virtual Energy-Based Encryption and Keying (VEBEK) aimed to reduce the energy consumption due to encryption based data transmission in the wireless networks [168]. This protocol worked based on RC4 encryption algorithm where the key was generated based on permutation of the codes generated for each byte taken as input. An individual key was generated for an individual data packet and different set of keys were generated for the successive data packets. This encryption algorithm was suitable for military applications where constant data transmission is necessary in highly constrained networks [168].

Some mathematical modelling in the algorithms considered the security systems to simultaneously position the nodes in the network based on a secured framework. These modern algorithms added complexities to the computational abilities while adding reliability to the transmission system.

2.5.2.2 Security Designing during Mathematical Modeling

A novel algorithm namely Double Guarantee Security Sensor Localization (DGSSL) was proposed in a recent work to ensure proper functioning of the wireless nodes in hostile environments subjected to different types of node attacks [169]. This algorithm was ideally suitable for enhancement of security in static network through detection of faulty node addresses and inappropriate data filtration. A new scheme of data transmission named SEEDA (Secure End-to-End Data Aggregation) was developed later for WSNs to transmit data by keeping a lot of privacy [170]. The average data to be transmitted through the nodes at each round was reduced to conserve energy. Nodes joining and quitting scheme (NJQS) is another modern algorithm that uses the method of node authentication to check the secret telecommunications in the network [171]. This method prevented unwanted nodes to interfere in the data transmission process. Data transmission though multipath signal fragmentation was attempted in a recent work which got accumulated together in the destination node to reconstruct the original signal [171]. This prevented the entire data getting lost through node attack in a particular transmission scheme. But ensuring security and retaining all the data simultaneously during data transmissions is a challenging task. A trade off between security enhancement and packet error ratio was attempted elsewhere to develop an energy aware secured network which aimed at maximum data transfer with utmost security [172]. The best wireless network performance was found to be depended upon the efficient data aggregation scheme at every node and possible encryption and decryption of data. End to end data security while data aggregation at the individual nodes helped to save more energy and enhance lifetime of the network.

While the control strategies and the security implementation schemes of the wireless network has ensured reliability enhancement against chances of data loss through interference, node attacks or signal crossover, equal importance must also be given to the network design features to ensure unhampered data delivery.

2.5.3 Improvement of Network Design Features

Maintenance of the network quality, implementation of the energy harvesting nodes and cost efficient network design has helped to propose reliable wireless structures for data monitoring applications. The quality of service of the network is defined by the parameters such as energy consumption in the network, lifetime and minimal path loss in the network.

2.5.3.1 Maintenance of Quality of Service (QoS) of the network

The monitoring of the path losses is necessary for multi path multi hop data transmission to ensure that no data is lost during recreation of the original signal in the base station. The data failure in these transmission paths is therefore dependent on measuring the signal strength of the received signal and comparing it with the original reference signal strength [173]. A later work focused on monitoring the loss of energy in the paths based on the transmission power of the different signals. This helped to give the researchers an account of energy lost at every round of data transmission. Excess consumption of transmission power helped to control the data transmission in the later stages [174]. The node concentration problem was also tried to be resolved while designing of the wireless network architectures through implementation of proper cluster head selection algorithms. The measurement of data delivery success rate through these clustering algorithms helped to identify the error related to data loss in the network. Node failures, transmission channel noise and malicious node attacks may also result to data loss during wireless transmission. Linear Cryptanalysis (LC) was one of the later methods implemented to prevent data loss through external attacks which aimed at data delivery in encrypted method in hostile environments [175]. This helped to develop an in built resistance of the network and identified the types of attacks in the networking thereby maintaining the quality of data transmission. The generation of Acknowledgement (ACK) signals from the nodes on receiving the data helped to detect the message loss in the network [176]. When the ACK signals were not received, the receiver node requested the source node to resend the data, hence ensuring the data is finally received. But maintain the quality of the network is necessary especially in video transmission applications of wireless sensor network [177]. But multipath data transmission helps to enhance the speed of data transmission in the wireless network without depleting the energy resources of a particular set of node. Moreover, the quality control of the data being sent over the different paths helped in increasing the quality of the multimedia data being sent. Shaikh et.al proposed a reliability framework for data transport that helped to carry the raw data collected to the sink node from the different sensor nodes to test the faulty conditions of the network [178]. This framework helped to ensure efficient data aggregation since loss of some raw data may reduce the accuracy of aggregated value. The quality of the network is also improved through designing of efficient routing protocols based on the type and extent of the wireless network application.

In order to address the limited energy supply problem of the wireless nodes, the modern technologies have focused on designing of energy harvesting nodes that help to supply back up power to improve the lifetime of the network.

2.5.3.2 Design of Energy Harvesting Nodes to Overcome Energy Supply Problem in Wireless Nodes

The modern design of the energy harvesting nodes has helped to provide the wireless nodes with special features of backup power facility in order to improve the lifetime of the nodes. Longer running of the nodes would help to reduce the chances of node death however adding to the built up costs. The mismatch in the energy consumption and early node deaths in the wireless framework has been somewhat reduced through this modern wireless nodes. The modern wireless nodes have been provided with Energy Aware Interface (EAI) that helps to supply the energy demand of the wireless network through an energy harvesting source in form of renewable energy along with a power management module (PMM) and an energy storage capacitor [179]. The model diagram of such energy harvesting architecture has been depicted in Figure 2.6.

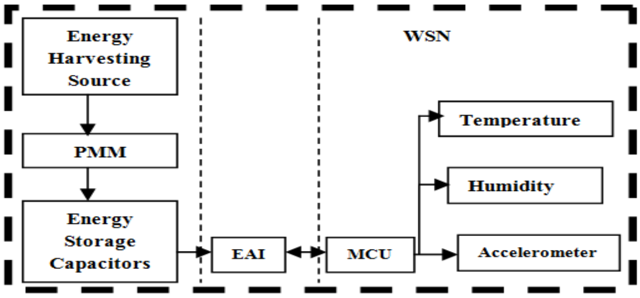


Figure 2.6 Block diagram of WSN architecture by Energy Harvesting [27]

These nodes were particular suitable in areas consisting of large number of sensors where energy requirement becomes high.A recent work focused on devising hybrid energy based harvesting system in the wireless nodes in the aim to extend the lifetime of the wireless network in the field of application [180]. This energy resource acted as continuous source of energy to reduce frequent recharging and replacement of batteries. The hybrid energy harvesting module aimed at collection of energy from the surrounding sources such as wind, solar radiation and thermal energy. A super-capacitor was also provided with the design that acted as a energy storage module. The experimental results suggested that appropriate integration of this hybrid systems ensured sufficient energy supply to meet long term requirements of WSN without batteries in field environment. A measurement done over 9 days for a certain application suggested that average daily energy generated from this hybrid set up was 7805.09J which was far more than the energy requirements of the WSN node which was about 2972.88J [180]. Thermoelectric energy harvesting system was also implemented elsewhere to generate energy for the wireless nodes operating in the network [181]. Water having high specific heat capacity was used as the phase change material and an intelligent module helped to maintain the temperature gradient upto 2^0C which was utilized in generating the electrical energy for the wireless nodes [181]. Lei et.al aimed at optimal energy management of the wireless network designed through energy harvesting nodes to reduce the chances of packet loss during delivery process [182]. This algorithm allowed one energy harvesting node to transmit data during a time slot and their batteries got recharged by external energy source. The data transmission was thereby divided into several slots of equal time intervals and the packet sizes were kept fixed to maintain uniformity in energy consumption of the energy harvesting nodes [182].

Maximizing the performance of the energy harvesting nodes under conditions of excess energy consumption is the main challenge. An energy harvesting genetic-based unequal clustering-optimal adaptive performance routing (EHGUC-OAPR) algorithm was proposed by Wu et.al in a research work that aimed at maintaining the energy supply to the network by process of energy harvesting from external sources instead of batteries [183]. The first part of the algorithm aimed at forming the clusters of unequal size and selecting the cluster head based on highest energy efficiency. The clusters near the base station had smaller size and it gradually increased with increase in distance from the base station. The routing pathway through the cluster heads was determined through the second part of the algorithm saving the energy consumption of the other nodes. The numerical results of this adopted approach helped to achieve network energy balance with increased data delivery compared to other existing routing protocols [183]. In another work, a design of low power energy harvesting wireless node having a hybrid storage unit in form of super-capacitor and a thin film battery was suggested [184]. Estimations were done regarding the duration after which the energy outage might occur in these storage systems before choosing the size of the systems based on the application. Considering the cost constraints, the optimized capacity of the storage system was decided based on the performance criteria by Monte Carlo simulations in MATLAB [184]. This ensured that proper precautions were taken while designing the wireless network for monitoring applications.

Other than the quality of service of the network and deployment of energy harvesting nodes, the cost of the network design is also an important constraint that controls the design strategy for a particular network. The study of cost of network design would help the engineers to choose the right network architecture for a certain application to attain both economic and performance benefits.

2.5.3.3 Study on Cost of Network Design

Cost analysis is one of the important factors that determine the economic benefits attained through per unit energy saving. The development cost is directly proportional to the number of nodes deployed in the network and therefore an analysis was performed in a certain research work to associate energy saving with increase in per unit cost [185]. The cost comparison was done for data transmission occurring in 2-level, 3-level and N-level hierarchy. The results showed that the initial deployment cost was highest for 3 level hierarchy related to maximum energy saving and it was found to be 375$/joule [185]. The N-level data transmission also incurred the cost almost in the same range. However, for uncorrelated event, it was found that the 2-level hierarchy transmission method and homogeneity based transmission incurred the same cost and least amongst all the tested transmission schemes [185]. It was observed in another research work that deployment of high power modules in the wireless network for performance enhancement increased the initial build up cost of the network even when the number of nodes was less [186]. Therefore, focus was given in choosing of the low cost technologies in order to build up efficient wireless nodes to lower the cost of entire network set up. The researchers in a certain project focused on designing of wireless nodes for implementation in indoor conditions through a specific hardware and software framework with minimum cost [187]. After having made a detailed study about the cost of the different components, Seeduino Stalker v2, a derived platform of Arduino model was chosen as the main hardware base to design the wireless node [187]. This microcontroller based module with low energy consumption microcontrollers provided added advantage related to functionalities and integration of external modules. This wireless board was supported by a ZigBee (XBee) module series 2 and a battery to build up a low price sensing device. This approach helped to design a wireless node in much lower cost compared to previous devices and additional enclosures were provided to protect the electrical circuits [187]. In another attempt, wireless sensor network based on Bluetooth and ZigBee protocol was designed for precision agriculture [188]. The results of cost comparison showed that high transmission range of ZigBee in comparison to Bluetooth reduced the number of initial nodes and thereby the deployment cost of the network. Two energy aware algorithms namely Exponential and Sine Cost Function based Route (ESCFR) and Double Cost Function based Route (DCFR) were proposed in a recent work that evaluated the cost savings of the network architecture related to energy aware routing in the network [189]. For the first algorithm, the cost was calculated based on small to large changes in the remaining energy of nodes during data transmission. DCFR algorithm estimated the energy consumption during end to end data transmission and the remaining nodal energy for evaluation of the cost function. Balanced and efficient energy usage helped to reduce the cost of link establishment in the network. This work aimed at attaining the objective of lifetime enhancement with minimum architectural cost where the objective function of estimating the cost was based on factors such as remaining node energy and required transmission energy.

2.6 Conclusion

The survey of the different works based on the sources of data loss has helped to establish the importance of data loss in the determination of the efficiency of the wireless network. The suitable control strategies and minimization of the data loss in the network based on the type of application has helped to determine the quality of the network. The supervision of the defining parameters of the network such as transmission delay, data overhead and throughput of the system has helped to determine the efficiency of the particular network. The network performance and the data delivery need to be improved especially when these are implemented in smart grids. The survey also presents different methodologies of handling data related to the type of network architecture for the chosen application. Security enhancement in the modern day wireless network designs has also been given importance to avoid data loss through node attacks. Energy consumption has been identified as one of the important factors that hamper the performance of the network related to network lifetime and communication breakdown due to node deaths. The different works found in literature suggests that there are several gaps related to implementation of the wireless network as the communication standard. Most of the works found in literature do not aim at signal attenuation minimization in the indoor area networks through efficient node placement. Improvement in network performance through maximization of data packet delivery is also not common in the literature works. The energy consumption while data aggregation in the clustering process has also been not taken care of while implementing the clustering algorithms. The maximization of energy through efficient role distribution amongst the nodes has not been found in literature which would be essentially helpful in case of dense network architectures. The cost of network design for wide area implementations is very sparse in literature. However, this factor is important for the choice of the topology and the designing of the communication architecture. Cost efficient network design is also necessary to help the engineers develop a network that provide both performance and economic benefits related to node deployment in indoor network.

This detailed learning of the different works has given the idea for establishment of proper strategies for node deployment in the wireless network in order to enhance reliability and lifetime of the network. Therefore in this work, the chances of packet loss in the network have been aimed to be reduced through minimization of signal attenuation in the network.

The signal attenuation minimization would help to reduce the chances of interference and signal crossover in the network. Increase in the packet delivery ratio for implementation of wireless networks in indoor networks has been considered in this work. In order to enhance the network lifetime and maintain the existence of the communication links for longer periods, a novel approach of selecting the cluster heads in the network has been attempted. This approach looks at balanced energy usage amongst the nodes through rotation of the deployed nodes. This is particularly helpful in case of dense wireless node deployment schemes where energy consumption is highest amongst the cluster head due to data handling from several nodes simultaneously. Cluster head selection and placement has been given importance in this work to enhance the performance of the network. Performance of the wireless network in indoor environment related to variation in cluster heads has also been studied to understand the effect of cluster variation in the chosen wireless network. This summarises that main objective of this research work will be to design a wireless network for indoor applications through performance improvement related to reliability and lifetime of the network. Cost benefit analysis related to the different wide area node deployments based on variation in number of nodes and base station positions is also studied to identify the most cost effective network architecture.

A survey of the different node placement strategies, node topologies and the routing protocols has been presented in the next chapter that helped to select the correct approach towards reliability and lifetime enhancement of the network. The applied soft computing techniques in various node placement strategies done till date have been compared also in the following chapter to identify a new approach to be undertaken for this work. The application of the wireless networks in such varied fields of society has also prompted the usage of wireless networks nowadays in monitoring of the performance of the non conventional source related power generation. These applications have also been surveyed to identify the non conventional source where implementation of wireless networks as a monitoring tool has been found to be easiest and error free.

Chapter 3

Node Deployment Strategies and Energy related Applications of Wireless Sensor Network

In order to accomplish the goal for error free application of Wireless Sensor Network in various fields of monitoring, suitable node placement strategy is a necessity. With the variation in the area and type of application, the strategy of node deployment needs to be changed. The same node deployment strategy cannot be used for outdoor and indoor environment. Lot of works have been previously done by researchers regarding node deployment to enhance the performance of WSN. This approach has helped to revolutionize the schemes related to communication standards, topology and optimization techniques to make WSN a more sophisticated option. An overview of the types of node to be deployed, the strategy of node placement based on node property and the objectives of optimization of node placement has been depicted in Figure 3.1.

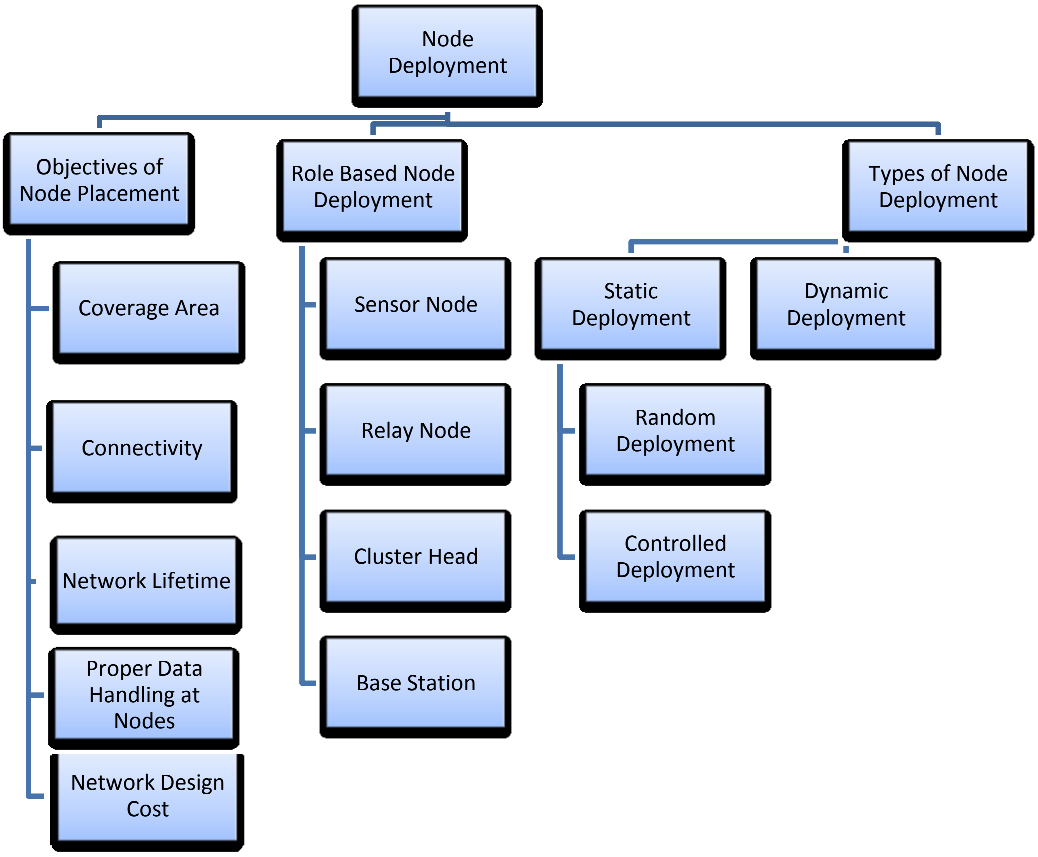


Figure 3.1 Overview of node deployment and its objective

In this chapter a review of the main objectives of node deployment in WSN, the various types of nodes to be deployed based on functions, different classifications of the node deployment strategies, the soft computation techniques undertaken till this date to meet the objectives and the deployment of wireless sensor nodes in various renewable monitoring based applications has been presented.

3.1 Objectives of Node Deployment

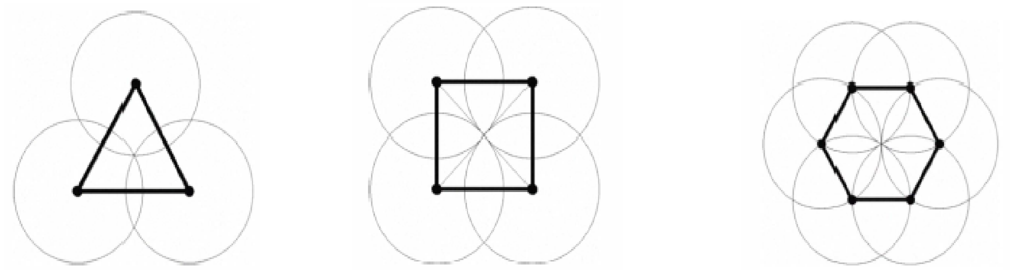
All the node deployment strategies work towards achieving the main objectives of network coverage, efficient node connectivity and enhanced lifetime of the network. Different works in literature have focused on improving the different factors linked with achieving these network objectives.

3.1.1 Network Coverage

Node deployment in the application area must aim at maximum coverage so that no part of the application remains unmonitored. In order to provide maximum coverage, all the points in the application area is provided with at least one sensor node so that no part of the application remains uncovered [190]. The sensing range of the wireless nodes can be adjusted based on the type of application for maximizing the area of coverage but it has some limitations due to the energy consumption and limited node capabilities.

3.1.1.1 Computational Geometry for Coverage

Computational geometry was the first thing to be implemented in order to deal with the coverage problem for deterministic deployment. The grid formations for positioning of the nodes were based on some geometrical shapes commonly equilateral triangle, unit square and hexagon as shown in Figure 3.2. Later, Wang et.al [191] compared mathematically the performance of the wireless sensor network based on all three grid based node deployment and it was concluded that sensor deployments in the form of equilateral triangle was better than square formation. It was also observed that the efficient coverage area ratio decreased on increasing number of sensor nodes.



a) Triangular pattern (b) Square pattern (c) Hexagonal pattern

Figure 3.2 Different grid layouts [191]

The Voronoi diagram was a popular computational geometry utilized for designing of optimal polygon structures in problems of node deployment [192]. This method of grid set up helped to provide the proximity information about a set of geometric nodes. A pictorial representation of the Voronoi diagram given in Figure 3.3 represents the arrangement nodes implemented in the application area in form of several polygons. Several algorithms based on the Voronoi diagram has been designed previously that has focused on optimizing the coverage area. The best and worst case formulations through Voronoi diagram was designed by Megerian et.al for a centralized uniform sensing model with homogeneous sensor nodes distributed in the area [193].

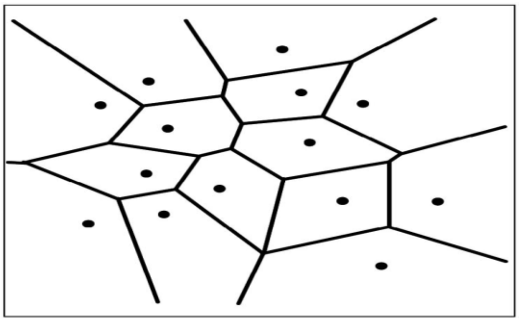


Figure 3.3 Voronoi diagram [192]

The Voronoi diagram formed a dual structure in 2-D plane based on formation of the triangle with minimum angles was termed as Delaunay Triangulation (DT) and has been depicted in Figure 3.4. This maximization of the formation of triangles collectively helped to maximize the area of coverage. Delaunay Triangulation was used in other works in literature to deploy a centralized and deterministic sensor network [194]. This Voronoi computation technique has helped to minimize the obstacles during data transmission in the network [192]. This DT method helped to check multiple connectivity of a node with other nodes and provided high fault tolerance capability.

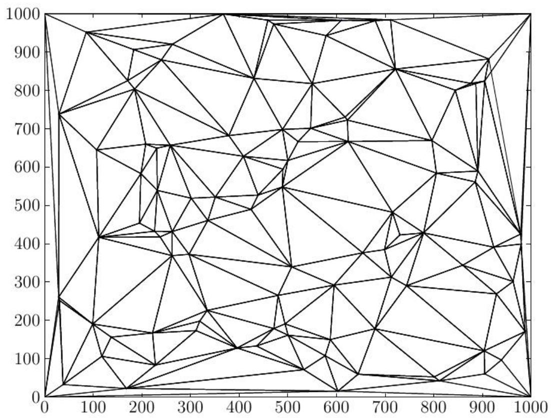


Figure 3.4 Delaunay triangulation [194]

3.1.1.2 Algorithms for Maximizing Coverage

Soft computation algorithms proved fruitful for solving the problem of deployment to maximize coverage in the network. Particle Swarm Optimization (PSO) was successfully applied in a previous work to maximize network coverage with least number of node implementation [195].Virtual force algorithm is a commonly used algorithm for virtual field concept as in robotics where dynamic and random deployment schemes of the network are more preferred [196]. In this algorithm, it was considered that the when the nodes being monitored are distant from each other, an attractive force works to bring the nodes nearer while when the nodes are far away, a repulsive force works to adjust the nodes in appropriate position. A survey done on various algorithms for coverage and connectivity in WSN is presented has also been presented in literature [197]. The next important objective of network connectivity has been maximized through node deployment strategy.

3.1.2 Network Connectivity

Providing full coverage of the network is alone not sufficient enough to establish the efficiency of the node deployment strategy. Network connectivity is another essential criterion of the wireless network which ensures that all sensor nodes can communicate with the base station in a single hop or multiple hops. The network connectivity is highly dependent on the wireless links that are established between the deployed nodes in the network and the maximum range of transmission of the wireless nodes. Often the failure in the network links can be attributed to the node failures which result in breakage of the communication path amongst the nodes. Frequently the data transmission amongst the nodes breakdown when the distance over which the data needs to be transferred exceeds the maximum transmission range of the wireless nodes. Multi-hop multi path data transmission strategy is therefore preferred in the wireless networks. The multi-hop transmission ensures that none of the sensors in the designed transmission pathway is out of the transmission range from another sensor node. The multi-path architecture provides an alternative pathway for data transmission if the primary pathway fails due to network link fails. The deployment strategy therefore should ensure that data transfer occurs reliably and continuously through an existent pathway between source and destination. The connectivity of a particular node with other nodes has been described as K-connectivity where K is the number of independent paths between every pair of nodes [198]. The value of K must be greater than or equal to 1 to ensure fault tolerance and ability of the network to handle node failure. The network connectivity established through the node deployment strategy ensures that it maximizes coordination, minimizes communication energy, interference and traffic. When considering a 3D grid based deployment of the wireless network, the focus is given on the how to eradicate problem of connectivity failure [199]. A numerical analysis on the percentage of network connectivity is performed based on two types of situation considering grid-based deployment with bounded uniform errors and with unbounded normal errors. A network design based on deterministic node deployment was proposed by Gueye et.al to provide good connectivity with least communication cost [200]. The research work utilized iterative algorithms for node deployment to position the relay nodes in order to strengthen connectivity in a network where the positions of other nodes are fixed.

3.1.3 Network Lifetime

The positioning of the wireless nodes in the network has huge impacts on the network lifetime. Akl et al. proposed a non-uniform grid based node deployment to attain a routing design to save the energy consumption of the network and improve the lifetime [76]. In another work, a model network design was proposed to improve the lifetime of the network by keeping in mind that the sensors near the base station consumed more energy than other sensors deployed in the network [125]. A mobile base-station was proposed in such a case in order to balance the energy consumption throughout the network. The main threat to network life is energy wastage caused due to energy-hole problem in the network, idle nodes and signal crossover.

3.1.3.1 Energy-Hole Problem

The problem related to extinction of energy of the wireless nodes is termed as energy hole problem and is found to have the highest adverse effect on the network lifetime. Certain nodes deployed in the wireless network suffer from faster battery power depletion when they are involved with more data transmissions compared to other nodes. This is most common amongst the nodes closer to the base station which exhausts their power earlier creating the problem of energy hole [125]. Failure of these nodes affects the network coverage and node connectivity. To overcome this problem, a deployment scheme for hexagonal cell based grid architecture was proposed in later works where energy balancing was taken care at every layers of data transmission to reduce the problem of energy-hole [201]. In another work, special types of sensor called micro-server nodes with higher energy capacity were deployed near the sink node to solve the problem of faster energy depletion [202]. This non-uniform wireless node deployment and data transmission through multi-hop routing scheme helped to efficiently achieve the objective of energy consumption minimization amongst all the nodes. Wireless sensor networks have come into the fray nowadays because of the suitability of the wireless nodes to be deployed even in harsh environments. In these situations, it becomes very difficult to regularly monitor the battery power and replace the batteries when exhausted. Thereby, minimization of energy consumption becomes a compulsion in WSN to extend the run time of the batteries. Recently various schemes have been proposed to minimize energy consumption in wireless sensor networks. In a work [203] author laid the concept of WPSN (wireless passive sensor network) where the sensor nodes were powered by alternatives source such as RF. But the routing schemes involved with data transmission through these nodes must also take care of minimal signal crossover to conserve the energy of the network.

3.1.3.2 Signal Crossover

The wireless communications in the network is mostly broadcasting type communication where a node in the network simultaneously forwards the collected data to all the nodes deployed in the network. Therefore, it becomes necessary to particularly address the recipient to which the data is intended to be forwarded. The signal crossover can occur due to multiple data transfer through the same frequency channel, obstacles present in the path of transmission, co-existence of several wireless networks in the same zone of application or effect of other electromagnetic waves on the established communication links [56]. This phenomenon is termed as interference which must be taken care as it affects the packet delivery ratio during data transmission in wireless sensor network. The interference may occur in any of the nodes and can occur multiple times irrespective of whether the designed network is static or dynamic in nature. Thus the routing scheme should be able to reduce the effect of interference, so that a reliable data communication network can be established. But in large and dense network, often the data is received by other nodes which need not want to receive the data. This leads to signal crossover leading to data error in the network. The effects of this overhearing and signal attenuation on the energy expenditure of the network energy have been discussed previously [204]. Here, the inefficiency of the minimum energy spanning trees in solving overhearing problem has been justified. An alternative method known as Tarjan's minimum branching/arborescence algorithm was thereby proposed which helped to overcome the signal crossover in the network [204]. In a later work, a hybrid MAC protocol is designed to minimize the energy expenditure of the communication network by synchronizing the nodes suffer from overhearing [205]. Energy of the network can also be conserved through proper handling of the idle nodes in the network.

3.1.3.3 Idle Nodes

Energy handling of the idle nodes in the network is one of the major problems to be taken care in case of wireless networks. The sensor nodes continue to consume power while waiting or listening to the next set of data even when they are not transmitting or receiving any data. In order to overcome this problem, a distributed coordination technology called 'Span' was proposed based on Time division multiple access (TDMA) based protocols to solve the energy consumption due to ideal listening in a multi-hop system [206]. Abrardo et.al designed a dual low power listening (DLPL) strategy for wireless sensor networks after it was identified that idle listening was one of the main causes of energy consumption in wireless sensor network [207]. Through this technique, the sender nodes transmit data to a particular node as soon as a reply/command signal from the receiver node is received to start sending the data. But load balancing amongst the nodes is an essential thing to avoid collision in communication channels and data errors in the network.

3.1.4 Proper Data Handling Amongst Nodes

The node deployment strategy should also look after the data handling facility of the network so that no data is lost due to collision or other security problems. Data aggregation at the nodes should occur efficiently to ensure no data is missed out during aggregation. However, this can result in excess energy consumption which should also be taken care simultaneously.

3.1.4.1 Data Collision

When more than one packet is received by a sensor node simultaneously before it has completed finishing the processing of the previous data, then these packets are said to suffer from collision/interference. Due to this collision, data packets get dumped and retransmissions of these packets are required resulting in unnecessary energy consumption [203]. Time division multiple access (TDMA), frequency division multiple access (FDMA) and carrier sense multiple access and collision detection (CSMA/CD) are some of the protocols proposed in the network layer to provide collision free communication and save network energy. An algorithm was designed recently to detect the location of occurrence of collision in a dynamic sensing field [208]. The advantage of this algorithm was that it did not affect the existing routing path after collision but the energy lost due to collision is minimized to conserve the energy of the network and help in lifetime enhancement.

3.1.4.2 Data Aggregation

The process of gathering data in a particular node from all the connected neighbouring sensor nodes is called "data aggregation" or "data fusion". This function is carried out at all the deployed nodes in the wireless network before it is ultimately sent to the control station [209]. The aggregation of the information from multiple nodes is the most energy consuming task of the wireless sensor network. Data aggregation is an additional task that has been dedicated in the intermediate nodes since in some of the application fields some sensors may be present very far from the control station. So, these nodes need intermediate hopes to transfer its accumulated data to the control station. If all the nodes are simultaneously transmitting the data through the same communication channel, it may lead to excess data collision consuming a lot of energy for all the nodes. Thus data aggregation becomes an important tool for transferring the data as well as saving a lot of energy. Multiple nodes by rotation perform the role of data aggregation thereby conserving the energy of the other nodes making data aggregation an important factor in designing an efficient monitoring network.

3.1.4.3 Data Fidelity

The assurance and reliability of best quality of data transfer in the wireless network is termed as Data Fidelity in the network. Data transmission should be very secured, so as to develop a reliable communication network. The designed wireless networks must keep focus on the security and authenticity during transferring the data. Data hacking and presence of malicious node to corrupt the data are some of the threats that affect the performance of the wireless sensor network [210]. The knowledge about the individual Medium Access Control (MAC) addresses should be known to the control station to effectively control the routing scheme. This ensures that any additional nodes coming into the network is easily identified and measures are taken so that the particular node is not chosen as one of the intermediate nodes while data transfer occur [81]. This would help to maintain the fidelity and security of the data in the network to a great extent.

3.1.5 Network Design Costs

Depending on the type of application, the number of sensor nodes deployed in the application area varies from few nodes to a large number of nodes. The number of nodes to be implemented further depends on whether the application is for indoor or outdoor networks. For indoor networks, the transmission range of the nodes reduces considerably leading to implementation of closely placed nodes whereas the nodes in outdoor applications has larger transmission range as data is transferred through the line of site direction [114]. The increase in transmission range facilitates deployment of lesser number of nodes in distributed architecture. The designed wireless networks can be classified as distributed network, large and dense scale networks and co-ordinated network. According to the design of the network, the design cost becomes one of the important constrains [211]. The cost of an individual node primarily constitutes of the cost of microcontroller, RF module & communication standard used by a sensor module as well as process of the fabrication. The network topology and the number of sensors implemented to maintain the communication links further settles on the total network cost. The frequency of battery replacement in the wireless nodes dependent on the energy consumption of the network also decides the cost efficiency of the wireless network implementation for a particular application.

Therefore, it becomes a very complicated task to meet the primary objective of node deployment and design constrains of WSN. This can somewhat be resolved through role based node deployment in the network where the functions of each node are predefined.

3.2 Role Base Node Deployment Strategies

The number and positioning of the nodes dependent on their function is highly essential to be predetermined before they are deployed in the designed WSN. The nodes can be classified into four categories hierarchically based on their function namely, the end device or tag; relay or router node; cluster head and base station [212, 213].

3.2.1 End Device or Tags

The first level of any wireless network consists of nodes which are directly attached with the sensors and are known as end devices or the tags. These wireless nodes are attached to the individual sensors to sense event, gather information, execute it and send out to base station. Each end device is enabled to gather data from more than one sensor simultaneously which requires optimized positioning of the tags. This ability of the end devices helps to reduce the number of nodes needed to be installed relative to the number of sensor data to be collected in the network. The network coverage area and the initial installation cost of the system are also taken care by this approach. In earlier works, a mixed-integer linear programming was formulated to estimate the number and positions of the end devices to collect data from the sensors [214]. This technique was designed based on the sensor activity schedules and analyzed the sensor-to-sink data flow routes. The positioning of the end devices is most essential for target tracking problems since co-ordination of these end devices in such applications helps to determine the performance of the network [215]. Later, optimal positioning of node was studied in respect to such tracking applications when the sensor in the network is mobile in nature. A decentralized control law governed the placement of the end devices for both static and dynamic sensors in such target tracking applications [215]. The collected data is then forwarded to the next level of nodes known as relay nodes which helps in connecting with the control station through intermediate hops.

3.2.2 Relay Node Placement

The relay nodes are provided with the task of data gathering and enable data transmission to other nodes and finally to the base station of the designed network. The low power low cost sensor nodes form the pathway for transmitting the data maintaining the connectivity throughout the network. The position of the relay nodes are decided after designing of the entire network since these nodes are not functioned to sense data strengthens the connectivity of the network. Several literature works have focused on optimal placement of the nodes based on some pre-defined specifications. A new algorithm based on designing appropriate subsets of the triangle needed to establish an interconnection between the nodes placed in the vertices of the triangle [216]. The links were studied between these triangles and if no connection was available, intermediate relay nodes were introduced in between them to establish new triangle vertices for interconnection. A branch and cut algorithm based on delay-constrained relay nodes were designed elsewhere to enable data delivery in the wireless network with minimum transmission delay [217]. The choice of relay nodes was done for a case study considering a wireless node of 50 sensor nodes. A multi-hop wireless mesh network was thereby designed through placement of additional number of relay nodes to establish connectivity between the sensor nodes and the sink. The shortest pathway for data transfer with minimum hops for meshed networked topologies was studied elsewhere to solve the problem of optimal number of relay node placement [218]. In order to prevent energy depletion of all the relay nodes simultaneously, a node amongst these relay nodes was chosen as the cluster head in some approaches to aggregate data in the next level before communicating it to the base station.

3.2.3 Cluster-Head Placement

Often there is an excess number of relay nodes needed to be deployed in the application region. These nodes are grouped or clustered together based on their task of data collection and all the data is transferred to a particular node which is denoted as the cluster head. In the same process, several clusters of relay nodes are established in the network which treats a common cluster head as the hopping node to transmit data from the tag to the base station. This technique of data aggregation reduces energy consumption during transmission by reducing the energy dissipation which may have occurred when the sensor node was placed far away from the sink. Moreover, in dense network architectures where the number of data packets is considerably more, cluster formation provides a better alternative to avoid data collision in the network. A typical formation of cluster in a WSN has been depicted in Figure 3.5 showing the cluster head (CH) and cluster members (CM) in a particular mesh.

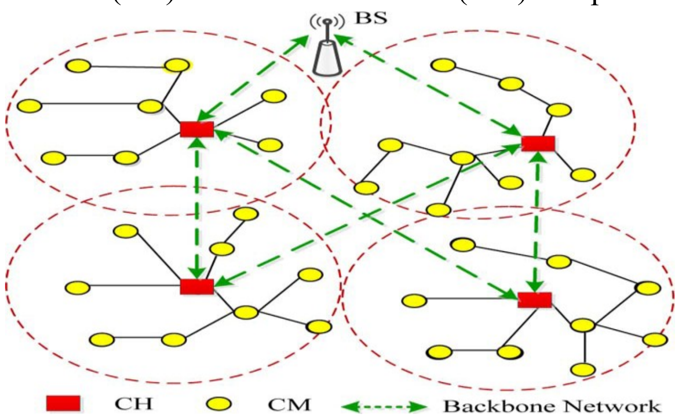


Figure 3.5 Clusters in WSN with cluster head [219]

The cluster formation and selecting cluster heads within a cluster is not an easy task. Several researchers have proposed different techniques for formation of clusters in the network. But group formation and selection of cluster head is not easy task. LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol is one of the most common protocols for cluster head formation in wireless sensor network [219]. This protocol helped to globally control the energy consumption of a distributed node area by rotating the role of the cluster heads in the network. Thereby, it performs well for both static and dynamic clustering since the cluster head formation determines the pathway for data transmission. Fuzzy logic was later utilized to select the cluster heads in the network by the base station [220]. The position of the sink in the network and its distance from the sensor nodes was used to determine the cluster heads amongst the nodes in the network. The relay nodes up to the sink node were selected in a probabilistic manner to compare the performance of the proposed technique with the existing LEACH protocol. In case that any cluster head in the network lost the accessibility and connectivity with the application area, the concept of presence of dual cluster head in the network was proposed in another work [221]. This design proposed by the authors served as a recovery model that ensured the continuous availability and enhanced lifetime of the cluster heads in the network. This model also checked the extent of damage to the network that may be faced from external attacks and provided security in three steps. The steps involved checking of external threats, detection of internal threats in the network and abnormality condition monitoring amongst the cluster heads. These cluster heads form the bridge for carrying the data forward upto the base station where the data is stored and processed.

3.2.4 Positioning of Base Station

The base station is the node placed at the highest hierarchical level which connects itself to the control station server to monitor and control the working of the entire WSN. The dual role of storing the collected data and generating the control signals for other nodes in the network is performed by the base Station. Thereby, placement of the base station is one of the important necessities of any wireless network. A recent research work pointed out the importance of base station positioning on the operation and performance of WSN [222]. This work presents a survey work on optimal positioning of base stations in the wireless network. Another research work later proposed about the optimization of number of base stations in the network with their accurate positioning based on NP-hard problem [223]. A novel meta-heuristic algorithm named as ‘Discrete PSO’ based on particle swarm optimization helped to optimize the position of the sink nodes. The determination of the sink node placement is dependent on the amount of data flow in the network. Multiple Objective Metric (MOM) method was presented by Kim et al. which focused on placement of base stations through four stages [224]. The first stage checked the availability of the number of sensor nodes in the network while the second stage focused on measuring the tolerance of the network. The tolerance of the network is based on the capacity of the network to perform during base station failure. The third stage of the base station placement focused on measuring the energy consumption of the network while the final stage concentrated on the data congestion near the base stations.

Several strategies have been undertaken by the researchers in previous works to fix up strategies of the different node deployment in the network to keep up the performance of the wireless sensor network.

3.3 Node Deployment Strategies

Good node deployment strategies must help to provide good coverage area and strong connectivity between nodes. This in turn helps to minimize the power consumption in the network by controlling the data aggregation in the network and ensuring reliable data transfer. This provides energy saving performance and reduces the node redundancy and the network costs. The area of application, type of application, sensor types and the maximum architectural cost of the network helps to determine the node deployment strategy to be chosen. The node deployment technique based on how they are placed can be classified into two major groups:

(1) Static deployment

(2) Dynamic deployment.

3.3.1 Static Deployment

In case of static deployment strategy, the position of the sensor nodes based on their role remains constant throughout the lifetime of the network [213]. To understand the efficiency and efficacy of the wireless network obtained by this static node deployment strategy, many authors have studied the advantage and drawbacks of static deployment in different application environment. In one of the earlier works, the author has aimed to establish an energy efficient wireless sensor network using static node deployment technique based on the pre-determined positions of the nodes in the network [225]. The authors have also studied the data generation rate of the network based on the positions of the sensors. The importance of a stable routing strategy was studied elsewhere to maintain a static mesh network for efficient data communication [226]. The paper focused on the routing stability problem in a static mesh network where the mobility of sensor is negligible. Two mesh networks were studied for first time measurement of data to characterize the routing stability. The data traffic load and effect of interference for such kind of deployment was also examined to prove the efficiency of static routing based wireless network. The data aggregation, reliability of network and its time response for statically deployed networks was examined in a later work [227]. For experimental purpose, 100 static nodes were placed in a 1x1 meter square area. The determination of routing pathway for static deployed network was performed based on four mechanisms – earliest-first, randomized, nearest-first, and weighted-randomized. It was observed through various simulations that data aggregation was found to be highest for earliest-first and nearest-first routing schemes. On the other hand the short time response and reliability of the network was observed to be best in case of randomized and weighted-randomized schemes. Based on network property, the static deployment can be subdivided into two categories namely random node (non-deterministic) deployment and controlled/deterministic node deployment [212].

3.3.1.1 Random Deployment

The wireless sensor network has facilitated data monitoring due to its ease of implementation in any environments such as forests, battlefields, surveillance fields and disaster restoration. But, it is not a realistic option to deploy the nodes to deal with such odd and harsh environment in a deterministic manner based on the network performance. This necessitates random deployment of nodes considering a fixed position of the base station at the centre of the network as shown in Figure 3.6. These randomly deployed sensors have self-organizing capability which helps them to establish connectivity on their own [228]. But these type of deployment results in uneven distribution of sensor nodes throughout the network which may result in unbalanced energy consumption amongst the nodes. When the energy capacity of one of the nodes gets reduced, node failure may occur in that particular area of the sensing field making the region uncovered and raises the problem of sensing hole. Till date many research works have been performed to study the effective performance of wireless network based on random deployment of nodes [229].

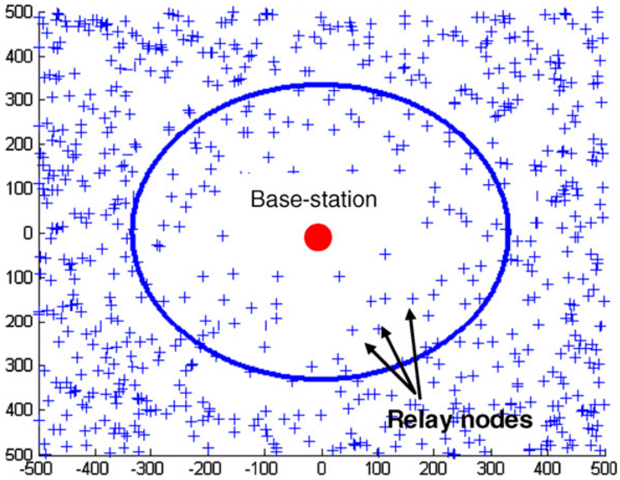


Figure 3.6 Random deployment of sensor node [212]

The primary concern related to random deployment is the improper coverage of the entire network. Previous research works have tried to find out solutions to overcome the problem of network coverage in case of random deployment. The effect of sensing as well as the probability of the number of sensors to be placed in the deployment region was decided based on the area being covered [230]. The problem of coverage in case of random deployment was also tried to be eliminated by adjusting the range of the sensor based on the number of targets to be monitored in another work [231]. This work considered a large area where the nodes were deployed in close proximity with the targets and the energy constraints related to proximity based node monitoring was also examined. In this context, two random deployment structures based on two-dimensional and three-dimensional architectures was studied for Underwater Acoustic Sensor Networks (UW-ASNs) where placement of nodes in pre-determined positions was impossible [130]. However, deterministic or controlled node deployment is preferred in whichever applications possible to provide more efficient performance related to wireless networks.

3.3.1.2 Controlled Deployment

Controlled deployment strategy in wireless networks ensures that the nodes are placed in the network deterministically. Before node deployment, the specifications of the area where the wireless network is to be implemented needs to be examined well. Several mathematical computations and other optimization techniques thereafter help to determine position of the wireless nodes before physical placement of the wireless nodes. Some sensors deployed in the network are given higher priority based on the importance and cost of the network. Controlled deployment has found maximum applications in case distributed networks and indoor networks where sufficient coverage with minimum number of nodes is intended [212]. A long term design of WSN is found to be highly correlated with controlled deployment of nodes in the network when only few nodes are available [232]. A controlled layer deployment (CLD) protocol was suggested in this work whose simulation results depict improvement in network lifetime through minimal deployment of sensor in the network. A recent work on deterministic node placement is proposed based on a multi-objective problem formulation known as Deployment and Power Assignment Problem (DPAP) [233]. This work applied multi-objective evolutionary algorithm based on decomposition (MOEA-D) for deterministic node deployment in a rectangular area with homogeneous sensor nodes having infinite energy. In another work, characteristics of a two dimensional plane coverage and a three dimensional space coverage through implementation of wireless nodes in real world application was discussed [234]. These two schemes helped to study the coverage ratio problem of the network and positioning of the nodes through controlled deployment.

The shortfalls of static node deployment due to fixed positioning of the nodes in the entire network can be overcome using dynamic deployment where the node placement is mobile.

3.3.2 Dynamic Deployment

The dynamic deployment of nodes facilitates to reallocate the wireless nodes in the network in order to enhance the performance of the WSNs. Since, these nodes are mobile in nature; the y can arrange themselves to desired positions in the network according to the requirement of the application [235]. This deployment strategy proves advantageous in case of applications subject to node failure or sensing-hole problem. In some works found in literature, it has been found that the sink nodes in dynamic deployment help to increase the network lifetime with energy-constrained nodes [236]. In this work, a linear optimization model was designed based on mobile sink node placement in the network. Initially the algorithm found out the nodes that need to be visited by the mobile sink and for how long so that the algorithm helps to elongate the time of first node death in the network. A holistic approach involving mobility of the relay nodes and wireless transmissions in the network was proposed elsewhere in order to optimize the total energy consumed in the network [214]. The effect of the energy consumption helps to determine the position of the mobile nodes in the network in order to enhance the network lifetime.

The different deployment strategies employed in the wireless network aims at fulfilling the common objectives through node deployment in the wireless network. The role based node deployment and the deployment strategies give better performance results based on the routing topology undertaken by the deployed nodes through which the data is transmitted in the designed wireless sensor network.

3.4 Topology Selection for Wireless Sensor Network Design

An overview of the existing topologies of the wireless network and the arrangement of the different nodes in that particular WSN is necessary to reduce the overall cost and complexity of the network. The choice of the correct topology helps to increase the efficiency, reliability and the lifetime of the components in the network. WSN has taken the traditional topologies to an entire new dimension through different configurations of node arrangement. The wireless network topologies can be classified as bus topology, ring topology, tree topology, grid topology, star topology and mesh topology. For indoor based applications subject to several sources of data loss, the star topology and the mesh topology has been found to be the two suitable topologies that ensure minimal energy consumption and enhanced reliability while data transmission. A vivid description related to the problems of other topologies and the need for choice of star and mesh topology has been presented here.

3.4.1 Problems related to Other Topologies

The most primitive topology of any communication medium is the bus topology where a node broadcasts the message in the network to be seen by all nodes. The intended node only accepts and processes the message. Although this topology is easy for installation, however it has the limitations of single path data delivery and chances of data traffic congestion. This topology is suitable for limited number of sensor nodes but its performance degrades in case of large number of nodes [237]. In case of Tree topology, a central hub known as "root node" acts as the main communication router. A central hub is placed below the root node in form of a star network. The tree topology is a combination of star and peer to peer network topology where the nodes can transmit their data through single hop or multi hop architecture. The sensor nodes collect the monitored data and send the data to the sink which is finally stored in the Root Node. Therefore, for such a topology, identification of the shortest path to transfer the data becomes necessary to maximize the lifetime and reduce the transmission delay in the network. Breakage of a particular link leads to communication breakdown since only one single path is available for active routing [238]. In ring network topology, the sensor nodes are arranged in a ring type structure where each node can communicate with exactly two of its neighbours. The messages in the ring topology were transmitted in a particular direction, either clockwise or anticlockwise. The limitation associated with topology was that if a node breaks down, it would cause the communication breakdown of the whole network [239]. The communication breakdown in these topologies mainly occurs due to excess data traffic in the communication channels or effects of interference due to presence of multiple wireless technologies. Star topology and mesh topology have been found to be the two most suitable topologies when considering data transmission in indoor networks.

3.4.2 Ideal Topologies for Indoor Networks

The indoor network applications are subject to data loss due to communication link failure and interferences. The presence of several obstacles in the network may lead to reduction in transmission range of the wireless nodes thus resulting in communication failure. Therefore, proper network topologies must be selected that ensure reliable data communication. The data communication in the network also takes care that higher number of nodes are not involved which may lead to increased network costs and energy consumption. The star topology and the mesh topology are the two most commonly used topologies in indoor network. The star topologies become ideal for implementation in closed square or rectangular areas while the long corridors and communication through multiple floors suits the mesh topology of wireless network.

3.4.2.1 Star Topology

In star network topology, several remote nodes or end devices are directly connected to the control station through a co-ordinator or gateway to send and receive data. The end devices in such a topology are able to communicate with the control station only but cannot exchange messages amongst each other. The main advantage of this type is the simplicity of its network design and the minimum energy consumption of the remote node [240]. The main constraint is the limited transmission range of the wireless nodes since the control station must be within the range of all the sensor nodes. Turbo-Like codes was suggested in previous works that enabled passage of two serial messages simultaneously for star connected wireless sensor network [241]. Two algorithms namely modified sum product algorithm (MSPA) and simplified feedback belief propagation algorithm (S-FBPA) was suggested to allow variable node updating during data communication. A combination of fuzzy logic and A-star algorithm was proposed in a later work to boost the lifetime of the whole wireless sensor network that implemented star topology [242]. The algorithm aimed to find the optimum path between the sensor node and the sink node based on traffic loads and also favouring highest remaining battery [242]. Figure 3.7 represents a typical star topology.

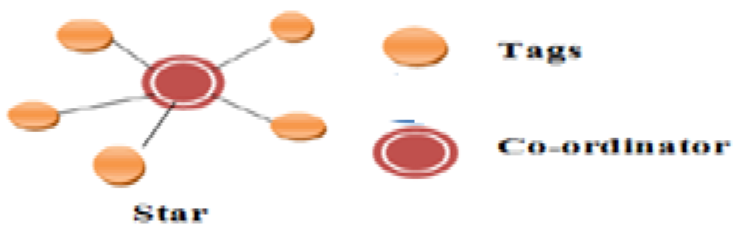


Figure 3.7 Star topology

3.4.2.2 Mesh Topology

In a mesh network, all the nodes are able to communicate with each other which are within its radio transmission range. This necessitates the use of multi-hop communications technique where a particular node exchanges messages with the control station by the help of intermediate routers when the control station is out of range. The intermediate nodes that aid in forwarding the message are called as the routers that help to store the message in the control station [240]. This in turn improves the redundancy and scalability of the network. During failure in operation of any particular node, the remote node continues to send its message to the coordinator through other routers in its range. The mesh topology facilitates data transmission from source to the destination through multiple paths. A full mesh network represents that every node in the network is connected to every other node deployed in the network whereas in a partial mesh network only some of the nodes are connected directly to other nodes. Architecture based on mesh network to ensure sharing of tasks between routers and node was proposed by Riggio et al. [243]. This approach helped to reduce the load on the various nodes of the network and helped to preserve the data integrity and confidentiality. Energy Aware Mesh Routing Protocol (EMRP) was a clustering based protocol designed for mesh networks which helped to fulfil the objectives of load balancing, reliable data transmission and high energy efficiency [244]. A typical mesh topology for data transmission in wireless networks has been shown in Figure 3.8.The mesh network topology has been found to be apt to be applicable in grid applications.

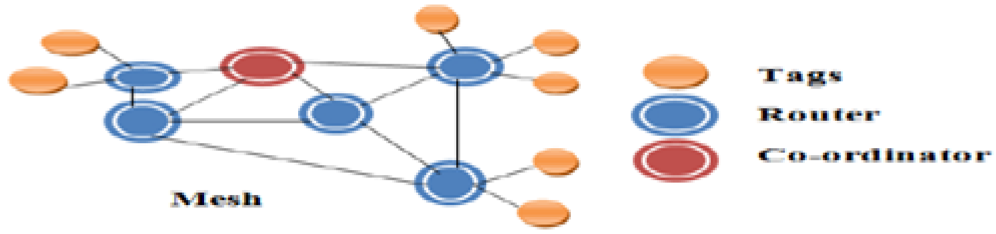


Figure 3.8 Mesh topology

3.4.3 Data Communication through Employed Topology in Grid Applications

When considering grid applications, the developed wireless network for data communication divides the entire application field into square grids of same size. The grids are so designed that at least one node in a particular grid must be in working state at anytime.

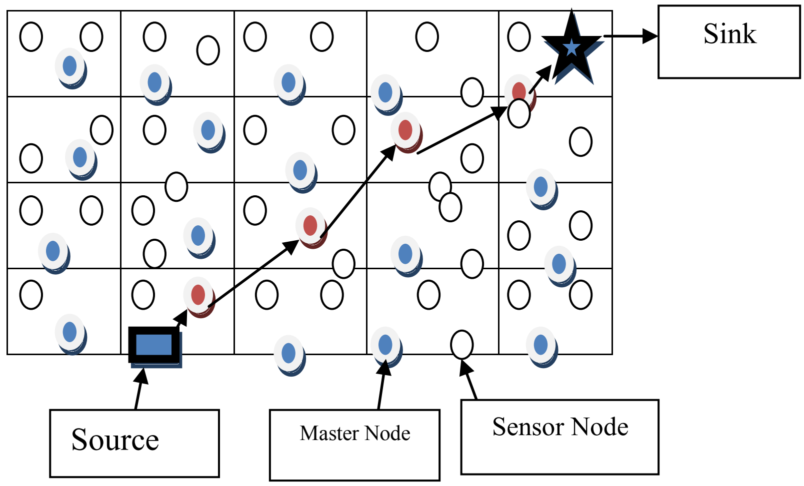


Figure 3.9 Data transmission in grid applications

Figure 3.9 shows the data communication in grid applications through the employed topologies in WSN. The nodes within a grid work by turn to share the load amongst the nodes in order to extend the lifetime of the network. In every grid, one of the nodes is considered as the grid head which helps in routing forward the collected information and enables transmitting of the data packet. This grid based routing topology thereby designs multi path architecture to transfer data packets very fast, increase the energy of the sensor nodes and prevents network congestion. Wei et al. organized the senor nodes by grid clustering where the cluster heads were chosen dynamically based on energy dissipation of the nodes [245]. In case of application of grid topology in congested areas, a congestion control mechanism was proposed to balance the data traffic load and conserve energy of the network [246]. A priority based algorithm was also designed in a later work to help eliminate congestion and achieves fairness in multi path and multi-hop WSN [247].

The reliability of the WSN through the designed network topology largely depends on the routing protocols used in that topology. The different routing protocols so far designed for reliable data transfer in WSN has been discussed in the next section.

3.5 The Designed Routing Protocols in Wireless Sensor Network

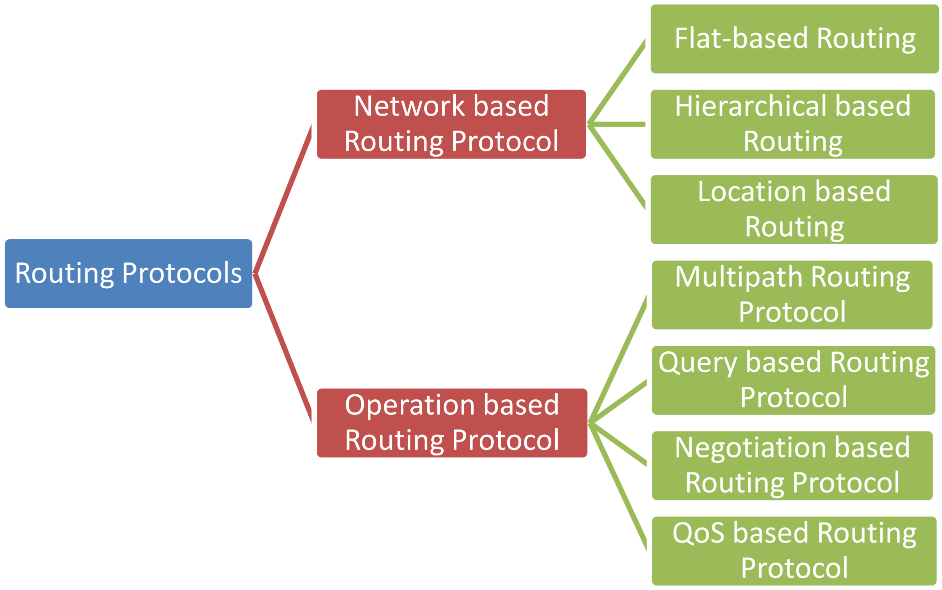


Figure 3.10 Classification of routing protocols [248]

The process of selecting the pathway between the established source node and the sink node to ensure reliable transmission of data is called 'Routing'. A well designed routing pathway helps to minimize the transmission delay in the network and ensures minimum power consumption during data transmission. The routing protocols should also take care that the network is able to handle node failures in the network, minimize interference while data transmission and provide secure routing [249]. A well-defined set of rules followed during development of the pathway is termed as routing protocol and the procedures which follow these rules to design the pathway amongst the nodes are termed as routing algorithms. The routing protocols are active in the network layer of the wireless sensor network and provide efficient data transmission in the wireless network. Various routing protocols and algorithms have been proposed for wireless sensor networks over the past few years based on different criteria have been elaborately discussed in Figure 3.10.

3.5.1 Network based Routing Protocols

Flat-based routing, hierarchical-based routing and location-based routing are the main classifications of the routing protocols based on the structure of the network as shown in Figure 3.10 [248].

3.5.1.1 Flat Based Routing

Flat-based routing protocol is suitable for large network structures where all the nodes are functioned to perform the same operation. Sensor Protocols for Information via Negotiation (SPIN), Energy Aware Data Centric Routing (EAR) and Directed Diffusion (DD) are some of the most popular protocols that come under this classification [248]. Sensor Protocols for Information via Negotiation (SPIN) protocol aimed at overcoming the problems of overlap and implosion occurring due to large number of nodes in the network [250]. This protocol functions based on the information obtained about the resources of the nodes. All the sensor nodes adhering to this protocol needs to be aware about the energy required to compute, send and receive data in the network. This protocol works based on two mechanisms namely resource adaptation and negotiation. The sensors negotiate with all the other nodes deployed in the network before transmitting the data to remove the problems of injection of useless and redundant data in the already designed network [251]. All the nodes through this SPIN protocol are provided with descriptors to avoid occurrence of overlap. The size of the data to be monitored is less than the memory capacity of the sensor node. The descriptors enable the sensor to know about their resource consumption before data processing and transmission enabling the sensors to adapt to any kind of change of its resources. Directed Diffusion is another of the protocols suitable for flat based routing to meet the needs of sensor query dissemination and processing [90]. This protocol is one of the important protocols which help to maintain the high energy efficiency, robustness and scalability of the wireless network. Initially the data rate is very low when the data diffusion process begins. After that the data rate gradually increases by resending the original messages after small intervals. When the rate of data flow increases the highest limit of data diffusion rate, one or more nodes in the neighbourhood are engaged to participate in the data transmission [251]. Energy Aware Data Centric Routing (EAD) protocol helps to build a virtual backbone for the network containing active sensors involved with data processing and relaying [251]. This protocol works by formation of a broadcast tree hat where all the sensors are placed and well connected with the gateway. The radio transceivers of the leaf nodes which are not participating in data relaying are turned off and that of the active sensors are turned on. The tree formation concentrates on formation of minimum number of leaves in the tree architecture so that the number of active sensor nodes in the network can be reduced. This approach is energy aware and thus helps to increase the lifetime of the whole network [252].

Energy conservation of the network can also be achieved if the nodes are arranged in hierarchical levels with the nodes at each hierarchy designed with a special function.

3.5.1.2 Hierarchical based Routing

Hierarchical based routing protocols are preferred for the networks where different nodes can be classified into different categories according to their role. These protocols are very common in cluster based wireless networks and hence also known as cluster based routing protocol [248]. The nodes involved with this type of routing are grouped into low energy nodes and high energy nodes. The low energy nodes perform the role of collection of data while the high energy nodes are selected as the cluster heads to transmit data in a synchronized manner to the base station. Hybrid Energy-Efficient Distributed Clustering (HEED), Threshold Sensitive Energy Efficient Sensor Network (TEEN) and Low Energy Adaptive Clustering Hierarchy (LEACH) are some of the protocols that belong to this category [249]. One of the most energy efficient and commonly used energy efficient hierarchical clustering algorithms for wireless sensor network is LEACH protocol. The clustering task is divided amongst the nodes deployed in the network through this protocol to increase the lifetime of the network [219]. Each cluster has a designated cluster head which communicates with the base station through multi hop fashion involving the other cluster heads. The total network load to be monitored is divided amongst the nodes in the network so that no sensor handles any data more than their memory size. Localized co-ordination is used in case of LEACH protocol which helps to reduce the amount of data dissemination and routing becomes more robust and scalable. In this protocol, all the nodes are given equal chance to become the cluster head, thereby conserving the battery energy of all the sensors leading to longer lifetime [219]. TEEN protocol also utilizes the same principle of dividing the available nodes into clusters each having a cluster head [253]. The selected cluster head forwards the data to a higher level cluster head and ultimately to the sink node. This protocol allows a trade-off between data accuracy, energy efficiency and response time. This allows TEEN protocol to be utilized in time critical applications which needs extended lifetime of batteries [253]. An extension of the concept of LEACH protocol was found in HEED protocol which helped in selecting cluster heads based on residual energy and node density of the network [254]. The lifetime is found to be more in case of HEED protocol than LEACH protocol since the cluster head selection is random in case of LEACH protocol. On the other hand residual energy of the nodes and the effective communication within the cluster determines the cluster head in HEED protocol.

The routing pathway amongst the nodes can also be chosen based on the geographical positions of the nodes in the designed wireless network and hence needs a detailed study.

3.5.1.3 Location Based Routing

Location based routing protocol is ideal for dispersed networks where the nodes are deployed randomly throughout the application area and their physical locations are determined by GPS or by other similar techniques [248]. These protocols are also suitable in case of mobile sensor nodes as the location of a particular sensor is estimated based on the signal strength transmitted by the sensor node. Examples of location based routing include Geographic Adaptive Fidelity (GAF), Geographic and Energy Aware Routing (GEAR), Graphic Random Forwarding (GeRaF) protocol and so on. In case of GAF protocol applied in WSN, the energy required for transmission and reception as well as the idle time of the node is considered to be main determining factors to identify the location of the nodes [255]. This protocol works on the basis of the idea that the unnecessary sensors are turned off without disturbing the data fidelity to minimize the amount of energy consumed. The entire field is divided into small square grids each containing several sensors. The sensor nodes share their location information by help of GPS to other sensor nodes to associate itself with the grid [256]. The working of the nodes under GAF protocol can be classified under three states: discovery, active and sleeping. In sleeping state, the sensor turns off its radio transceiver for saving energy of the nodes. In discovery state, the sensors exchange their messages with each other. In active state, the sensor broadcasts its message to inform others about its location. The sensor nodes in the three states through this protocol work in a collaborative manner to increase the network lifetime by having only one active sensor node attached to each grid. The decision about the state of the nodes deployed in the network is taken based on their energy levels. GEAR is a routing protocol in which queries are targeted to the sensor field about the locations of the nodes in the application area before forwarding the collected data [257]. Here also the sensor nodes are provided with a GPS unit that helps other nodes to know about their current positions. An idea about the residual energy and location of other neighbouring nodes are also provided to the node through this protocol [258]. Based on this information, the GEAR protocol helps the sensors to transfer the packet to the next destination using energy aware heuristics and after that it uses geographic forwarding algorithm to scatter the packet in the target region. Graphic Random Forwarding (GeRaF) is a geographic routing protocol but this protocol does not guarantee that the nodes will be able to transfer their data to the ultimate destination [259]. It is assumed through this protocol that all the sensors are aware of their individual locations and location of the sink. In this protocol, the sensor after sensing the data broadcasts a request-to-send (RTS) message to all its active neighbours to get sure about the location of the nodes and the sink. The area around the sink is divided into regions based on priority of the locations of the sensors from nearest to the farthest. On receiving the messages from the active neighbours, the data is transmitted from the source to the sink based on the priority level of the nodes.

The routing protocols in the wireless sensor network can also be determined based on the type of operation they undertake while forwarding the data to the control station.

3.5.2 Operation based Routing Protocols

Four major category of routing protocols can also be classified based on their operation which has been briefed below.

3.5.2.1 Multipath Routing Protocols

The routing protocols that utilize multiple paths to forward the sensed data to the base station come under the category of multipath routing protocols. The reliability related to system performance is enhanced through these routing protocols since alternative pathways are available to continue the data monitoring even if one of the links fail. Higher power consumption of the network during multi path data transmission is the major disadvantage related to this protocol implementation in WSN. Disjoint Multipath, Braided Multipath and N to 1 Multipath Discovery are few examples of multi-path routing protocols. N to1 Multipath Discovery is based on simple flooding technique divided into two phases namely Branch aware flooding and Multipath extension flooding [248]. Both the phases use the same routing messages to create multiple paths for every sensor. Salvaging of the data packets in every hop is enabled to ensure reduced sensor failure and increase in reliability of the network. In case of disjoint multipath routing, minimum number of alternate paths along with a primary path is formed to eliminate the constraint that none of the paths have any sensor in common [260]. The alternate path is independent of the primary path so that the alternate paths remain unaffected during failure of the primary path. The primary path for data transmission is chosen based on low loss and delay in the network. Braided paths are also a type of disjoint multipath data routing scheme. In this protocol, initially the primary path is constructed based on energy efficiency of the nodes [248]. An alternative pathway for every sensor upto the sink is chosen that does not involve any sensor from the primary path. These alternate paths are called ‘braided paths’ and the energy of both the paths are almost same.

3.5.2.2 Query based Routing Protocols

As the name suggests, these protocols work on the basis of the query signal sent by the nodes deployed in the network. The nodes which are able to process the data send the query signal in high level languages and the data possessing node reply back to the node which initiated the query. Query based routing protocols include DD (Directed Diffusion) protocol, Rumour Routing protocol, Active Query Forwarding in Sensor Networks (ACQUIRE)to name a few. Rumour Routing is one of the query based routing protocols that utilizes the combination of event flooding and query flooding simultaneously [248]. The data packet is broadcasted through the entire network to gain information about each sensor and about the queries generated by each sensor in the network. The data packet through this particular protocol is forwarded to the sink node based on a certain pre fixed number of hops or else the transmission process terminates. An event list about the distance between the sensors and the point of data monitoring is maintained to estimate the hops required for data transmission related to that particular event [261]. Thus whenever a query is received from a particular sensor, it is synchronized with the event list so as to maintain the shortest path for data communication. ACQUIRE protocol enables optimization of the superior queries for replicated data. This protocol works on the basis of a combination of several sub queries that have simple resources [262]. The relevant sensor is chosen as the next hop if it satisfactorily responds to the sub query based on the currently stored data. A specified trajectory for data transmission is determined related to the queries answered by the sensors on the path by the use of an update mechanism.

3.5.2.3 Negotiation based Routing Protocol

High-level data descriptors called meta-data are implemented in the network using negotiation based routing protocol to eliminate redundant data during data transmission. Directed Diffusion protocol, Sensor Protocols for Information via Negotiation (SPIN) and Scalable Energy-Efficient Asynchronous Dissemination (SEAD) protocol are some of the protocols that belong to this category of routing [248]. SPIN and DD protocol have already been discussed under Flat Based Routing protocol in Section 3.7.1.1. In case of SEAD protocol, a trade-off is allowed between the energy savings and reduction in transmission delay while data forwarding to the sink [263]. These types of negotiations in the network help to eliminate the redundant data and simultaneously send the collected data to multiple sinks in the network. The working of the protocol can be subdivided into three parts namely dissemination tree construction, data dissemination and maintaining links between mobile sinks. This allows each sensor to have an idea about its own location and allows itself to become a part of some dissemination tree.

3.5.2.4 Quality of Service (QoS) Based Routing Protocols

These types of protocols are designed to ensure that the quality of the service of the network related to data transmission without transmission delay is achieved. These protocols find a balance between the power consumption of the network and the quality of data being transmitted [248]. Few common QoS based routing protocols are Stateless Protocol for Real-

Time Communication (SPEED), Sequential Assignment Routing (SAR) and Energy Aware QoS routing protocol. Sequential Assignment Routing (SAR) is the first QoS based routing protocol designed for WSN. This protocol helps to transmit data in multipath approach based on three factors namely QoS of each path, energy resources and priority level of packets [264]. Multiple paths are created based on formation of tree topology on the basis of the above factors. One path is selected as the primary path for data delivery while the other paths ensure that data communication is restored automatically if one of the links of the primary path fails. Energy consumed by SAR is less than minimum-energy metric algorithm since data delivery is performed based on priority of the data and the related energy consumption in the network. This protocol has the advantage of easy recovery and fault tolerance, but has the limitation of high overhead. In case of SPEED protocol, each sensor node keeps itself updated about its neighbouring nodes and determines the pathway best suited for data forwarding upto the bases station [265]. In order to make decision about the transmission pathway, the end to end transmission delay for each pathway is estimated by dividing the distance of that node from the sink with that of the speed associated with data delivery in the network. The delay related to each node is estimated by calculating the elapsed time between the transmitted data and the receipt of acknowledgement (ACK)) message from its neighbour. This protocol has been found to perform better than Ad-Hoc on demand routing (AODV) and dynamic source routing (DSR) protocol in terms of packet error ratio and end to end delay. Energy-Aware QoS Routing Protocol utilized an energy efficient and low cost path to meet the end to end delay in connection [266]. The pathway for data transmission through this protocol was determined using a cost function which considered node's energy, error rate, transmission energy and other communication parameters. Dijkstra's algorithm helped to find least cost paths, out of which, the best path that meets the end to end delay requirement is chosen.

The choice of the suitable routing protocol should aim at fulfilling all the required objectives of an energy efficient WSN and take care of the designing constraints. The best performance related to data routing can be achieved in a wireless network only if the routers or relay nodes are placed at the desired positions in the network. Soft computation techniques related to node placement for efficient clustering and routing have proved to be the ideal solution in all engineering domains to find such optimal results [141].

3.6 Soft Computing Techniques Applied in Node Placement related problems of WSN

Chances of fault occurrence, node failure due to battery energy breakdown and interference are all uncertain in nature. The network connectivity, scalability and the lifetime of the network therefore becomes interdependent on each other. Keeping all the factors in mind, node placement becomes an essential issue for designing of an efficient monitoring wireless sensor network involving lesser number of intermediate nodes to maintain the total cost of the network. The soft computation techniques related to node placement to achieve the objectives of efficient clustering and routing has been discussed here.

3.6.1 Application of Clustering Techniques in Cluster Head Placement

The soft computation techniques have been found to be utilized in addition to different clustering techniques to find the position of cluster heads in the communication architecture. Efficient cluster head placement takes care of the problem of unequal energy consumption in the wireless network architecture and thereby aims at increasing the lifetime of the designed wireless network.

3.6.1.1 Energy Conservation during Positioning of Cluster Heads by Clustering Algorithms

One of the earliest approaches named as Centralized Low Energy Adaptive Clustering Hierarchy (LEACH-C) protocol chose the cluster head position in the network through a soft computation technique known as Simulated Annealing technique [267]. The node to be chosen as the cluster head was rotated after every round of data transmission to evenly distribute the load amongst the nodes in the aim to conserve energy. In a later work, Particle Swarm Optimization (PSO) based clustering approach known as enhanced optimized energy efficient routing protocol (E-OEERP) took care that no nodes were left from being part of any cluster [268]. The cluster head selection was dependent on the cluster heads and the base station distance. This approach however resulted in selection of the nodes near to the base station as cluster heads leading to non uniform cluster head distribution. In a later work, an energy efficient technique based on particle swarm optimization was proposed for cluster head selection which considered residual energy, intra-cluster distance and distance of the sink from the selected cluster heads as the fitness function parameters [269]. Initially this protocol aimed at selection of a set of nodes as cluster head candidates. Next, a PSO based meta-heuristic optimization technique finalized the best cluster heads and their optimal positions in the designed network. However, non-uniform cluster head distribution problem may result in unbalanced energy consumption in the network. In a later work, Attea et.al proposed an evolutionary based clustering protocol (ERP) that focused on better energy handling of the network through a trade off between the reliability and lifetime of the network [270]. Two main factors namely cohesion and separation error were tested in regards to the deployed nodes in the network while designing the fitness function. In a later attempt, a novel Chemical Reaction based Optimization (nCRO) algorithm was proposed that aimed at forming smaller size clusters near the base station compared to the clusters formed far away during the clustering phase [271]. This approach helped to eliminate the problems of unequal consumption as observed under different network scenarios. Adnan et.al proposed a cuckoo based clustering algorithm to maintain the energy conservation of the network based on two types of nodes [272]. This protocol considered that 20% of the nodes had higher amount of energy left in them compared to the rest 80% of the nodes and the cluster heads were selected amongst these 20% nodes to prevent early node death. But these nodes with higher energy were chosen randomly leading to unequal cluster head distribution thereby affecting the network reliability. In another attempt Least Distance Clustering (LDC) protocol aimed at linking the normal nodes to the nearest available Cluster Head (CH) in the aim to make the data transfer process faster and with minimum energy consumption. However, this approach led to non uniform distribution of node members amongst each cluster especially in large scale applications leading to early node deaths of some nodes [273].

The proper cluster head selection should not only enhance the energy conserved in the network but also aim at enhancing the network lifetime. In this aim, different clustering algorithms were designed with the sole aim of increasing the lifetime of the designed wireless network.

3.6.1.2 Implemented Clustering Algorithms to Enhance Network Lifetime

Stable Election Protocol (SEP) aimed at network lifetime enhancement through choice of three types of heterogeneous nodes namely normal nodes, advanced nodes and super nodes [274]. The approach of cluster head selection of this technique was same as the LEACH protocol considering a variation where the advanced nodes selected as cluster heads were modelled to perform the same amount of work as the normal nodes. The energy drain out from the nodes was reduced to an extent through this approach thereby increasing the network lifetime and stability. An advanced clustering technique named as Multi-hop Clustering and Routing (MCR) protocol functioned in a manner where the cluster heads transmitted the data to the base station via intermediate hops in the next nearest cluster head [275]. Weighted Election Probability (WEP) rule was chosen to select the high energy nodes as the cluster head. This method allowed only a small number of cluster heads to react with the base station thereby reducing the burden and consequently the energy dissipation at the base station [275]. Experimental results suggested that the protocol ran for longer duration for 50% of the nodes to die in comparison to other protocols such as LEACH, SEP or PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [276]. EEMHR (Energy-Efficient Multilevel Heterogeneous Routing) protocol helped to decide minimum threshold energy for the nodes to continue data transmission. The main problem of this approach was that when number of node deaths increased, more number of deployed nodes functioned as cluster heads often leading to data collision in the network and affecting the network stability.

Energy Efficient Multilevel and Distance Aware Clustering (EEMDC) protocol was designed to improve the network stability and the cluster head selection was based on the distance between the nodes [277]. The entire network was divided into three different layers based on heterogeneous node deployment and the next hop in the consecutive layers was determined by incorporating average energy calculation while electing a node as cluster head in each layer. This approach helped to maintain uniformity in the cluster size and improved network stability although the complexity in detecting the optimum data transmission pathway was increased [277]. In order to handle the problem of data overhead in the network, the researchers later modified the MCR protocol to design Distance-Based Multi Hop Clustering and Routing (DBMCR) algorithm [278]. The only difference between MCR and DBMCR was that a spectrum was allocated in the communicating channels for a fixed amount of data to be transmitted in the designed network. This prevented data collision and loss of burst data in the network. This approach aimed at transmitting the data through the best available communicating channel thereby improving the network performance.

Several other soft computation methodologies have been adopted in wireless network node placement problems. Special mention must be made to Fuzzy logic based techniques which were quite often utilized for research objectives related to node placement.

3.6.2 Fuzzy Logic based Node Placement Techniques

Fuzzy logic based soft computation approaches are recently coming into recognition in different fields of engineering. Similarly, reliable node placement and enhancement of the network lifetime of the wireless networks has also been looked into through use of fuzzy based algorithms in various design approaches.

3.6.2.1 Reliable Node Placement through Fuzzy Logic

In this trend, an unequal clustering protocol based on fuzzy algorithm to select the positions of the cluster head was designed based on input parameters namely node energy and the source-sink distance [279]. A similar work based on swarm-intelligence based fuzzy routing was proposed which aimed at overcoming the problem of random clustering that leads to improper load distribution and high energy consumption was performed recently which helped to overcome the problems of random clustering [280]. Munir et al. proposed a fuzzy logic based algorithm which helps to design a network based on QoS by minimizing the congestion due to various traffics present in the network [281]. In a different work, an energy aware model based on fuzzy algorithm was proposed for reliable delivery of data packets in wireless sensor network [282]. This work also focused on utilization of Fuzzy logic for the selection of cluster heads in a wireless sensor network by calculating the probability of each sensor to become the culture head.

The proper selection and positioning of the cluster heads through Fuzzy logic algorithms would only prove to be an efficient solution if these approaches can attain the objective of network lifetime enhancement for the designed wireless network. This has prompted researchers to undertake different approaches related to combination of fuzzy algorithms to enhance the network lifetime.

3.6.2.2 Fuzzy based Applications for Enhancement of Lifetime

An adaptive fuzzy clustering protocol namely LEACH-SF was introduced for efficient selection of cluster heads based on Sugeno Fuzzy (SF) inference system. This algorithm considered input parameters such as node residual energy and the distance between the sink to find out the best position of the cluster heads [283]. In this direction, Fuzzy Shuffled Frog Leaping Algorithm (FSFLA) was another work that aimed at improving results related to network lifetime, residual energy and packets successfully received at the base station [284]. A fuzzy-based hyper round policy (FHRP) proposed elsewhere that helped to diminish the problem of unequal energy consumption during clustering task [285]. In this approach, clustering was performed at the beginning of every Hyper Round (HR) and the duration of this HR was computed using a fuzzy inference system. The residual energy of the nodes and distance of the cluster heads from the sink were chosen as inputs to the fuzzy system which helped to determine the HR length at its output. This helped in reducing data overhead during clustering, lengthening network lifetime and conserving the energy of the nodes [285]. A combination of fuzzy approach and A-star algorithm was attempted in a later work to determine the optimal routing path from the source to the destination [286]. The path determining parameters were highest remaining battery power, minimum number of hops and minimum traffic loads of the network. This hybrid approach helped to enhance the network lifetime by 25% compared to A-star algorithm and about 20% with respect to the fuzzy approach [286].

In these clustering approaches, the load balancing was achieved by rotating the role of the cluster heads for each rounds of data transmission. But selection of position of the whole set of cluster heads at every round of transmission is also necessary to preserve the reliability of the network. Several meta-heuristic and nature inspired algorithms have been utilized in this direction to maintain the reliability of the network and fulfil the objectives of network design.

3.6.3 Reliable Routing Approaches through Soft Computation in WSN

The reliable routing approaches for data transmission in the designed wireless network can only be achieved through proper node placement. The recent routing approaches through meta-heuristic techniques have aimed to plan efficient node placement in the network and have also tried to maintain the network performance related to various parameters.

3.6.3.1 Application of Meta-Heuristic Techniques in Node Placement Problem

Several soft computation techniques based on nature inspired algorithms and meta-heuristic approach has been designed for node placement problems in wireless sensor network applications. This section discusses some of the commonly used algorithms in wireless sensor network applications.

3.6.3.1.1 Genetic Algorithm

Evolutionary algorithms like genetic algorithms have been previously utilized in fields of wireless sensor network for placement of mesh router nodes [287]. Xhafa et al. proposed an approach based on genetic algorithm where the whole area is divided in form of grids of small cells and the mesh nodes were arranged within each grid to establish an energy efficient connectivity throughout the network. In a later work, Genetic algorithm was used in smart clustering architecture to reduce the connectivity distance amongst the nodes [288]. To achieve this connectivity throughout the network, optimization of the cluster heads was given focus in this approach.

3.6.3.1.2 Particle Swarm Optimization Algorithm

Nature inspired Particle Swarm Optimization (PSO) algorithm has proved to be an efficient tool for solving multi-objective problems in wireless sensor network. PSO was initially utilized in a research work to solve the problem of optimal placement of dynamic routers in dynamic routing strategy maintaining the connectivity of the system [289]. Various experiments related to the network architecture based on PSO helped to evaluate the performance of PSO in dynamic routing approach. PSO was utilized elsewhere to solve the coverage problem of wireless sensor network was developed [290]. This work aimed at maximizing the coverage area of the network by use of optimal number of sensor nodes. The performance of PSO and GA in generating energy aware cluster based protocol was protocol for wireless network was compared keeping the size of population and maximum generations constant. It was observed that the convergence rate was higher for PSO than genetic algorithm to obtain the global minimum value related to the designed problem [291].

3.6.3.1.3 Simulated Annealing Technique

In order to find out the global minimum of a certain designed problem along with several local minima, a probabilistic based approach known as Simulated Annealing (SA) was utilized in wireless network problems. An optimum number of routers provided with priority constraints were estimated by the simulated annealing approach in one of the research works [292]. This approach helped to improve the accuracy and reliability of the network which was later utilised by Lin et al. to design an energy efficient WSN for surveillance [293]. In a later work, simulated annealing was utilized to correct the ambiguous location of the nodes in the network during data transmission [294]. This work was divided into two phases, the first phase concentrated on having the knowledge of location of the nodes and the second phase estimates the ambiguous location of those nodes. The locations are then corrected by using neighbourhood node information through SA and placed in proper positions [294].

3.6.3.1.4 Ant and Bee Colony based Optimization

Energy and quality of service aware algorithms for multimedia content routing in wireless networks have been designed based on nature inspired Ant colony optimization technique [295]. Many research works related to finding of a high linked quality and reliable path to minimize the total energy consumption in the wireless network has helped to establish the sovereignty of this algorithm in the field of routing. Ant Colony algorithms have also been utilized elsewhere in efficient data aggregation in wireless networks known as DAACA (Data Aggregation Ant Colony Algorithm) [296]. A similar kind of nature inspired algorithm known as Bee colony algorithm was utilized in various wireless sensor network applications. Artificial bee colony algorithm is a modification of the original bee colony optimization technique to design a reliable data packet delivery with minimum energy consumption by choosing optimal position of the cluster heads in the network [297]. This algorithm takes care of the QoS of the network based on clustering and helps to improve the lifetime of the network.

3.6.1.3.5 Cultural Algorithm

Cultural Algorithm (CA) has been recently used in very few works related to router placement in wireless sensor network. Improvement in network coverage in wireless sensor network was achieved recently by optimization using a quantum-inspired cultural algorithm by Guo et al. in a recent work [298]. In a different approach, a hybrid algorithm involving cultural algorithm and ant colony optimization was used in node deployment problem [299]. The dual optimization approach helped to provide better and more stable network architecture related to node deployment in the wireless network.

3.6.1.3.6 Other Soft computing Techniques used

Several other meta-heuristic algorithms have been utilized for optimum router placement in wireless sensor network to establish a reliable path for data communication. Tabu Search (TS) was utilized in a recent work for placement of mesh routers in the wireless network and its performance was compared with GA based on Friedman test [300]. The results showed that when the communication distance between the source and the sink node was high, GA performed better than TS algorithm. A newly developed meta-heuristic algorithm termed as Glow worm Swarm Optimization Localization (GSOL) algorithm was recently proposed in a research work to improve the precision of localization of the unknown nodes in the wireless network through multiple iterations [301]. Parallel Firefly Algorithm (PFA) was later utilized by Van et al. to solve the problem of node localization based on received signal strength (RSS) measurements [302]. This algorithm was seen to perform better than PSO and GA algorithm in terms of performance related to node placement and routing path development in the wireless network. Memetic Algorithm was another algorithm of this trend that aimed at optimized cluster design in mobile wireless networks to avoid topology maintenance for overhead messages [303].

Soft computing based optimization techniques have proven to be efficient previously to find out suitable placement of nodes in wireless mesh networks. But it is also necessary to keep up the network performance while positioning the nodes in the network. The works done in this regard thereby needs a detailed study to understand the important parameters that need to be taken care for network performance improvement.

3.6.3.2 Improvement in Network Performance through Soft Computation Algorithms

Genetic Algorithm (GA) was employed as the soft computing optimization technique which helped to develop the complete connectivity of the network by connecting each cell to its neighbourhood cells to reduce the energy consumption [288]. Later to solve the problem of network coverage in indoor environment, Particle Swarm Optimization (PSO) was employed that aimed at maximizing coverage through reduced number of nodes [290]. In another attempt, Artificial Bee Colony Algorithm was designed to ensure reliable data packet delivery through relay node positioning with minimum energy consumption [295]. The Quality of Service (QoS) and the communication links between the different nodes were checked to design the cluster formation while forwarding a certain parameter data. A quantum inspired Cultural Ant Colony algorithm was implemented in a later work that helped to place the nodes in a dispersed fashion in the network in such a way that no sensor data remains uncovered [299]. In another attempt, Idrees et.al aimed at node distribution by dividing the entire area into several sub regions and the sensor nodes were placed at the centre of this region to establish the transmission pathway. This protocol was termed as Perimeter-based Coverage Optimization Protocol [304]. Hyper-geometric Energy Factor based Semi-Markov Prediction Mechanism (HEFSPM) aimed at effective cluster head election process that helped to balance the data traffic load in the network and improved network lifetime by 22% compared to other existing algorithms [305]. In order to study the network performance in an optimized wireless network, several researchers considered examining variant parameters that determine the network quality.

Node selection based on shortest path only may lead to data overhead in a particular node leading to data congestion, delay in the network and depletion of the node's resources including memory, battery and bandwidth [306]. An experimental work had been performed on calculating the throughput of the devices present in a strongly interfering network due to presence of more than one wireless network [56]. The performance evaluation related to signal attenuation and packet error ratio for wireless network designed for smart home and home automation networks was studied elsewhere [307]. Based on the connectivity of the employed devices with the control station, the performance of the employed wireless technologies were studied in European indoor scenario. The parameters like network coverage, network connectivity and network lifetime was given focus in a later work by help of Proximity Avoidance Coverage-preserving Operator (PACO) algorithm [308]. In order to ensure efficient power consumption of the network, a sender node opted to choose multiple disjointed routing paths for data transmission. To minimize the path cost, paths with smaller hop counts were preferred leading to high level of interference. To overcome the situation above, a recent work focused on interference-aware multipath routing protocol to maintain the Quality of Service (QoS) of the network for multimedia and real time applications through wireless sensor network [309]. This proposed protocol aimed at reducing packet drops through effective bandwidth pre-evaluation and interference susceptibility. Energy Efficient Maximum Lifetime Routing (EEMLR) was proposed to choose the routing pathways based on calculation of the minimum energy cost path to maintain the energy balance of the entire network [310]. It finds a subset of the links that forms an optimal path that includes every node, where total cost of all the links in that path is minimized. When all the nodes of the network have been added to the optimal path, a greedy heuristic route is constructed for a network. With the updated energy information of the links after every round of data transfer, the energy path is recalculated until any node in the designed path drains out its entire residual energy [310].

There are several other meta-heuristic algorithms which still needs better utilization in optimization problems related to wireless networks. Soft computation techniques also find its utilization in joint routing and clustering approaches in WSN to improve the performance related to the networks but these works have been found to be very sparse in literature.

3.6.4 Joint Routing and Clustering Approaches in WSN

Recent attempts focused on joint utilization of routing and clustering algorithm. Akhtar et.al presented a RSSI (Received Signal Strength Indicator) based soft computation approach to design an energy aware intra-cluster routing protocol for wireless networks [311]. The application of this algorithm was tested with TOSSIM simulator which proved that the energy efficiency of the network increased up to 17% [311]. However, this approach did not consider the inter cluster routing to establish the reliable pathway from the sensor to the gateway. Srividya et.al designed an energy efficient distance joint approach that aimed at enhancement of lifetime of cognitive radio–based heterogeneous WSN [312]. This algorithm was known as Energy Proficient Clustering Technique (EPCT) as it maintained uniformity in energy consumption by dividing the entire region of wireless network into different regions and allocated a unique spectrum in the communication channel. The dynamic clustering approach helped to achieve energy efficiency during multi-hop data communication which in turn improved the network stability during data transmission [312]. Particle swarm optimization based energy efficient cluster head selection (PSO-ECHS) protocol was proposed recently that utilized the residual energy of the nodes, intra-cluster distance and the distance between cluster head and sink node to find out the best position of CHs in the network [269]. This protocol initially selected a random set of nodes available for the choice of cluster heads and then applied PSO technique to choose the actual cluster heads and their positions in the network. But this approach did not ensure entire network coverage as it concentrated on the main parameter of cluster head and sink distance to minimize the energy consumption in the network. To attain the objective of joint optimization of clustering and routing, Cuckoo Search algorithm was utilized along with Harmony Search algorithm in a recent work [313]. The cuckoo search algorithm helped to determine the set of cluster heads amongst the deployed nodes in the network considering parameters such as energy reserve of the node, uniform distribution of the nodes within the clusters and maximum network coverage. After the position of cluster heads were determined Harmony Search algorithm helped to estimate the routing path for transmitting the data packet from the CHs to the sink node. This integrated clustering and routing protocol proved superiority in performance over other previously utilized protocols in same types of problems considering efficient routing strategies [313]. However, these protocols did not look after optimal positioning of the cluster heads based on distance between other cluster heads and the sink node in the designed network.

The modern developments related to network topology, routing protocols and optimized node placement in wireless network has helped to fulfil all the objectives of WSN. The usefulness of the wireless network has made it suitable to be utilized in varied fields of applications. Renewable energy sources are also important upcoming technologies which are being installed in various forms in different parts of the society to support the depleting conventional sources. The monitoring of the performance of these renewable installations has become important to understand the energy generated from these sources. The performance monitoring of the renewable sources also ensure that the systems are efficiently replaced when their performance gets degraded. Thereby nowadays focus has been given in utilization of WSN in monitoring of the renewable energy based applications.

3.7 Wireless Networks in Renewable Energy Monitoring Applications

The dependence on renewable energy sources has increased immensely in the recent days to support the increased load demand of the customers and become an integral part of the modern smart grid architectures. These renewable energy sources require continuous performance monitoring and fault identification of the system to support the architecture. Wireless networks have come up as the most suitable communication architecture for real time monitoring of the systems.

3.7.1 WSN in Solar Energy Monitoring

Wireless sensor networks have recently gained its importance as the communication architecture in PV power applications. WSN has been utilized in an earlier work as the integrated communication technology to achieve the maximum power point tracking (MPPT) for a biaxial solar tracking system [314]. A Global Positioning System (GPS) was utilised to obtain the geographical coordinates of the sun in real time to use the values as a reference for digital control of the azimuthal angle. The designed WSN used IEEE 802.15.4 as the communication protocol to supervise and monitor the performance of the PV plant. The efficient working of the proposed architecture was tested in a 2.4kW prototype system [314]. In a later work, wireless monitoring system was implemented as the control system for a solar photovoltaic distributed generator (PV-DG) to be implemented in a microgrid [315]. For experimental purpose a small scale PV-DG system using a 1.28kWp assembly of PV panels was chosen. A ZigBee based WSN architecture was deployed as the measurement and control system with this architecture. This wireless architecture was connected with the control system using a digital signal processor (DSP) and human-machine interface (HMI) software. This proposed system helped to provide the users with an overview of the systems hardware and enabled testing of the integrated system. Wireless sensor network implemented in solar power monitoring elsewhere employed installation of sensor nodes to the individual components of the PV panel [316]. The proposed system architecture succeeded in improving tracking efficiency and identifying the failures and weaknesses from a single cell up to the whole infrastructure. This system therefore enabled better decision contributing to reduction in failures and consequently the costs of the infrastructure. Nowadays, integration of renewable power systems to smart grid architectures requires complicated monitoring and control. A typical photovoltaic power plant requires temperature, electric current and component faults monitoring simultaneously. Wireless sensor nodes have enabled replacement of the costly monitoring structures through these low cost devices. But practical applications of WSN in such large PV power applications are scarce in literature. In a recent research work, the authors have aimed to find out the practical issues related to limited resources, energy and data processing ability encountered during WSN implementation in smart grids. An overall design based on trade-offs for solar PV monitoring based on wireless sensor platforms has been presented by addressing the issues of suitable network topology and ranging of the sensor nodes [317]. In a later work, WSN was implemented for supervision of the photovoltaic plants connected with the grid in real time. Real time monitoring of the intermittent and unpredictable nature of production from the PV plant helped in efficient synchronization of the PV plant with the grid with high precision. Proper working of this proposed architecture would enable massive integration of distributed generation in the smart grid [318].

The successful integration of the wireless network infrastructures in the solar power plant monitoring motivated the researchers to test the efficiency of WSN in more complex renewable systems monitoring such as wind power plants and nuclear power plants.

3.7.2 Wind Energy Monitoring by WSN

Condition monitoring, diagnosis of the faults and structural health monitoring of the components associated with the wind power plant are some of the advantages attained with the implementation of wireless network. Early warning of the damages is often sent out using the wireless network when the wind plant is installed in hostile environments hard to access.

The installed wireless network for structural health monitoring of the wind system offered two main advantages with respect to commonly used wiring system in terms of reduction in maintenance and installation cost and reduction in monitoring time [319].The key challenge for installation of the wind power plant lies in the proper and timely identification of the damages associated with the wind turbine. In this work, a recent work proposed an architecture named as Delphos which worked as a damage prediction system for wind turbines involving wireless sensor and actuator networks [320]. The Delphos structure enabled accurate prediction about when the turbine might reach the damage state thus allowing time replacement of the turbine to prevent chances of accidents, reducing maintenance costs and time delay related to monitoring. Economical and flexible wireless networks can be installed within a large structure which helps to install a low cost monitoring architecture. In another wind farm based application wireless networks helped to monitor the different structures related to wind turbine and provided efficient response to loading and controlling of the generator parameters [321]. The disperse deployment of the wind farms, random wind power generation resource and seasonal characteristic variation affects the performance of the wind power plant. WSNs have been found to efficiently overcome these difficulties of disperse and remote monitoring in comparison to SCADA for wind power plants [322]. Similar response through WSN has been obtained for nuclear power plants in terms of performance and radiation monitoring.

3.7.3 WSN Application in Nuclear Energy Monitoring

Integrated wireless network architectures for conditional monitoring in different essential equipment of next generation nuclear reactors were developed by Analysis and Measurement Services Corporation (AMS) funded by U.S. Department of Energy (DOE) [323]. This system helped to test the operation related to the nuclear power plants installed in laboratories. In large scale application, this wireless integrated architecture was implemented for equipment health monitoring in an entire nuclear power plant. The electromagnetic compatibility of the wireless system with the different plant equipment was also tested to resolve the implementation issues and develop the procedures for implementation of WSN in nuclear power plants [323]. The existing monitoring and control interface for nuclear power plants is not perfect since they are influenced by radiations which affect the accuracy of monitoring. The wireless networks based on ZigBee technology helped to overcome the problems of existing monitoring systems and enabled real time monitoring to prevent accidents in the nuclear power plants. The integration of wireless networks would therefore help to develop a nuclear power plant safety monitoring system [324]. The small wireless nodes implemented in the nuclear power plant were capable of sensing physical attributes like temperature, pressure, humidity, light, sound, radiation, vibration, etc [325]. These devices thereby enabled identification related to abnormality in a specific physical parameter affecting the performance of the nuclear power plant. A proper designing of the nuclear power plant with WSN equipped sensors helps in detection of harmful radiations in the wireless network. Connecting the sensors to the world-wide-web (WWW) through the control station helped to transmit the continuously monitored information about the radiations allowing taking the measures to reduce the threat posed by radiation hazards [325]. Two main benefits obtained by adding wireless networks to nuclear power plants has increased reliability of the networks as the wireless networks has serves as a backup network to the wired system for monitoring. A new fault model based on time dependent faults was proposed known as 'bitvector' which involved wireless networks to detect the fault duration time as an indicator of network stability [326]. This wireless fault detection model provided best results when the network size was large.

Wireless networks have also found its application in several other applications involving renewable monitoring systems but applications has been sparse in literature since correct measures for efficient design have not been identified properly yet for these technologies.

3.7.4 Other Renewable Applications involving WSN

A fuel cell fault diagnosis system for Proton Exchange Membrane Fuel Cells (PEMFCs) was designed based on ZigBee based wireless networks [327]. The sensor modules were used to collect the data related to voltage, current, temperature and supplied gas pressure for the PEMFC. The fault diagnosis mathematical problem was developed using an extension of neural network (ENN) based method and the fault forecasting system was observed using a LabVIEW man machine interface. The effectiveness of the proposed design was established after experiments were conducted on 400 sets of PEMFC with encouraging results [327]. Self powered, low cost wireless sensor devices have proved to be ideal candidate for efficient monitoring and control of waste water treatment plants (WWTPs) since they does not need to alter the existing infrastructures [328]. This design has helped to address an important public issue related to cost of electricity as the quality requirement for water processing improves through easier installation of the wireless devices in wastewater processing tanks. The energy storage system associated with the distributed renewable energy generation systems also needs efficient management to enhance the life of the electrical networks in future. Pervasive monitoring and control of the energy storage systems aims at designing of secure and economic operation of energy storage systems associated to microgrids or wide system integration [329]. Hardware implementation of the wireless devices allows testing of the storage systems and helps to design more complex models for large scale applications. The wireless network technology helps to provide distributed intelligence to control the effective performance of the storage system associated with the power system architecture [329]. These wireless sensor applications have also found importance in environmental and patient condition monitoring. These applications include CO_2 concentration monitoring of atmosphere and home environments for in house patients. Data collection from the deployed sensors help to create a database for future analysis by the ecologists and medical professionals related to pollution and creation of power supply sources through renewable generation [330].

3.8 Conclusion

A detailed study about the node deployment strategies of the wireless sensor network, the objectives and design constraints related to node deployment and the different routing protocols have been made. The unbalanced energy consumption in the network related to node deployment has been one of the major drawbacks for the works found in literature. The cluster head placement problem did not take care of the distances between other cluster heads and the sink node while positioning the cluster head in the network. The node deployment architectures often did not take care of the signal attenuation in the network leading to data packet losses which has been given focus in this work. The plan of deployment of nodes based on geometrical shapes was found to be difficult when considering large application areas or large number of node deployments, hence ideal topologies were looked into through this research work. These drawbacks related to the works found in literature were attempted to be overcome in this work through efficient node placement. The applications of soft computation techniques have also gained importance nowadays in node placement related wireless network problems for efficient clustering and routing in the network. However, Cuckoo search algorithm is a modern soft computation technique which has been sparsely used for wireless node deployment problems due to its disadvantage of usage of binary inputs. In this thesis, cuckoo search algorithm has therefore been chosen as the primary soft computation tool which has been utilized in a modified form and in association with other protocols to develop the joint objective of energy efficient clustering and routing. The existing clustering algorithms have been found to randomly choose the cluster heads at every round of rotation. This often leads to the same node being chosen as the cluster head every time. The random selection of the cluster heads leads to uneven energy consumption in the network and the network load is not properly balanced. The existing LEACH algorithm has been found to be the most primitive type of clustering algorithm which has been re-modified in this work to select the cluster heads based on residual energy of the nodes. The problem of the previous works related to early node death and breakage of the communication links has been somewhat tried to be overcome through this unified approach. In order to overcome the excess wiring issues related to maintenance and installation cost for monitoring of the data in home environments, WSN has been chosen as the best alternative to set up the bidirectional communication architecture in home environment. The variety of application fields of wireless networks related to renewable energy monitoring have helped to provide an idea about implementation of wireless integrated renewable energy systems for this work.

A detailed study of the previous works helped to identify the gaps related to the communication infrastructure set up by the wireless sensor network. The problems of data loss due to signal crossover and presence of other electromagnetic waves need to be overcome through efficient node placement. As the transmission range of the nodes decreases due to these problems, the routing algorithms must focus on positioning of the intermediate nodes to ensure maximum numbers of packets are delivered. The necessity of the study of the parameters such as message delivery success ratio and transmission delay which are sparse in literature has also been attempted here to study the reliability of the network. The energy consumption is a critical issue in case of battery based nodes. However, the energy consumed during data aggregation or selection of cluster heads based on residual energy of the nodes has not been given focus previously. But this is an important issue while employing the battery based nodes to ensure longer lifetime of the network and existence of the communication links amongst the deployed nodes. The cost is also important while designing of the network which needs to be given parallel importance while designing the network. These gaps of wireless network implementation have been mainly given focus while planning the work. Novel algorithms and solution techniques have been given focus to attain the objective of reliability and lifetime enhancement of the network. The efficient design plan of the wireless network has helped to choose WSN as the communication infrastructure to control the appliance operation in home energy management applications in the last part of the work.

In view of the above this research work has been planned in three parts based on the literature survey performed. The first part of the work focuses on designing of efficient node placement strategy through a modified approach of cuckoo search algorithm. Cascaded Cuckoo Search Algorithm has been preferred in this work where simultaneously the objective of node placement and signal attenuation minimization has been attained in two loops. Cuckoo search algorithm utilizes lesser parameters and ease of use of cuckoo search algorithm makes it useful for wireless networks. Two routing protocols based on flat based routing protocol and hierarchical based routing protocol respectively have been studied to understand the performance related to wireless networks. Two topologies common to wireless networks based on star and mesh topology are chosen for cost efficient node placement study. The second part of the work determines efficient clustering and routing through utilization of a clustering protocol LEACH and soft computation technique in Cuckoo Search Algorithm. LEACH protocol is chosen because of its most suitability in choosing of cluster heads and ability to rotate the cluster heads in every round of data transmission. The efficiency of the wireless networks in monitoring the renewable energy sources and the advantage of bidirectional communication provided by the WSN communication architecture has helped to plan the idea of utilizing the wireless sensor network as the controlling framework. In the last part of this work, wireless controlled demand side management system design has been proposed by installation of rooftop solar panels. The bidirectional data transmission facility of the wireless sensor networks helps to develop an efficient energy management unit which would facilitate appliance shifting to reduce electricity cost. The details of the current demand side management structure and future time of day tariff schemes to be adopted for low demand prosumers through utilization of renewable energy sources have been discussed in the next chapter. The results and observations related to the various wireless network implications discussed later proved the efficiency of the proposed designs for indoor environments by WSN and their suitability in home energy management systems.

Chapter 4

Wireless Network Controlled Renewable Integrated Home Energy Management

The Annual Energy Outlook Report presented by the U.S. Energy Information Administration in 2010 forecasted that the energy consumption in the residential sector will increase by 24% in the upcoming decade [331]. Almost the same trend is expected to be observed for the developing countries like India where modern appliances have started to become an integral part of most of the households. This sudden increase in energy consumption in the residential sector is taking a toll on the traditional grids. The conventional sources of power generation in these traditional grids are getting extinct, thereby leading to a mismatch between the demand and the supply of power in the society. Absence of proper monitoring tool prevents timely forecast of excess demand leading to major blackouts of the traditional grid. The latest major blackout in INDIA took place in July 30-31, 2012 in the Northern, Western, Eastern and North Eastern grids simultaneously due to excess power drawn by the states [332]. This has led to the idea of development of smart grid network architectures that enable bidirectional power flow between the grids and the customers. The concept of prosumers has come into forefront where the customers generate power at their own households to support their own need and the excess energy is sold back to the grid. Integration of renewable energy sources with demand response strategy in micro grids has gained importance nowadays to develop new energy management systems [333]. The Demand Side Management (DSM) schemes have also enabled management of energy usage based on the availability of power and the tariff structure prevalent in the society. Real time monitoring and control infrastructures have been implemented in such networks which aid advance control of appliance operation. This chapter deals with the various DSM programs undertaken in the residential sector that have shown significant effect on consumer's electricity consumption based on effective usage of energy and appliance scheduling based on tariff structure. The concept of prosumers and the design of co-ordinated control of the appliances have been elaborated that yield economic benefits when considering dynamic pricing throughout the day. Smart metering infrastructures and integration of distributed resources like solar PV systems are found useful to set up residential energy management system [334]. The application of soft computing techniques in setting up appliance schedule and cost minimization of electricity bills for customers have also been discussed while designing an efficient home energy management scheme.

4.1 Residential Energy Management Infrastructure

The urban society of any developing country can be modelled into three different types of electricity customers, namely industrial, commercial and residential customers, based on the electricity consumption pattern [335]. Although the energy demand is highest amongst the industrial customers, however the residential energy sector needs equal importance due to the number of users in the society and increase in load demand due to installations of modern appliances in almost every household. Therefore, the energy management in the residential sector is an important task for the power system operators. Several measures have been undertaken in the households to reduce the load consumption in order to maintain a normal load pattern throughout the day. The most primary step undertaken needs the customers to curtail their load consumption in specific periods of time. This approach also needs the customer to reduce the overall consumption through dimming of lighting level, decreasing the temperature set points of air conditions and so on [336]. This overall helps to reduce the electricity bill for the customers for energy consumption. These demand side management programs does not reduce the average energy consumption of the customers but helps in efficient distribution of the load consumption throughout the day to achieve economic benefits.

4.1.1 Demand Side Management Programs

Demand side management program comprises of planning, implementing and monitoring the activities of the concerned utilities to control the use of electricity on consumer end [337]. The main objective of the modern DSM programs is to convince customer to reduce power usage during peak load hours or to shift energy during off-peak period to flatten the demand curve. It is evident that pre-planned shifting of loads from peak period to off-peak period will help in flattening the load curve throughout a particular period. This activity is the essence of demand side management and demand response program. Demand side management (DSM) gives an option to improve the energy usage system from customer side by managing intermittent nature of renewable integrated sources [338]. Consumption of power or shifting of the appliances based on the availability of the renewable resources is one of the other important functions of the Demand Side Management programs.

4.1.1.1 Demand Side Management through Availability of Renewable Sources

Previous works in literature has focussed on integrating the renewable energy sources as a part of the demand side management programs to support the load demand in peak hours. The earlier works looked at the concept of integrating the renewable energy sources with intelligent Demand Side Management (DSM) program through forecasting of the energy generation by the Renewable Energy (RE) sources and the user's load demands [338]. Intermittent generation through solar and wind generators constituted the source of renewable energy generation while the load demands were classified as base (uncontrollable) loads and flexible (controllable) loads. The base loads were the priority loads and needed to be operated in original time while the flexible loads were operated according to the availability of supply. A day-ahead prediction mechanism for the renewable energy sources was undertaken to pre schedule the appliance operation for a day based on the historical data of energy consumption

[338]. In the process, some predictions were attained with certain level of forecasting errors leading to imbalance in supply and demands at certain periods during operation. This uncertainty in RE generation sometimes made the power system unstable. The low maintenance requirements and emission of lesser greenhouse gas (GHG) compared to fossil fuel-based combustion energy sources has made integration of renewable energy sources more suitable for remote and inaccessible areas [339]. Considering the energy demands in case of some islands, fossil fuel based generators are operationally expensive due to high fuel and transportation costs. Installation of renewable based stand alone microgrids for these islands would help to provide competitive energy costs while reducing the dependence of the island to the mainland for energy supply. For this work, a micro-grid containing a photovoltaic power source, wind turbine, diesel generator, and a battery storage system was chosen. Integrating some demand management strategies helped to reduce the burden of the battery storage systems and reduced the overall installation and operation cost. Operational and financial optimization obtained through two stage mixed integer linear programming (MILP) helped to define both the optimal system sizing and scheduling for each system component [339]. The increase in penetration of the renewable sources like solar or wind in the traditional grid affects the grid network security issues. Incorporation of the DSM programs along with energy storage devices helped to provide a solution to these problems [340]. An adaptive power flow control (APFC) strategy adopted in this work helped to reduce the peak grid demand and increased the self consumption of the renewable energy sources thus reducing the imbalance in energy between demand and supply. This APFC strategy aimed to control the operation of the high power consuming appliances and also managed the charging and discharging of the battery storage unit for instantaneous power demands. This approach considered the historical data records related to daily energy consumption and availability of renewable energy sources to manage the loads and the battery storage during course of a day. A test case simulation for a community of one hundred houses consisting of 114kWp of PV arrays, and a 350kWh battery system showed that this approach reduced the average peak power demand by 35% while utilization of the PV-battery energy increased by 64% [340]. The integration of battery resources with the PV system also ensured an additional cost savings of £2300 in comparison to the DSM program with only PV sources. The demand side flexibilities and the renewable generation portfolio design serves as an excellent opportunity to avoid excessive dependence on conventional power plants and reduction in costs for balancing power. Gottwalt et.al provided a comprehensive centralized scheduling model to provide demand flexibility of the residential services [341]. This work aimed to identify the key characteristics that determined the scheduling of the appliances and the design of the renewable generation structure when integrating in large scale. It was observed that the potential of the appliances to directly utilize intermittent renewable generation helped to decide the composition of the renewable energy source portfolio [341]. An extended DSM framework based on optimized strategies to reduce the electricity bills has proved to provide better scheduling of load under supply constraints. Noor et.al presented a game theory based DSM framework to model the supply constrained environments in order to address the complexity in operation of the consumer's utility and the integrated system performance [342]. This model aimed at reducing the peak to average ratio (PAR) to lessen the impact of supply constraints and provided economic benefits to the customers. The

reduction in load during the peak periods helped to reduce the requirement for installation of other resources for extra generation capacity [342]. The storage units installed in the model provided additional energy under load shedding/supply constraints as per consumers' preferences through this demand management approach. Thus, the consumers were provided with more freedom to schedule their loads and lowered their discomfort [342]. Integration of storage elements with small scale renewable generation through rooftop solar can pave way for more economic benefits through integration of distributed and efficient energy system with the DSM framework.

In order to achieve a reduction in electricity consumption price, often the energy usage is shifted from peak to off peak period to respond to the high electricity price or availability of the energy resources. The various tariff structures formulated generally help to design the load shifting strategies according to the need of the application.

4.1.1.2 Demand Side Management based on Tariff Structures

The power distribution companies have decided to set policies to vary the price of electricity over time of a day to encourage the customers to minimize their electricity bills through variation in their load consumption pattern. The prices are set by the electrical companies in a fashion that the prices are highest when the demand of the customers is highest. The prices of electricity often dynamically change according to the day, week and year and the existing reserve margin [337, 343]. The literature survey suggests that the different pricing strategies that have been adopted by the electrical companies can be classified into three groups namely: Time-of-Day (ToD) pricing, Real time Pricing (RtP) and Critical peak Pricing (CpP) [337]. The ToD pricing scheme divides the entire day into different blocks of time and assigns prices during different locks. In this scheme generally the day is divided into two or maximum three pricing periods and designated as peak period, off-peak period and mid-peak period. The price remains highest during the peak period and it curtails off to give minimum price during the off peak period. Accordingly, it motivates the customer to change their electricity usage pattern from high price to low price period thereby enabling energy management through demand shifting [337]. For the RtP scheme the entire day was divided into 24 one-hour slots and the price dynamically changed depending on the load pattern over the 24 slots [343]. Critical peak Pricing (CpP) scheme was a hybrid approach that followed ToD pricing scheme during the off peak periods and followed RtP scheme in peak hours. The flat rate given by the electricity companies are followed during most parts of the day while the higher rates are followed during limited number of hours throughout the course of the day in this pricing scheme. Out of all these pricing schemes, the residential customers follow the ToD pricing scheme for efficient energy management through appliance shifting. These price based demand response programs allow load shifting of appliances from peak load hours (high pricing period) to lean load hours (low price hours) for residential and commercial customers. In a later work, the different shiftable appliances were modelled into three categories based on the characteristic and the operating time of the appliances over a day [344].The first of the models named as base load shift model (BLSm) were assumed to run for specific periods of time and consume fixed amount of power during their run time. For uninterrupted operation of these appliances, the shifting of the appliance involves entire block of energy being shifted and is mainly applicable to appliances like washing machine, dryers, dish washer, etc. [345]. The second type of loads allow interruption during their operation to create fine control over the consumption of load and are thereby termed as Interruptible load shift model (ILSm) [344]. The third model is the Continuous Switching model that involves periodic control of power usage depending upon some set constraints. Low and high temperature set point in cooling appliances helps to control the load consumption in the air cooler through a normal on/off regulator that switches the cooling on at the higher set point and switches it off at lower set point. Any other periodic disturbances through external influences, such as opening of the freezer in the refrigerators, were assumed to be additional uncontrollable loads that affected the periodic scheduling of the appliances [345]. The behaviour of the loads were modelled using Gaussian function elsewhere whose peak value was considered to be peak energy consumption from considered appliance and the integral of the function suggested the energy consumption over the course of the day. These formulations were tried for all the type of load models. The characteristic standard deviation of the Gaussian function indicated duration of the work cycle and the mean value helped to identify the time in which the working cycle was half completed [346]. This approach of demand side management helped to achieve the objective of uniform electricity distribution amongst the customers and helped the customers to adjust the consumption pattern depending on the dynamics of the energy markets.

Bi-directional information exchange regarding the load consumption and operation of the utilities with the energy management unit helps to efficiently design the schedule for appliance shifting in residential environment. The information exchange between the traditional grid and the energy distribution hub lets the customers know about the pricing structure and accordingly informs the customers to participate in DSM program to earn economic benefits.

4.1.2 Bi Directional Information Exchange

An efficient demand side management program largely depends upon the employed bi-directional communication architecture. Based on these bi directional information exchange architectures, previous works have tried to design energy management schemes through real time communication among the various involved units namely the home appliances, the associated smart meters, a central energy management and the storage unit inside home [50]. The idea of designing a power hub was presented elsewhere that kept control over all the loads individually through real time information exchange [347]. The function of the hub was to detect the demand of the customers during peak periods and reduced the load during this period by switching off the unwanted loads based on apriority initially set by the consumer. Game theory algorithm was adopted in this work to schedule the load usage based on design of possible schedule vectors keeping in mind that demand is never raised for any time slot. This approach was found to be suitable for appliance usage of individual customers as well as for multi users of a community. Based on the frequency of the appliance usage, the algorithm helped to create an order of importance for the loads. A non-linear programming model was proposed later to optimize the residential energy consumption through shedding of electricity at peak periods and increasing consumption at off peaks [348]. This approach helped to reduce the cost of electricity generation at peak periods and earned revenues for the generating companies during off peak periods. The fitness function designed to solve the problem aimed at regulating the energy consumption and earned economic benefits through load shedding and load shifting for end users. The generating companies were not required to produce energy beyond their capacity during peaks at high cost to maintain the required power supply to the residential customers. In a later work, a home automation controller was aimed to be designed that helped to shift or interrupt the appliance operation based on the real time pricing scheme provided by the supplier [349]. A binary vector array helped to describe the operational status of the appliances based on their performance characteristics in different time slots. This binary representation of the appliance status helped to make scheduling process easier to maximize economic benefits for residential customers. Real time information flow from the different appliances like fridge, freezer, dishwasher, washer and dryer, stove, water heater, hot tub, and pool pumps helped to mathematically model the operational characteristics of the appliances in the control station [350]. The feedback signal designed helped to minimize energy consumption through efficient consideration of customer preferences and comfort level of operation.

The modern design of the smart home systems have focused on integrating proper communication architectures that enable bidirectional data flow in form of measured data and control signals between the utilities and the energy management unit. Smart Home systems have utilized wireless sensor networks as the main backbone of communication architecture due to its ease of installation and reliable performance related to data monitoring.

4.1.3 Introduction to Smart Home Systems

Performance evaluation of different wireless technologies in Home Area Networks proved that IEEE 802.15.4 protocol based wireless network architectures provided best results for home area networks due to its low range and low data rate features [307]. These features of the IEEE protocol helped to reduce the interference in the network as the chances of signal attenuation reduced with low range of transmission. A comparative study of the efficiency in monitoring of appliances through ZigBee and Wi-Fi based systems was performed [351]. The results proved that ZigBee based wireless helped in energy efficient data communication as it suffered lesser interference from the walls of the building during information flow to the control station placed outside of the building. This helped the researchers to choose ZigBee based wireless nodes as the ideal nodes to operate in indoor home networks. In later works, ZigBee based network was utilized to sense information from different physical parameters in the home environment and store the data in the control station. To generate a clear view of the monitored data and improve the network performance of ZigBee based networks, the pathway of data transmission from the utilities to the control station was determined based on DMPR (Disjoint Multi Path based Routing) [352]. This smart network design was utilized to study the indoor temperature of the environment and accordingly invoked the air cooler or the fan to get switched on or off based on the temperature set points. In another application of the same wireless based data monitoring in indoor networks, light sensors were used to estimate the occupancy of the room and the information was carried onto the control station in a multi hop fashion determined by the Kruskal's algorithm [352]. Future wireless node designs aimed at integrating Internet Protocol version 6 (IPv6) which increased the 32 bit memory space to 128 bits enabling multiple end devices to simultaneously integrate with the network [353].

Thereby, it was observed from varied literature works that proper demand side management programs aiding load scheduling along with efficient communication architectures helped to earn economic benefits for dynamic pricing scheme. Integration of distributed energy sources at the customer end and feeding of the power to the grid regularly had been attempted recently with the aim to yield more economic benefits. The phenomenon of consumers taking part in the energy production process has been recently observed in countries like Germany, China, Canada, etc. that has led to the idea of prosumers becoming an integral part of restructured energy market.

4.2 Introduction to the Idea of Prosumers

In order to maximize profits, today's business strategies have focussed on mass production of highly customized products from varied sellers to reduce the cost of product selling through competition. Energy prosumers have come up recently with the same concept to actively participate in the energy market. Prosumers are not only the consumers that produce energy but they are also sellers of their produced energy [354]. If a producer would have consumed all the energy he had produced, then only the demand side of the market would have improved. Feeding the surplus energy to the grid or selling the energy for a given price would also influence the supply side of the energy market. This double role as producer and consumer and also active participation in the energy market completely depends on the tactical choice of the prosumers. It may also happen that the prosumer may sell their entire generated energy at a given price and buy the required energy at a lower price from other suppliers thereby benefitting from the arbitrage [355]. The strategy he undertakes to earn economic benefits from this energy market entirely depends upon the flexibility of the customer to adapt to the current market scenario. Shifting the energy demand or supply along with time based on forecasted data would enable the prosumer to maximize benefits in terms of their own needs and also in accordance with the state grid and market clearing price [355].

With focus on generation of energy at the consumer side, renewable sources have gained importance to be installed in the home energy management systems. Renewable integration increases the uncertainty associated with the system due to the unpredictability and stochastic nature associated with the renewable sources. However, provisions for flexible management of loads, for example temporary interruption on air conditioners or activations of washing machines in certain time frames, should exist in order to meet the challenge of balancing the supply and demand with renewable integration in the system.

4.2.1 Generation of Power through Renewable Sources at Load End

In order to meet the increased demand of electricity amongst the customers due to usage of high power appliances, renewable energy sources are being considered nowadays to limit the depletion of natural resources thereby maintaining energy supply as and when needed. Solar energy, wind energy and biomass energy have come up as options for renewable energy sources to be integrated with the home energy management systems. These renewable sources allow generation of low cost environment friendly electricity during times of excess energy demand and permit the prosumers to actively participate in the energy auction market [356]. Primarily, the demand side management programs have looked upon solar energy for energy generation for the prosumers participating in the energy market. In a previous work, the DSM program implemented for household applications utilized an isolated hybrid system consisting of solar, diesel generator and battery to supply the own demands of the customer [357]. The DSM strategy applied to the appliances helped to meet the customer's demand and even contributed to the decision regarding the size of the system components. This energy management program also helped to achieve the additional benefits of minimizing the fuel cost of diesel generator set and extended the battery lifetime through reduction of storage system charge cycle [357]. Tomar et.al in a later work discussed the feasibility of integration of grid connection of solar rooftop power systems for supplying the loads of the household devices [334]. This study involved utilization of net metering infrastructure and time of day tariff regulation schemes for three kinds of households using low, middle and high amount of loads in New Delhi, India. The HOMER software was utilized for techno-economic analysis of the implemented DSM program with grid-connected rooftop solar panels. With increase in the capacity of the solar panels, the energy cost related to the load requirements was seen to be reduced. For the customers with low loads, often the net electrical cost was found to be zero due to the amount of energy generated from the solar installations [334]. An assessment of the effectiveness of the demand response program related to the time-of-use (ToU) tariff trials and higher level of power generation from wind energy sources was studied elsewhere [358]. The demand response program kept a track of the time and the amount of power generation from the installed wind energy systems. The appliance operations were shifted based on the tariff structure to the time intervals where energy was generated from the wind energy source in order to reduce the amount of energy to be bought from the grid during peak pricing [358].

The load consumption of the customers generally varies from day to day and also from hour to hour within a day. Huge differences in the load demand during the off peak period and the peak period brings up a doubt regarding reliable power supply from the conventional generators. The renewable sources integrated with the system are also intermittent in nature and does not generate energy following the load pattern. Thereby, the demand response programs associated with the prosumers aim at electricity usage adjustment subjected to price changes and predictions of availability of energy resources during that time of the day.

4.2.2 Appliance Scheduling for Customers based on Energy Resource and Tariff Scheme for Cost Benefits

Appliance scheduling of the customers have been attempted in several works earlier to help load reduction during certain time frames in order to design an efficient energy management infrastructure. Bisceglie et al. was one of the first researchers to work on home energy optimization scheme based on day ahead pricing [359]. This work aimed at minimizing the peak load demand through efficient distribution of the working of the appliances used in the home throughout the course of the day. This work also considered the possible amount of energy that could be supplied from the installed Distributed Energy Resources during times of excess demand in order to schedule the appliances [359]. A later work based on the Linear Programming (LPP model) divided the entire day into equal time slots based on variation of prices of electricity consumption [360]. The cost effective modelling function considered the consumer's request to switch on a certain appliance as the programming input and returned the suitable time slot for the appliance operation as the output [360]. A two stage optimization based on mixed-integer linear programming was proposed for building energy management scheme elsewhere. The optimization function aimed at cost of energy minimization by properly balancing the predictions of the generation from the local generators and the consumption of energy by the different appliances involved in the system [361]. The improved Appliance Coordination (ACORD) scheme aimed at shifting the consumer loads to off peak periods based on Time-of-Use (ToU) tariff system to claim economic benefits from the DSM program [362]. A backtracking based energy management scheme designed elsewhere aimed at scheduling of the appliances based on the operation cycle duration, operational time frame and the consumption profile of the appliances [363]. The controller unit associated with the control station scheduled the appliances one after other based on the amount of task associated with each appliance. This backtracking of the control signals from the control station has helped to achieve proper load controls to smoothen the load curve for the household energy consumption.

The Load control programs based on the different block rates of electricity supply has proved to reduce the energy bill by 8-12% through energy scheduling combined with price prediction programs [364]. A simulation study based on low carbon electricity supply for residential buildings in Australia was done to assess the economic benefits earned through load shifting and renewable energy integration [365]. The air conditioner load was considered as the shiftable load whose operation was transferred from peak to off peak periods. In the process, air-condition may get switched on few hours ahead of need and switched off during high demand periods. Efficient load shifting allowed lower sizes of renewable sources to be installed adding to the economic benefits of the system [365]. A new demand side management scheme for future smart home environments involved the installation of an Energy Consumption Control (ECC) unit that was connected with all the neighbours of the society through a local area network. Future works may allow this ECC unit to co-ordinate the operation of the appliances of all the users in the locality. Facchini et.al in a recent work proposed the idea of giving incentives to the residential customers based on the lower usage of the appliances in the peak periods [366].

To ensure proper monitoring and control of the appliances, the communication infrastructure needs special attention since the Energy Management Unit (EMU) needs to send control signals for controlled operation of the appliances with the goal of minimizing the bill. Wireless networks have been found to be the ideal solution for quick and error free data delivery in the home environment scenario.

4.3 Controlling Functions of Wireless Sensor Network in the Energy Management Unit

The Wireless Sensor Network (WSN) has found its application in various environments. The bidirectional communication infrastructure helped to transmit back the generated control signals from the control station to schedule the appliances based on the tariff structures and availability of the energy resources. The wireless networks enable integration of a variety of sensors in the network according to the type of application and read data from all the sensors. The low cost low power architecture make the wireless networks most suitable monitoring tool for the performance study of the installed renewable sources. The efficient control design for scheduling of the appliances based on the signal from the EMU has been also designed through utilization of different wireless nodes in previous works.

4.3.1 Utilization of Wireless Sensor Nodes in Home Energy Monitoring Systems

InfoPods were one of the new smart nodes that were designed for smart home monitoring that involved integration of a ZigBee protocol [367]. The microcontroller associated with the kit had the features of a 96kB RAM, 4 input ADC and 2 wire serial interface. This microcontroller formed the heart of the sensor node that controlled the function of all the other associated components. These wireless nodes helped to design cost effective communication architecture by allowing users to monitor multiple appliance statuses simultaneously in a single building. The to and fro data flow facility in the network was designed based on the ZigBee transceiver. A ZigBee-based intelligent self-adjusting sensor (ZiSAS) was implemented elsewhere that aimed at efficient data monitoring in smart home services [368]. Similar to the previous node, this also consisted of a 16 bit microcontroller which communicated with the central control unit by the help of IEEE 802.15.4 based ZigBee transceiver. A study related to the deployment topology of these nodes in home area applications was carried out to identify the best suited topology for maximal performance. The results proved that the star topology provided good results for closed areas like rectangular rooms while in case of long areas like corridors, peer to peer networks proved to be the most suitable [368]. The smart node designs based on the VLSI technology prevailed over the disadvantages of fixed system architecture and provided energy efficient solution for network design. Another type of wireless node termed as the Automated Power Switch (APS) was designed in a later work that utilized PIC16F877A as the microcontroller and was connected to the remote station through a GSM modem by help of RS 232 port [369]. The wireless network designed through these node implementation aimed at designing a proper communication infrastructure for residential energy management schemes which focused not only on connecting the home network to the utility assets but also developed a communicating framework between the different homes in the residential area [48]. Improved Home Energy Management (iHEM) scheme was proposed for domestic energy management elsewhere that involved design of Wireless Sensor based Home Area Network (WSHAN) where all the smart appliances were effectively connected with the Energy Management Unit (EMU) [370]. This design approach helped to obtain co-ordinated appliance by satisfying the consumer demands during real time operation. In broader applications of smart network development, IEEE 802.15.4 based Wireless Sensor Networks were utilized in substations where time critical monitoring is necessary to ensure no delay is suffered during control of the utilities in such delicate applications.

The integration of the renewable energy with the demand side management programs needs efficient set up of decision support systems and monitoring infrastructures to take the decisions about switching the appliances based on the demand at certain time of the day.

4.3.2 Performance Monitoring of Renewable Installations at Customer Side

To co-ordinate the working of the Distributed Energy Resources (DERs), the smart homes considered a Decision support Tool (DsT) for designing a co-ordinated working scheme of the appliances and the renewable sources in smart home environments [371]. For case study, a space heater, a pool pump, a Plug-in hybrid Electric Vehicle (PHEV), a Photo Voltaic (PV) system and a water heater were all considered to be a part of the designed Residential Energy Management Scheme. The DsT unit helped to take decisions related to the switching control of the appliances based on the available energy resources. Wireless networks have also been utilized for in situ performance monitoring of the solar photovoltaic panels installed as a part of demand side management program [372].The developed communication network presented the performance related data of the solar panels to a remote co-ordinator that performed the calculation of the electricity production based on the performance parameters of each PV panel and estimated the extent of customer's needs being fulfilled through this generation. Today's restructured energy market scenarios have prompted design of optimal bidding strategies to supply the local loads at lowest cost from the renewable energy resources. Thereby, the performance of the integrated renewable sources and storage of the information of the surplus energy to be sold in the EMU is necessary for the prosumers to actively take part in the energy market. The WSN has proved to perform the dual role of monitoring the performance of the renewable sources and transmitting the control signals based on energy availability to schedule the appliances.

Home Appliances Coordination Scheme for Energy Management (HACS4EM) was one of the recently designed Demand side management program for the households where wireless networks have been put to use in residential energy management [50]. A wireless sensor home area network (WSHAN) had been considered in this work where the ZigBee protocol based communication architecture was employed for relaying the messages among the different entities in the HEM scheme. This protocol aimed at reducing domestic electricity consumption charges through proper appliance control based on real time information exchange amongst the smart appliances and a central energy management unit (EMU) through established WSN. The results related to demand side management also represent considerable load reduction over a span of 7 months [50]. In a later work, three case studies were undertaken to find the suitable methodology for implementation of ZigBee devices in different applications for reduced effects of interference [373]. The first experimental set up involved monitoring of solar PV panels installed by a water treatment and distribution company. No interference effects were observed since the data transmission took place through line of sight area. The second case involved testing of interference for the implemented wireless networks inside the control house of a wind farm. Substantial interference was observed due to presence of the metallic door which was made to overcome by additional deployment of nodes. For the third case, an eleven floor building was selected for deployment of the wireless nodes and the interference was found to be huge due to the walls and elevator shaft. Thereby, it was found necessary to estimate the suitable positioning of the ZigBee routers in home environment applications to monitor real time data from distributed renewable generation sources and smart metering systems [373].

Several approaches including optimization based on meta-heuristic algorithms are performed in the EMU to provide a co-ordinated working of the appliances and scheduling of the renewable energy sources. The soft computation techniques aim at minimizing the electricity consumption for the residential customers through proper development of a DSM program.

4.4 Application of Soft Computation Technique in Demand Side Management

Several meta-heuristic approaches have been found to be implemented in literature which took care of the cost benefits related to customers through demand side management. One of the earlier attempts involved utilization of Co-evolutionary Particle Swarm Optimization (CPSO) algorithm to design an energy efficient service model based on varied ToU prices. This approach helped to generate a scheduling of the appliances through efficient control of the DERs. Later, Khan et. al proposed a Home Energy Management System (HEMS) that utilized a hybrid approach using Genetic Algorithm (GA) and Crow Search Algorithm (CSA) [374]. Integration of renewable sources with the micro-grids based on the consumption of residential loads was attempted elsewhere to ensure economic dispatch from the micro grids by help of a Genetic Algorithm protocol [375]. The demand side management in this work was performed through GA that considered load demand data for the customers throughout the course of the day and the cost of energy related with the loads. The appliances were classified into three different sets based on their level of energy consumption and was accordingly shifted based on the Real time Pricing (RTP). This approach enabled reduction in electricity bills but often the devices were made to wait for a longer time which is undesirable in some situations [375]. Enhanced Differential Evolution (EDE) and Chicken Swarm Optimization (CSO) algorithms were associated with Demand Side Management (DSM) strategies elsewhere to shift the load from on peak to off peak hours [376]. Recent trends of work have involved Game theory based optimization technique in order to reduce the peak loads in every time interval through proper scheduling of appliances [377]. Nash equilibrium helped to identify the minimal energy cost for a certain time period and the appliance performance scheduling was thereby designed based on the minimal cost scheme for a certain period [28].

4.5 Conclusion

The different ideas obtained through the works available in literature have helped to generate an idea about the utility of demand side management programs to reduce the imbalance between the supply and demand of power amongst the residential customers. Efficient controlling of the operation, scheduling and generation from the renewable energy sources have helped to design energy management schemes for residential customers. The implementation of the demand side management programs has helped to provide cost benefits to the customers subjected to efficient energy usage based on time of day tariff structures and availability of renewable energy sources. Wireless Sensor Network (WSN) has proved to be most suitable communicating medium to transmit the information about the various loads being monitored from each of the house to the central energy management unit (EMU).The EMU in unison with the WSN helps to efficiently perform the duties of controlling and scheduling the appliances based on time of day tariff scheme for the devices installed in the different houses. Optimization related to estimation of cost benefits and operational scheduling has been tested in various previous works through utilization of meta-heuristic soft computation techniques. But the appliance shifting operation in the past works did not consider the customer comforts during scheduling the appliances. The concept of prosumers is also sparse in literature as it is an upcoming concept. The utilization of grid connected solar rooftops for low demand prosumers has not been given focus in the previous works that may help to add to the economic benefits for the low demand customers.

Based on this survey of previous works, this work has a component that aimed to design a cost efficient energy management scheme for a housing co-operative consisting of 50 bungalows with almost identical load consumption pattern. Integration of rooftop solar panels have been thought off for each prosumer and the surplus energy from each prosumer has been planned to be integrated in a central co-operative power distribution unit which feeds this power to the grid. Appliance shifting has been aimed to be performed based on the time of day tariff structure to reduce the load demands during the peak tariff periods. This appliance shifting scheme has also taken into consideration the comfort zone of use of an appliance and a maximum waiting period for usage of an appliance for a customer. ZigBee based wireless sensor network has been chosen to perform the duty of bidirectional communication from the households to the EMU and vice versa. A meta-heuristic optimization technique in form of Cuckoo Search (CS) algorithm has been implemented to optimize the cost benefits related to the home energy management scheme. Optimization in the DSM problems based on CS algorithm has been very sparse in literature and is unique for this type of problem which focuses jointly on customer satisfaction and economic benefits. The cost benefits obtained through the strategy of appliance scheduling and integration of rooftop solar installations would grow an interest among the residential prosumers to generate more power from distributed energy resources in the near future and participate in energy bidding in the restructured market scenario. The detailed study of the applications of the wireless sensor network in home area environment has prompted the idea of WSN based smart grid infrastructure in a university campus in the future. The mathematical formulations designed for the home energy management structure have been discussed in details in the following chapter to give an idea about the methodology undertaken to reduce the load during the peak pricing periods and the energy cost throughout the day. The customer comfort constraints have also been dealt with while designing the objective function to be minimized using CS algorithm. Economic benefits related to the size of the rooftop solar panels and their energy availability has been studied through different mathematical equations. Those have been properly described in the next chapter.

Chapter 5

Problem Formulation and related Mathematical Proposition

After a thorough survey of the works found in literature, this current work focused on improving reliability and lifetime of the designed wireless network. The main factor related to data loss has been found to be the interference produced in the network from several obstacles and other electromagnetic waves in the area. Therefore, efficient node placement has been aimed in the first part of the work through minimized signal attenuation. The mathematical formulations are newly proposed helped to find the best positions of the routers for reduced signal attenuation. The mathematical formulations related to the calculation of other network parameters such as energy consumption and SNR has also been discussed. The packet error ratio subject to the signal attenuation based on router placement has been also evaluated based on a mathematical formulation to establish the reliability of the network. The extent of signal crossovers and the network coverage has also been tested through design of a novel mathematical parameter which has been discussed in details in this chapter. The mathematical equations related to the cost benefit analysis between the star and the mesh network architecture for wide area wireless implementations has also been presented here. The second part of the work deals with enhancement in the network lifetime of the designed wireless network. The equation that governs the LEACH protocol for selection of cluster head has been remodelled in this work based on the left over energy of the nodes. The modified equations for selection of cluster heads through rotation in every data transmission cycle have also been discussed here. The multidimensional multivariable objective function particularly designed in this work for positioning of the cluster heads in the network has been presented in this chapter. The mathematical representations of the individual parameters has also been talked about for better understanding of the reader about how these parameters affect the positioning of cluster head in the network. The effectiveness in performance of the wireless sensor network as a monitoring tool has encouraged designing a home energy management scheme based on scheduling of appliances in household. WSN has been chosen as the communication framework to enable bi directional data and control signal flow in the considered home environment. The problem description and the mathematical equations related to this home energy management scheme have also been conferred here that govern the appliance scheduling in the network. Rooftop solar installations for low demand prosumers has also been proposed as a part of this problem. The equations related to the cost benefits earned from the joint approach of appliance scheduling and solar installations for this energy management scheme has also been discussed in this chapter.

5.1 Problem Formulation related to Node Placement in WSN

Based on the theoretical surveys on the various works performed previously, it was found that interference in the network and the corresponding signal attenuation significantly affects the wireless network performance. The indoor network is subjected to high signal attenuation due to the presence of thick walls, metallic structures and other radio frequency waves which affect the performance of the wireless network. Therefore, utmost care must be taken related to minimal signal attenuation while designing a network for indoor applications. Several parameters related to network performance such as signal to noise ratio (SNR), the energy required for per packet data transmission and packet error ratio are highly dependent on the signal attenuation of the network. Thereby, the first part of the thesis work focused on optimal node placement in the wireless network to reduce signal attenuation of the network and ensure reliable communication architecture. A model application area of 150×150 m^2 scaled down to an equivalent 15×15 grid has been considered where the nodes are dispersedly placed throughout the network. One (1) unit in the considered grid corresponds to ten (10) m of the application area. The gateway position has been considered to be fixed in the network to store the collected data in the control station. The number of intermediate routers required and their appropriate positions in the network to develop good communication architecture has been kept as the only variants in the desired problem. The position of the routers should be such that they are placed within the maximum transmission range of the nearby sensor nodes and it covers the maximum coverage area [219]. Considering the ZigBee based transceivers to have an ideal range of thirty (30) metres in indoor scenario, the transmission range for the following problem has been considered to be 3 units based on the considered scaling of the following problem. This transmission range gets affected by sufficient signal attenuation due to the walls, floors and the metallic structures within the building. In aim of this, a novel objective function was designed that considers minimization of the signal attenuation as the main factor through the selection of optimal number of routers in a selected application area.

5.1.1 Objective Function Formulation for Signal Attenuation Minimization in WSN

The proposed mathematical formulation in this work is a modification of a previous equation found in literature to determine the signal attenuation in the links between two sensor nodes [307]. The previously found equation in the literature has been stated in Equation (5.1) which evaluated the signal attenuation generated over the individual links considering the position of the sensor and the control station to be fixed in the network.

$$L_B = \dot{\eta} \times 10 \times log10 \times \frac{D}{d_0} + 20 \times log10 \times \frac{4 \times \pi \times d_0 \times f}{C_0} + L_{walls} \times N_{walls} + L_{floors} \times N_{floors} \quad (5.1)$$

The distance between the node and the control station and the maximum transmission range of transmission for each of the wireless nodes was the governing factors that determined the signal attenuation over individual links. When considering the wireless network implementation over a large area, the signal attenuation in the network gets determined based on the extent of coverage of the network through the placed routers. This has been targeted in this work and therefore the factors of entire area of application and the area of coverage by individual node has been considered. The novel mathematical equation formulated in this work by modification of Eq. (5.1) has been represented by Equation (5.2) which aims to minimize the signal attenuation (L_B) that may occur during data transmission in the network through optimal choice of routers in the network.

$$L_B(in\ dB) = \dot{\eta} \times 10 \times \log\left(\frac{Plotarea}{N_r \times A}\right) + 20 * \log\left(\frac{4 \times \pi \times r_s \times f \times L}{C_0}\right) + L_{walls} \times N_{walls} \qquad (5.2)$$

The mathematical formulation designed to estimate the signal attenuation in the network depends upon three factors namely: the transmission power decay subject to inappropriate coverage of the entire area. The loss in signal is also caused in the communication links owing to the presence of other electromagnetic waves. The walls and floors in the network form the third factor for signal attenuation in the network. The power decay calculated by the first term of the equation is based on the total area of selected domain represented by "*plot area*". The optimal number of routers obtained through simulation is represented by N_r and the path loss co-efficient for 2.4GHz communication channel, $\dot{\eta}$, is taken equal to 2.3 [307]. Coverage area of each sensor node is given by A and r_s is the range of transmission for each node. The frequency band of transmission is represented by$f$ $(= 2.4 * 10^9 Hz)$, the number of communication links established between node for data exchange as L. To understand the effect of other electromagnetic waves on the wireless links in the second term of the designed equation, the speed of transmission for those waves has been assumed to be equal to speed of light and is represented by C_0 $(= 3 \times 10^8$ m/s$^2)$. The electromagnetic waves from other sources present in the area of application can travel in vacuum and they can potentially interfere with the radio frequency waves governing the wireless communications. It has found in literature that all the electromagnetic waves travel with the same speed and light also being an electromagnetic wave, the speed of transmission of other waves has been considered to travel at same speed as of light. The effect of the other electromagnetic waves has its effect on all the established links in the designed wireless network. Therefore, the signal attenuation for each of the links has a negative effect on the total network performance. The electrostatic waves or the mechanical waves do not travel through vacuum and thereby do not cause any interference through signal crossovers with the wireless transmission waves. The signal attenuation for walls and floors is taken to be uniform as 6dB for each wall as found in literature [307] and represented by L_{walls} [307]. The number of walls, N_{walls} , has been assumed to be 5 for this model deployment area which is quite considerable considering the extent of the application area. Considering a rectangular area of deployment, the effect of signal attenuation due to the walls and the floors has been considered to be equal. The selection and positioning of the optimal number of routers are subject to constraints that no router is placed within the area of coverage of a certain wireless node and at least a single router is associated with every sensor node so that no sensor is left uncovered.

5.1.2 Constraint Equations for Selection of Routers

Equation (5.3) represents the coverage area, A, of each sensor node within which no other sensor node is placed and this coverage area is uniform for all the deployed nodes in the network.

$$A = \pi {r_s}^2 \quad (5.3)$$

Here, the range of transmission for each node is denoted by r_s. All the sensor nodes lying within the range of one router can aggregate their data in this single router through clustering. The number of intermediate hops through router placement required to establish the pathway for transmission from each of the active sensors to the gateway is given as in Eq. (5.4) [378]:

$$[(\sqrt{\{(x_i - x_j)^2 + (y_i - y_j)^2\}}) / r_s] = h_r \quad (5.4)$$

In the designed equation, (x_i, y_i) is the co-ordinate of the sensors while (x_j, y_j) represents the gateway co-ordinates which remains fixed for a designed network. The distance between the sensor and the gateway is divided by the maximum range of transmission of the sensor nodes to find out the number of intermediate hops represented by h_r. The optimal number of node selection and placement ensure that the signal attenuation of the designed network is minimal. All the other parameters interrelated with signal attenuation are estimated to understand the system performance.

5.1.3 Formulation for Other Performance Parameter Estimation

It is desired for a good communication medium that the signal to noise ratio (SNR) is always maintained at greater than 20dB [307]. The mathematical formulation related to calculation of SNR based on signal attenuation is given in Eq. (5.5).

$$SNR(in\ dB) = P_S - P_t - L_B \quad (5.5)$$

The signal power is provided by the manufacturer, PervCom Consulting Pvt. Ltd. [379], for the used kits as 2dB and is represented by the variable P_S. The noise power generated in the transmission channel of the wireless kits is termed as Johnson noise and is represented by P_t which varies according to channel of transmission. The signal attenuation calculated from Eq. (5.2) is L_B which directly affects the transmission energy related to packet transmission through the designed wireless links. The equation to evaluate the average energy required for transmission or reception of each packet through the communication links is represented by Eq. (5.6) depending on certain parameters as previously obtained from literature [307].

$$E_{pac}\,(Joule) = \frac{1}{L}\left[\frac{K \times T \times B}{R} \times P_l \times 10^{\frac{SNR}{10}} \times 10^{\frac{L_B}{10}}\right] \quad (5.6)$$

In the given equation (5.6), K represents Boltzmann constant ($= 1.38 * 10^{-23}\ J/K$), the temperature of the environment, T, is considered to be at a constant of 298K, the bandwidth of the transmission, B, is 2MHz and the data rate R is 250kbps in the used wireless kits. All other parameters have the same denotation as stated before and their values have been obtained from the previously stated equations. The number of bits being not received erroneously during data transmission divided by the total number of bits sent from the end device is given as Bit error ratio (*BER*) [379]. The mathematical equation that determines the bit error rate in the network has been represented in Equation (5.7).

$$BER = 1/2 \times (1 - (\sqrt{SNR} \div \sqrt{2 + SNR})) \quad (5.7)$$

The number of undelivered packets or the number of corrupted packets amongst the total number of packets sent to the sink node is termed as Packet Error ratio (*PER*) which is dependent directly on BER. Each packet considered for transmission has a packet length equal to 500 bits for the given transmission network and is represented by P_l. The mathematical formulation to calculate the packet error ratio has been given in Eq. (5.8). An ideal network structure ensures all the data packets related to a certain measurement are transmitted. However, this indicates that *PER* for a network should be as low as possible to eliminate the errors during real time data monitoring [380].

$$PER = 1 - (1 - BER)^{P_l} \tag{5.8}$$

Once the reliability of the wireless network is ensured, the main focus lies on reduction in network design cost and lifetime improvement to ensure a stable and cost efficient wireless network design. The energy conservation in the network and increased residual energy amongst the nodes results in delayed node death. This necessitates proper energy modeling in the wireless network.

5.2 The Energy Modelling of Wireless Sensor Network

The energy modeling of the wireless system has been adopted from literature based on the data packet size and the source-sink distance [219, 267]. Equation (5.9) defines the energy consumption of the sensor node during transmission based on data aggregation energy and chances of energy dissipation in the network.

$$E_{TX}(l,d) = \begin{cases} l \times E_{elec} + l \times \varepsilon_{fs} \times d^2, & if d < d_0 \\ l \times E_{elec} + l \times \varepsilon_{mp} \times d^4, & if d \geq d_0 \end{cases} \tag{5.9}$$

Here, the number of bits in a sent data packet is represented by l and d is the distance between the sensor and the receiver. The amount of energy required for data aggregation of each bit during transmission of data is denoted by E_{elec}. The amplification co-efficient of the transmission amplifier in free space and during multi-path transmission is represented by ε_{fs} and ε_{mp} respectively. The maximum transmission range of each sensor node based on the amplification coefficients is almost equal to $\sqrt{(\varepsilon_{fs}/\varepsilon_{mp})}$ [219]. On the receiving side, the amount of energy consumed E_{RX} depends on l bits to be received and is given by Eq. (5.10) [219]:

$$E_{RX}(l) = l \times E_{elec} \tag{5.10}$$

The energy consumption in the network determined by these networks affects the battery energy supplied to the nodes. The reduction in energy consumption of the network results in lesser battery replacements of the network and increased run time of the batteries thus lowering the cost of network architecture.

5.3 Testing of Node Placement Efficiency and Cost Benefits in WSN

The cost efficiency in the proposed node placement technique and testing of the placement efficiency to attain the maximum coverage of the network is essential for WSN design.

5.3.1 Fitness Function for Node Placement and Testing of Node Placement Efficiency

In case of mesh network topology, a novel equation was designed for determining the number and position of the intermediate routers. Minimum signal overlap and maximum sensor data coverage were the two constraints taken care of while designing the novel fitness function. The fitness functions consists of three factors namely total number of routers, number of overlapping sensors and sensors that are not covered as depicted in Eq. (5.11). The penalty factors associated with the overlapping sensors and uncovered sensors are W_c and W_u respectively [381]. The values of W_c and W_u have been decided by trial and error method but it has been kept in mind that W_c is less than W_u since it is unwanted that a sensor data remains unattended in the network. Here, total number of routers employed is denoted by N_r, N_s is the number of sensor nodes, N_{ci} is number of cross-over routers for i^{th} sensor node and N_u is number of uncovered sensor nodes.

$$F = N_r + \sum_{i=1}^{Ns} W_c * N_{ci} + W_u * N_u \tag{5.11}$$

The placement of the routers are subjected to two constraint equations described in Eq. (5.3) and Eq. (5.4) that ensures no router lies within the coverage area of another router and at least one router is associated with a sensor node in the network. This further ensures that optimal number of routers is placed in the network. Higher number of routers would result in more signal overlaps while lesser number of sensors would not help in building the communication links amongst all the deployed sensor nodes. After the sensors are placed in mesh architecture, a newly designed factor namely "Router Placement Efficiency (RPE)" is tested to study the effective coverage of the network. This takes into consideration the number of routers suffering from signal crossover, number of uncovered sensors and the number of inactive routers in the network. The estimation of RPE is done using the designed equation in (5.12).

$$RPE = \{(N_G + N_A + N_S) - (N_U + N_{IN} + N_{CR})\} / N \tag{5.12}$$

In the designed equation the number of sensors deployed is given by N_S, the number of base stations as N_G and the number of active routers participating in data transmission is given by N_A. The number of excess routers placed in the network which may not participate in data transmission is given by N_{IN}. The number of routers suffering from signal crossover is denoted by N_{CR} while the number of uncovered sensor in the network is given as N_U. The total number of sensor nodes in the network that includes sensors, routers and gateway is denoted by N.

This designed equation to test router placement efficiency and efficient network coverage is solved using three different soft computation techniques namely Cultural Algorithm, Genetic Algorithm and Cuckoo Search Algorithm to understand the most effective soft computation technique for this kind of wireless network problems. After the node placement is found to be efficient in terms of network coverage, it is also necessary to decide if the proposed strategy is cost effective which requires study related to cost benefits for different wireless network topologies.

5.3.2 Cost Benefit Study related to Node Placement through Different Topologies

The developing countries like India, Russia, China, Brazil have nowadays focused on development of residential conclaves consisting of variety of customers [382, 383]. These customers utilize a varied type of power consuming appliances which need constant monitoring. Thereby, a low power and low cost communication architecture is desired to be designed which would help to maintain the reliability related to data transmission. ZigBee based wireless networks have come up as the best suited communication architecture for such wide area problems. In order to understand the best suited topology of WSN for wide area applications such as residential conclaves or housing societies, two network designs based on star topology and mesh topology are proposed. The two schemes are named as Scheme 1 and Scheme 2 which involves star topology and mesh topology respectively. In case of star topology in Scheme 1, the sensor nodes directly communicate with the base station and hence the wireless nodes operate in high power mode to transmit the data through larger distances. But the difficulty associated with this topology is that, once the base station becomes out of the maximum range of transmission of the sensor nodes, data cannot be transmitted efficiently. For Scheme 2, the wireless nodes operate in low power mode and enables maximum data transmission upto a distance till which there is no power decay. Therefore, this network design scheme requires implementation of additional intermediate routers which is achieved by utilizing Eq. (5.11). The amount of energy required to transmit the data in the two designed topologies are calculated by the energy equation modelled in Eq. (5.9). For Scheme 1, the data is supposed to be transmitted over longer distances and the transmission range is taken to be 90m in case of star topology. Higher is the distance of transmission considered, higher are the chances of the network to suffer from signal attenuation due to presence of obstacles. The energy consumption related to data transmission simultaneously increases since a lot of the energy is required to overcome the signal attenuation in the network. In the second case, it is taken care that data transmission occurs over shorter distances to avoid power decay due to the obstacles and the transmission range is taken to be 30m. Similar types of batteries with rating 1.5V, 2400mAH are chosen to power the wireless nodes [384]. Four such batteries supply the energy to the wireless nodes.

Although the power supply from the conventional sources is an option while implementation of the nodes in the indoor environment, but battery based wireless nodes are a preferred option. The wireless nodes operate on DC power which is easily supplied by help of the batteries. Additional circuitry would have been necessary to convert the AC into DC if the conventional sources were used that would have added up to the manufacturing cost of the wireless nodes. Moreover, when considering optimal placement of the routers in the indoor network to overcome the problem of signal attenuation, it may not be always possible that the facility of electrical installations are present at the desired location. Creation of multiple power supply points throughout the residential enclave to supply power to the wireless nodes deployed would affect the aesthetics of the household. The customer would have no option for alteration of the appliance positions since the nodes are needed to be fixed at their installed positions when considering conventional power supply. The battery based supply to wireless nodes provides an additional advantage of multi-hop multi-path architecture which is desired for wireless networks designed for reliable and continuous monitoring. But frequent replacement of batteries would become laborious for the customer and add to the network build up cost. This necessitates enhancement of the network lifetime for battery based wireless network which can be achieved through lower energy consumption in the network. Thereby, cost efficient study through minimal energy consumption and satisfying the requirements of a good communicating medium becomes necessary in networks designed for wide area residential complexes. Choice of ideal network architecture based on best suited topology needs to be identified depending on the extent of application.

The profits attained through implementation of intermediate routers in Scheme 2 for different case studies considering different network sizes and varied number of sensor node deployment is evaluated by (5.13). It is considered that the designed wireless network would be in operation continuously over a period of 1 year monitoring data from different sensors deployed in the network.

$$Profit = N_s \times \frac{8760}{RunTime} \times B_c - [\,(N_s + N_r) \times \frac{8760}{RunTime} \times B_c + N_r \times I_{nC} + MC] \quad (5.13)$$

Here, the number of sensor nodes has been represented by N_s. The total number of additional routers employed in Scheme 2 is denoted by N_r, B_c is the battery cost for 4 batteries supplying energy to each node, I_{nC} is the extra installation cost incurred for the additional routers in the network while the extra annual maintenance cost for the additional routers is denoted by MC.The factor "$Run\,Time$" represents the duration in hours for which the installed batteries can supply energy to the wireless nodes. This is evaluated by dividing the initial energy supplied from the batteries by the energy required during packets transmission. The first part of the Equation (5.13) represents the annual running cost through Scheme 1 while the second part of the equation considers the annual running cost of Scheme 2, the additional installation and maintenance costs due to placement of extra routers in the network. The profits attained through the two network designs helps to choose the apt topology for wireless network in wide area monitoring. The node density in the area and the size of the deployment area helps to decide the best fit topology based on the results obtained through solution of this designed cost function.

Enhancement of lifetime of the wireless networks is another important factor that needs to be taken care to ensure that the entire network remains active for higher number of rounds of data transmission. The efficient cluster head selection based on residual energy of the nodes through rotation at every round of data transmission helps to balance the load amongst the different employed nodes in the network. The lifetime of the network can only be improved through proper placement of the cluster heads in the network that can help in data clustering from maximal number of nodes and equally ensure coverage of the entire network. The different multi-dimensional objective functions designed for lifetime enhancement has been discussed in details in the next sub section.

5.4 Multi-Dimensional Objective Function Design for Cluster Head Selection and Routing in Wireless Network

The joint clustering and routing approach in the wireless sensor network enables proper management of network energy to accomplish the objective of enhanced lifetime of the wireless sensor network. The study of the rounds for First Node Death (FND), Half Node Death (HND) and the Last Node Death (LND) provides the readers an idea about the extension of lifetime [312]. The simple logic to the solution is to conserve the residual energy of the nodes so that the nodes remain active for longer periods. The network design based on efficient clustering should also focus on preventing unequal energy consumption amongst the cluster heads, especially those that are situated near the base station. The first step related to the clustering approach is the selection of the cluster head on the network based on the residual energy of the nodes. It is necessary that the role of cluster head in rotated amongst the nodes deployed or amongst the cluster members to ensure that a particular node is not entrusted with constant high load handling.

5.4.1 Residual Energy related to Cluster Head Selection

It is a very well known fact till now that the formation of clusters in the network has resulted in efficient load handling and eliminated the problems of unequal energy consumption of the network. Initially when cluster formation starts, a decision is taken by the cluster members if it wants to become the cluster head. In order to equally distribute the role amongst the members by turn, this decision is made at every round of data transmission in order to keep the maximum number of nodes alive for a longer duration. All the members of the cluster initially display their candidature to become the cluster head in the current round of data transmission but the nodes with the highest residual energy are finally chosen. For the first few rounds the cluster head is chosen randomly as initially all the nodes have equal residual energy. But with increase in rounds of transmission, the election of cluster head becomes highly dependent on the residual energy of the nodes. This is done so that the energy supplied to a particular node does not completely die out to prevent earlier node death. This engineering approach has helped to improve the network stability by delaying the first node death in the network.

Initially all the cluster members interested to participate in the cluster head selection process are allowed to choose a random number between 0 and 1. A threshold value *ET (n)* helps to determine the nodes as the cluster head for that particular round if their chosen number comes to be less than the threshold value. The primary equation has been taken from literature involving LEACH algorithm as the cluster head selection and has been expressed in Eq. (5.14) [219].

$$ET(n) = \begin{cases} \frac{P}{1-P*(r mod \frac{1}{P})} & if n \epsilon G \\ 0 & otherwise \end{cases} \quad (5.14)$$

As the cluster head selection in this work has been decided to be done based on residual energy of the nodes, the novel equation designed here is a slight variation of the original LEACH algorithm [219]. The residual of a particular node compared to the total residual energy of the network has been additionally considered here to calculate the threshold value *ET (n)* as given in Eq. (5.15)

$$ET(n) = \begin{cases} \frac{P}{1-P*(r mod \frac{1}{P})} * \left(\frac{E(n)}{E_{total\ residual}}\right) & if n \epsilon G \\ 0 & otherwise \end{cases} \quad (5.15)$$

Here, the probability of a node being chosen as the cluster head is represented by P while the current round of data transmission is denoted by *r*. The value of P chosen for this problem is 0.1. The set of nodes that have not been selected as cluster heads for the last *1/P* rounds is denoted by G. For n^{th} node, the energy of the node is given by $E(n)$ and the total residual energy of the network is denoted by $E_{total\ residual}$. The total residual energy of the network is obtained by subtracting the total energy consumed during transmission and reception from the total initial energy of the nodes and is depicted in Eq. (5.16). The available energy, $E(n)$, for a particular node is calculated by subtracting the energy required for transmission and reception of data determined by Eq. (5.9) and Eq.(5.10) from the initial energy of the node. Equation (5.16) denotes the formulation for calculation of the residual energy on the network after *k* rounds of data gathering in the chosen area of interest.

$$E_{total\ residual} = \sum_{i=1}^{n} E_{i,k} - \sum_{i=1}^{n} (E_{i,TX} + E_{i,RX}) \quad (5.16)$$

A particular node is considered to be dead when the residual energy of that node becomes less than the minimum threshold energy required for the node to perform the role of data transmission. The nodes with some part of the residual energy are considered to be alive nodes and the cluster heads after *k* rounds of data transmission are chosen from this set of nodes. Thereby, cluster head selection through this modified formulation becomes dependent on the available energy of a particular node and the total residual energy of the network.

In order to study the effect of variation of number of cluster heads in the network, the original designed equation of LEACH algorithm was slightly remodelled for this equation as depicted in Eq. (5.17) and this did not take into account the residual energy of the nodes while selection of cluster heads. The fraction of nodes permissible to be chosen as the cluster head replaced the factor probability of the node to become the cluster head in this equation.

$$\mathrm{T}(n) = \begin{cases} \frac{m_c}{1-p*(r\ mod\ \frac{1}{p})} & if\ n\ \epsilon\ G \\ 0 & otherwise \end{cases} \quad (5.17)$$

In the above equation, m_c is the fraction of the nodes that are maximum permissible cluster head and all the other parameters have the same denotations as previously used in Eq. (5.15). The threshold value for selection of cluster heads is given by *T (n)* and the decision for a node to become a cluster head is taken in the same fashion as described before as in Eq. (5.15). The maximum permissible cluster, m_c, is chosen to be 0.05 or 0.1 of total number of nodes for different case studies [269].

After selection of the cluster heads, the positioning of the cluster heads help to aggregate the data from all the Cluster Members (CM) and the aggregated data is transmitted to the control station through multi-hop communication. The optimal selection of the position of the cluster heads thereby depends upon several parameters according to the need of the problem.

5.4.2 Objective Function Design and Individual Parameter Description

For the first case study, maximizing the network lifetime of WSN depends on optimal positioning of the cluster heads chosen based on residual energy of the nodes. In the aim of this, a multi dimensional multi objective fitness function was designed that contains five parameters namely degree of node, number of hops, intra-cluster distance, inter-cluster distance and coverage ratio. When considering a cluster based network, the cluster head has the highest responsibility to ensure efficient data aggregation from all its members and balanced energy consumption so that the residual energy of the nodes remains maximal. This requires that more or less equal number of nodes become the members of a particular cluster so as to equally the balance the data load amongst all the cluster heads. The maximum number of nodes that can form the part of a certain cluster for a particular round of data transmission is denoted by Node Degree, N_{degree} . Minimization of this parameter ensures that no cluster head is associated with collection of data from huge number of nodes and is determined by help of Eq. (5.18) [313]:

$$N_{degree} = \sum_{i=1}^{m} |CM_i| \tag{5.18}$$

Here, the number of cluster members of the i^{th}cluster in a certain round of data transmission is denoted by $|CM_i|$ and while m represents the number of cluster heads (CHs) chosen in that round of data transmission through Eq. (5.15) and Eq. (5.17) for the two considered approaches of selecting the cluster head in the two problems. Once the number of cluster members in a particular cluster has been fixed, the distance between each of the cluster members and its cluster head for the i^{th} cluster is evaluated to ensure that the cluster head is accessible from all the members in the cluster. This approach ensures improvement in performance of transmission amongst the members of the cluster and maximizes the communication link quality amongst the nodes. The average distance between the nodes and the cluster head has been termed as the intra-cluster distance ($D_{intra-cluster}$)and given as Eq. (5.19) [313] :

$$D_{intra-cluster} = \sum_{j=1}^{m} \left[\frac{\sum_{i=1}^{|CM_j|} d(CH_j, CM_i)}{|CM_i|} \right] \tag{5.19}$$

Here, the Euclidean distance between the j^{th} cluster head and the i^{th} cluster member of the j^{th} cluster is given by $d(CH_j, CM_i)$. The evaluation is done for all the members of that particular cluster and the summation of the distances is divided by the total number of cluster members to obtain the average intra cluster distance. In order to establish an optimal pathway from the source to the sink node, the distances between the cluster heads is necessary to be evaluated in order to position the next cluster head in the network. The positioning of the intermediate cluster heads determines the hops for the data to reach the sink from a particular sensor node through a proper communicating data pathway. The average distance between the cluster heads is termed as inter-cluster distance ($D_{inter-cluster}$) and the equation for inter-cluster distance ($D_{inter-cluster}$) is given by Eq. (5.20):

$$D_{inter-cluster} = \frac{\sum_{i=1}^{m} d(CH_{i+1}, CH_i)}{m} \tag{5.20}$$

Here, $d(CH_{i+1}, CH_i)$ is the Euclidean distance between $(i+1)^{\text{th}}CH$ and the ith CH and m is the total number of cluster heads determined in each round of data transmission. The average distance between two cluster heads is aimed to be maintained at a constant for all the cluster heads and is obtained by dividing the total Euclidean distance obtained with the total number of cluster heads in the network. The total number of hops required between each cluster head and the sink is given by N_r which is determined by Eq. (5.21) [378]:

$$N_r = [(\sqrt{\{(x_i - x_j)^2 + (y_i - y_j)^2\}})/d_0] \tag{5.21}$$

The positioning of the cluster heads should be such that the number of hops required is minimal and no extra nodes are needed to be introduced in the network. This is evaluated by calculating the distance between the cluster heads and the sink divided the maximal range of transmission of each cluster head. In the given equation, the co-ordinates of the cluster heads is given by (x_i, y_i) while (x_j, y_j) represents the co-ordinate of the sink node which is fixed in this problem. The maximum data transmission range for the nodes is taken as d_0 for the designed network. It is also important to be taken care that the entire area of application is covered well and none of the nodes are left out thus making this factor one of the primary aims of designing any cluster based wireless sensor network. A parameter termed as Network Coverage (*NC*) is evaluated by the designed equation in Eq. (5.22) to ensure participation of all the nodes [313].

$$NC = \frac{(N-m) - \sum_{j=1}^{m}|CM_j|}{\sum_{j=1}^{m}|CM_j|} \tag{5.22}$$

Here, N is the total number of sensor nodes, m is number of CHs and $|CM_j|$ represents number of nodes in the jth cluster. This factor needs to yield a result ideally close to zero to ensure no node is left out from being a member of any cluster. A previous work found in literature utilized some of the factors to design the multi dimensional objective function for cluster head placement in the network through Cuckoo Search-Harmony Search algorithm. The utilized objective function for that problem has been displayed in Equation (5.23).

$$F = w_1 \times Node_{energy} + w_2 \times N_{degree} + w_3 \times D_{intra-cluster} + w_4 \times NC \tag{5.23}$$

The final designed multi dimensional objective function (*F1*) expressed below in Eq. (5.24) has considered few more parameters and is formulated as the weighted sum of all the above mentioned parameters which helps to choose the positions of the cluster heads. The modification to the objective function has been done based on addition of two parameters: the number of hopes and inter cluster distance. The number of hops helped to establish the pathway based on involvement of minimum number of cluster heads between source and the sink node while the parameter 'inter-cluster distance' helps to keep the distance between all the cluster heads equal so that no cluster head needs to spend more energy for data transmission. The factor 'Node-energy' considered in Eq. (5.23) has not been used during the placement since the selection of cluster head has been on the basis of residual energy of the nodes.

$$F1 = N_r + w_1 \times NC + w_2 \times N_{degree} + w_3 \times D_{inter-cluster} + w_4 \times D_{intra-cluster} \quad (5.24)$$

Here, four weight factors, $w_1, w_2, w_3, w_4,$ whose values lie between 0 and 1, are associated with each of the parameters that help to determine the optimal placement of the cluster heads. It is necessary to ensure that only optimized number of nodes need to participate in routing of the data from the cluster heads and the sink node to preserve the residual energy of the nodes and thereby the number of hops, N_r, needs to be kept minimal. Thereby, this parameter has been given the highest priority amongst all the parameters to choose the position of the cluster heads and thereby no weight factor is associated with this term. All the other factors that are part of the final objective function are interrelated with each other and finally to the designed number of hops. The next important objective for efficient cluster head placement is to take care that all sensor nodes have become a member of any cluster and that can be achieved only if the nodes are can access all the designed hops of the network. Therefore, the parameter, NC, closely relates to the parameter N_{degree}. The number of nodes within a cluster is denoted by N_{degree} and the position of the cluster heads helps to determine the inter-cluster and the intra cluster distance, namely $D_{inter-cluster}$ and $D_{intra-cluster}$. The constraint has been fixed to ensure that all these distances lie within the maximum transmission range of each sensor node which is same for all the deployed nodes in the network. All these factors thereafter help to determine the number of cluster heads and subsequently the number of clusters in the network to achieve efficient routing through distributed clustering approach.

In the other approach, the effect on the network lifetime and the energy consumption of the network is studied based on pre fixed amount of cluster heads in the network. The final multi-dimensional objective function (*F2*) designed for this problem given in Eq. (5.25) is a slight modification of the objective function designed in Eq. (5.23). This fitness function is also expressed as a weighted sum of various parameters as expressed below in Eq. (5.25). Here, w_1, w_2, w_3, w_4 are the weight factors associated with each of the factors determining the optimal placement of the cluster heads.

$$F2 = w_1 \times Node_{energy} + w_2 \times N_{degree} + w_3 \times D_{avg} + w_4 \times NC \quad (5.25)$$

The implications of each of the parameters used in the designed objective function needs a detailed understanding to sense its effect on position of the cluster heads. As the number of cluster heads to be implemented in the wireless network is already pre-stated for this particular problem, the residual energy of the nodes was not considered a factor useful while election of the cluster heads are done. However, reciprocal of the residual energy of a particular node, represented by N_{energy} in Eq. (5.26) becomes one of the determining functions to meet the objective of finding out the best positions of the cluster heads in this problem [313].

$$Node_{energy} = \sum_{i=1}^{m} \frac{1}{E_{CH_i}} \quad (5.26)$$

Here, the residual energy of the i^{th} $CH$is determined by E_{CH_i}which is obtained by subtracting the energy consumed during data transmission from the initial energy of the nodes. The number of CHs in each round of data transmission is represented by m which is pre stated for this particular problem but varies according to the extent of application. The average distance between a source sensor node and the base station becomes a determining factor for positioning of the cluster heads and is represented by the factor D_{avg} and is given by Eq. (5.27). The lesser is the distance between the sensor node and the base station, lesser is the requirement of intermediate cluster heads to be involved in data transmission

$$D_{avg} = \sum_{j=1}^{m} \frac{1}{N_j} \times (D_{intra-cluster} + D_{inter-cluster} + D_{cluster-sink}) \qquad (5.27)$$

The variables $D_{inter-cluster}$ and $D_{intra-cluster}$ represent the inter cluster and intra cluster distances as stated above by Eq. 5.19 and 5.18 respectively and have the same implications. The variable $D_{cluster-sink}$ denotes the distance of the cluster heads from the base station. The total number of cluster heads and thereby the number of clusters is denoted by N_j while m represents the maximum allowable cluster heads in a certain round of data transmission. All the other parameters of the designed function have the same implications as was in the case of Eq. (5.24) and these parameters are evaluated by help of the equations (5.18) to Eq. (5.22).

The designed objective functions for the above two problems are subjected to satisfaction of some of the constraint functions.

5.4.3 Constraints related to Objective Function Design

The minimization of the two designed linear multi-dimensional multi-objective fitness function needs to satisfy the constraint equations given by Eq. (5.28), (5.29), (5.30), (5.31) and (5.32) which is common to both the problems.

$$Node_{energy} > E_{th} \qquad (5.28)$$

$$m \leq M_c \qquad (5.29)$$

$$N_{degree} \leq N \qquad (5.30)$$

$$D_{intra-cluster}, D_{inter-cluster}, D_{cluster-sink}, D_{avg} \leq d_0 \qquad (5.31)$$

$$w_1 + w_2 + w_3 + w_4 = 1; \; w_1, w_2, w_3 \, and \, w_4 \, \epsilon (0,1) \qquad (5.32)$$

For the stated constraint equations, the minimum threshold energy required for a node to perform the operation of data transmission is denoted by E_{th}. The maximum permissible cluster heads in the network is represented by M_c which is selected amongst the deployed nodes in the network. The maximum number of nodes employed in the network for the considered case has been denoted by N. The maximum transmission distance for each sensor node is given by$d_0$and all the distances between the different deployed nodes must be less than this maximum range to ensure there is no breakage in the communication link. The weight factors w_1, w_2, w_3 and w_4 associated with the different parameters of the objective function should lie between 0 and 1 and the summation of these weight factors must be equal to 1. The most determining factor out of all the considered parameters in the first designed objective function is the number of hops, N_r and its importance is considered to be equal to the summation of the importance of all the other parameters. Network Coverage, NC is the second factor in the priority list and thereby the weight factor w_1 is associated with it has the maximum importance amongst all the weight factors. The number of node members in a cluster, N_{degree} , helps to determine efficient load distribution amongst all the clusters and the second most weightage is associated to this factor. The other two factors dependent on the inter cluster and intra cluster distance in Eq. (5.24) are mutually dependent on each other and the weight factors w_3 *and* w_4 are given equal importance in this problem. The values of the weight factors are chosen in the order: $w_1 > w_2 > w_3 \geq w_4$ for the objective function designed in Eq. (5.24) according to the priorities of the factors associated with node placement. After several hit and trial runs, the best case results for minimization of objective function and cluster head placement by Eq. (5.24) were obtained for values of w_1, w_2, w_3 *and* w_4 as 0.4, 0.3, 0.15 and 0.15 respectively. For the designed objective function in Eq. (5.25), the weight factors are chosen in order: $w_1 > w_4 > w_2 > w_3$ according to the priority of the parameters determining the placement of the cluster heads in the network.

The efficient clustering and routing technology obtained through the designed problem promoted the use of wireless networks in real time monitoring applications involving renewable energy sources. The wireless sensor network controlled energy management unit was utilized in home energy management system in order to reduce the electricity consumption costs of the customers. Rooftop solar panels installed in the houses of the prosumers was efficiently monitored using the wireless sensor network to determine their energy production and its effect on the profits earned for the customer.

5.5 Design of Home Energy Management Scheme for Low Demand Prosumers

The shifting of the load operation from the peak periods to the off peak periods have helped in generating cost savings related to energy consumption. The load shifting program designed in this work has also focused on meeting the customer's need of allowing the appliances to run in the time periods of their choice. This designed problem helps to project an idea for co-ordinated operation of the appliances in future smart home networks based on Time of Day (ToD) tariff schemes. All the calculations has been done keeping in mind the specifications related to the chosen appliances and by predicting the future tariff structures which may be employed in home environments in the future due to excess usage of high power appliances in every household. The calculations related to installation of the solar panels to support the home energy management system and the payback period has been done based on the current prices of the solar panels. However, modified tariff structures in the future may help to yield lower payback period for installation of the solar panels. The economic benefits obtained by the residential prosumers through load shifting and power generation from rooftop solar installations would generate an interest among prosumers to implement this home energy management scheme. This model would help to generate energy business prospect through bidding in the near future.

5.5.1 The Proposed Roof Top Solar Integrated Residential Energy Management Scheme

Figure 5.1 depicts the proposed residential energy management scheme by integration of rooftop solar panels for low demand prosumers.

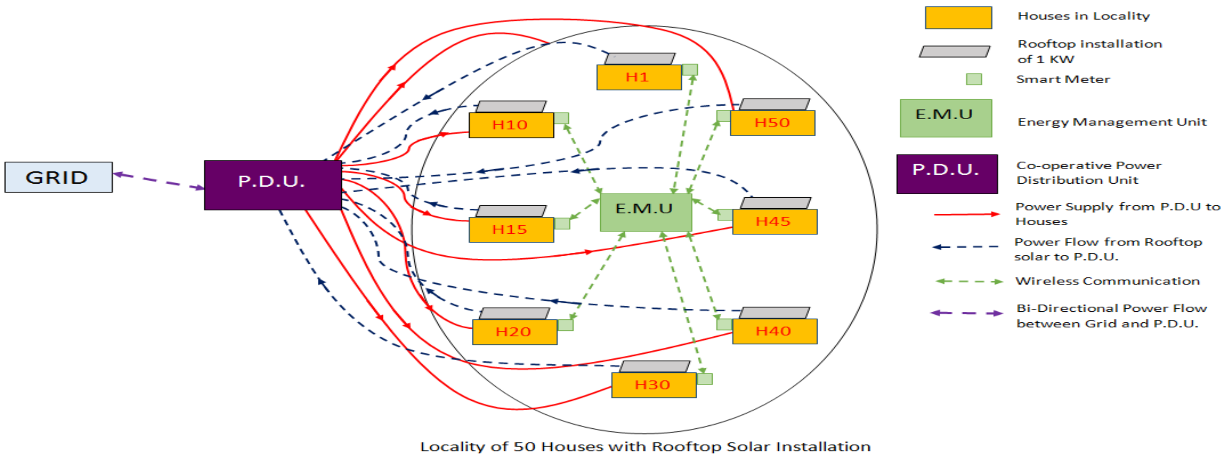


Figure 5.1 Proposed residential energy management scheme

In the designed residential energy management scheme, it has been considered that the power flows from the grid to a central co-operative power distribution unit. This power distribution unit is assigned the role of distributing the power according to the load demands amongst the fifty (50) bungalows built in the considered locality. Considering the living style of all the customers in the bungalows to be similar and they use the same set of appliances, the power distribution is uniformly maintained throughout the houses. Smart metering provided at every bungalow helps to monitor the power consumption and performance related data of the appliance. The implemented WSN architecture forwards the collected data to the Energy management Unit (EMU). The demand side management related operation and the control signals to shift the hour of operation of the appliances is sent back to the appliances via the wireless sensor network in the reverse path. Thereby, the designed WSN helps in bidirectional information flow with low power consuming and low cost communication architecture. Additional power generation from the installed solar rooftop panels is facilitated at all the 50 bungalows in the locality and the generated power from each household is accumulated at the central co-operative power station. The central co-operative power station helps to feed back this generated power from the rooftop solar into the traditional grid. The performance related to the solar panels, power generation and fault analysis related to solar panels are monitored by the designed wireless sensor network.

The wireless sensor network acts as the main heart of the controlling architecture in the proposed renewable integrated demand side management scheme. The communication framework developed between the different considered elements of the designed network architecture by the help of the wireless sensor network is shown in Figures 5.2(a) and (b). Figure 5.2(a) depicts the stepwise information flow between the grid and the smart sensors via the intermediate Energy Management Unit.

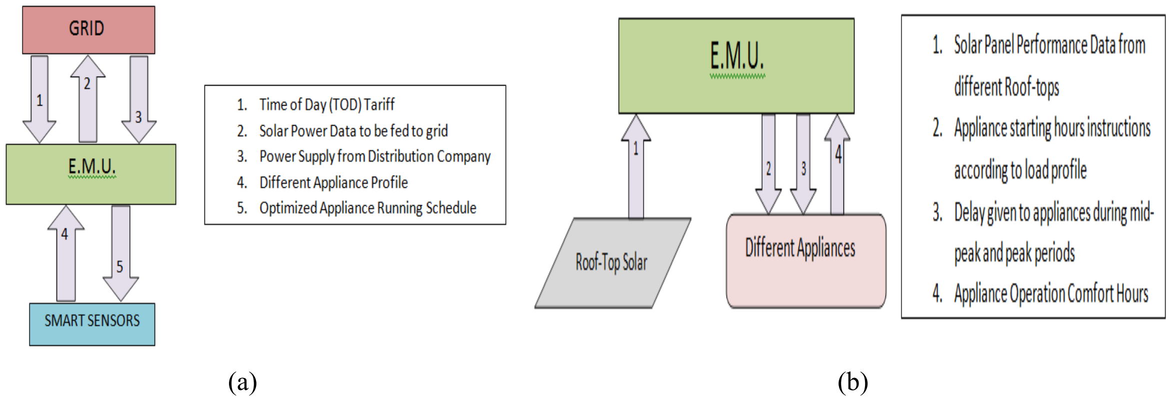


Figure 5.2 Flow of information in the proposed architecture: (a) between grid and smart sensors via EMU; (b) between roof top solar and different appliances with EMU

The input data related to the time of the day pricing and the power supply data from the distribution company is stored in Energy Management Unit to perform the role of appliance scheduling. The E.M.U communicates with the smart sensors in order to know their present status and choice of their operation hours. The proposed home energy management scheme helps to generate an optimized running schedule to attain minimum energy cost related to the operation of the appliances throughout the day. The information related to the delay of the operation hours and ideal time for appliance operation starting is carried to the appliances by the designed WSN. The solar power generated is sent back from the EMU to the grid via the intermediate central power distribution unit. The performance of the solar panels related to their power generation and efficiency over the course of the year has also been planned to be monitored by help of the implemented wireless network control framework to calculate perfectly the cost benefits earned from the proposed energy management scheme. This information flow in the EMU is aided by the wireless sensor network as shown in Figure 5.2(b).

Four (04) modern appliances very common to every households nowadays are considered to be installed at every houses whose operation hours needs to shifted at different times of the day for a certain household. Some non-shiftable loads like lights, fans, television are also considered for calculation of the energy cost which accounts for an average energy consumption of 5kWh per day in each of the 50 bungalows. Based on the Time of Day (ToD) tariff scheme, the operation of the four appliances are shifted to low price periods in order to reduce the energy cost throughout the day.

5.5.2 Appliance Scheduling Cost Function Design

The appliance scheduling in the residential energy management scheme is dependent on the reduction of load during the peak pricing periods in order to show its positive implications on the energy cost throughout the day. In order to ensure efficient shifting of the loads during the course of the day, some equations based on demand side management have been designed for a single household. An Energy Management Unit (EMU) performs the shifting operation of the appliances throughout the course of the day based on the tariff for that particular time of the day. The information regarding the demands of the appliances to operate in a particular time slot and the control signals from the EMU to shift the appliance operation is sent to the appliances by help of efficient wireless network design. The 24 hours of a day is initially divided into 48 equal time period cycles and the status of the appliances is randomly generated over these cycles. The status matrixes of the individual appliances over the 48 cycles are given by Eq. (5.33) [50].

$$S_n \triangleq [\, S_n^1, \ldots.., S_n^H \,] \tag{5.33}$$

The status of each appliance in single time period is denoted by S_n. The number of appliances installed in the house is represented by n while the maximum number of time periods is represented by H which is 48 in the considered problem. For each appliance, initially such a status matrix is generated randomly over the entire time period and the status of the appliances is updated after iteration until the condition for minimum energy cost is attained. The total energy consumption of the individual appliances over the entire day is evaluated by Eq. (5.34) as [50].

$$E_n = \sum_{h=1}^{H} z_n^h \tag{5.34}$$

The total energy consumption is represented by E_n while the energy consumption of a certain appliance in a certain time period is represented by z_n^h. The rest of the symbols have the same meaning as specified previously. The Time-of-Day (ToD) tariff scheme is essential to decide the shifting of the appliances to other time periods based on the hour of operation and the electricity price at that hour. The price based condition that decides the appliance shifting is depicted in Eq. (5.35).

$$U_{h_p} > U_{h_{mp}} \quad ; U_{h_{mp}} > U_{h_o} \tag{5.35}$$

$$\text{Where, } 23 \leq h_p \leq 32, \qquad 39 \leq h_o \leq 48,$$

$$0 \leq h_{mp} \leq 22 \quad \&\& \quad 33 \leq h_{mp} \leq 38$$

The unit prices during the peak, mid peak and off peak period are represented by U_{h_p}, $U_{h_{mp}}$ and U_{h_o} and if the conditions described in Eq. (5.31) are attained, the energy management unit sends a signal for shifting of the appliances. The 24 hour cycle has been considered to start at 6AM on a day and finishes on 6AM on the next day. This indicates that 6-6.30AM on the 1st day represent time period 1 while 5.30AM-6AM on the next day represent the 48th time period. Accordingly the time periods during which the peak period, mid peak period and off peak period is dominant are represented by h_p, h_{mp} and h_o. The hour of operations for the appliances according to customer's choice is given by the constraint equation (5.36).

$$L_k \leq H \leq M_k \tag{5.36}$$

In the above equation, the lower and upper boundary of operation hours of a certain appliance is represented by L_k and M_k while H represents the suggested run hour of operation by the EMU. All the time periods are of equal duration and is represented by D_i while the status of the appliance at that time period is represented by S_t^i.The total duration of the appliance in each operation cycle is given as Eq. (5.37) and is represented byD_N.

$$\sum_{i=1}^{H} D_i S_t^i = D_N \tag{5.37}$$

The final designed objective function given by Eq. (5.38) is optimized to obtain the minimum energy cost over the entire day by satisfying the input constraints given by previous equations.

$$C = \sum_{i=1}^{I} \sum_{j=1}^{N} \sum_{t=1}^{T} \sum_{k=1}^{K} E_i\, D_j\, U_t S_N^{ijk} \tag{5.38}$$

In Eq. (5.38), the power rating of each appliance is given by$E_i$and D_j represents the total duration for which an appliance works in its each operation cycle. The unit price at 't'th time period is denoted as U_t while S_N^{ijk} represents the status of 'k'th appliance in the 'i'th hour for 'j' time periods of that particular appliance. The total summation of the incurred cost due to operation of the different appliances over the entire day gives the electricity cost incurred by the customer. The proposed appliance shifting method in demand side management scheme helps to minimize the electricity cost and provides economic benefits to the customer. In the aim to attain more economical benefits, the customers may install rooftop solar panels and the generated power is directly sold to the grid in order to reduce their own electricity bills.

5.5.3 Economic Benefit Analysis Related to Solar Roof Top Installation

Grid connected solar roof top panels can be installed as a part of the demand side management scheme which generates power over the year and this power is directly fed to the grid. The number of units generated from the roof top solar panels is adjusted with the monthly energy consumption of the customers and it gets reflected in the customer's electricity bill every month. The generated solar power is sold back to the grid at the same average cost by which the customer buys power from the grid. The average rooftop area of an average house to install a solar rooftop panel varies from 300ft^2 to 400ft^2. However, the effective area of the roof on which the solar panel can be installed will be somewhat less than the total area due to other constructions and unequal solar insolation over the entire roof area. The thumb rule states that 10m^2 or about 125ft^2 of rooftop area can support solar panels of 1kW power capacity [385]. Thereby, for the considered houses, it is estimated that rooftop solar panels upto a maximum capacity of 3kW can be supported. As the availability of the sunlight is stochastic in nature, the maximum output from the solar panel is highly dependent on the panel efficiency and the number of hours for which the sunlight is received. The proposed design of including rooftop solar panels in demand side management scheme is for houses situated in the eastern parts of India where the availability of sunlight is relatively higher. The factor that determines the output from the solar panel over a year is defined as Capacity Utility Factor (CUF) [385]. This is quite low since the amount of solar radiation varies over the months in a year. The solar radiation is highest and for maximum duration in the summer but it becomes less in winter. In the monsoon, there are several days when sunlight is absent for the whole day. Based on the CUF, which is typically considered to be 19% for INDIA [385], the total generated output from the solar panel is given by Eq. (5.39).

$$Units\ Generated = System\ Size\ in\ kW \times CUF \times 365 \times 24 \quad (5.39)$$

The total generation from the rooftop solar panel over the course of a year is calculated based on the system size and CUF which is sold back to the grid through the intermediate co-operative power distribution centre. The price at which the distribution companies buy back the power generated from rooftop solar panels is the weighted average of the tariffs considered throughout the day and it has been calculated to be Rs 6.45/kWh for this application. The total cost benefits attained through the unified demand side management scheme and the solar rooftop installation for a certain bungalow has been represented by Eq. (5.40) as given below.

$$Economic\ Benefit = (Initial\ Energy\ Cost - C) \times 365 + Units\ generated \times 6.45 \quad (5.40)$$

In the designed equation (5.40), C represents the minimal cost attained by appliance shifting as obtained by Eq. (5.38) and the amount of solar unit generated is calculated from Eq. (5.39). The initial installation cost of the rooftop solar panels in India is considered at the stated price of Rs 55 per Watt for installations ranging from 10kW to 100kW by Ministry of Non Renewable Energy, Government of India [386]. Considering the installation is done over the entire society consisting of 50 bungalows, the total solar installation of the area will be a maximum of 100kW and hence this stated price can be considered as the installation cost of roof top solar panels in the entire society. The payback period for this proposed solar installation is calculated by dividing the initial investment costs by the total generated profit at the end of the year as evaluated from Eq. (5.40). The performance monitoring of the rooftop solar panels is done by the designed wireless network architecture which continuously sends the information to the designated energy management unit. The bidirectional information flow through the wireless network facilitates easier integration of the roof top solar panels to the demand side management structures.

The different mathematical formulations suggested in this chapter related to the reliability enhancement and lifetime improvement of the wireless sensor network has been attempted to be solved using soft computation algorithms. A modified approach of Cuckoo Search Algorithm in form of Cascaded Cuckoo Search Algorithm has been utilized to solve the problem of node placement related to minimal signal attenuation in the network. A novel approach involving joint utilization of LEACH and Cuckoo Search Algorithm to solve the problem of routing and clustering in the network has been proposed. This approach has been named as Residual Energy based Distributed Routing and Clustering (REDCR) algorithm which helps to attain the objective of lifetime improvement in the network. The mathematical formulations related to the home energy management scheme has been solved using Cuckoo Search algorithm to find out the optimized results related to cost benefits of low demand prosumers. The novel solution approaches proposed have been discussed in details in the following chapter so that they can be implemented in other engineering fields in the near future. Different solution techniques have been utilised to obtain the best case results through in house programs developed in the MATLAB platform [387].

Chapter 6

The Implemented Solution Methodologies

The different mathematical formulations designed for the considered problems of the wireless sensor network need suitable engineering optimization tools for solution. Optimization techniques can be classified as the deterministic technique and the stochastic technique depending on the type of problem. Deterministic techniques are mainly used for mathematical problems whose performance depends upon the primary state inputs. On the other hand, stochastic techniques are utilized for problems where the variables initially chosen randomly evolve in iterations with certain probabilities and their performance related to the designed problem is traced. The quick convergence and accuracy in results obtained through the stochastic methods help to choose the stochastic techniques as the optimization tool. Stochastic techniques can be further sub divided into heuristic and meta-heuristic technique. The heuristic techniques aim to solve problems by trial and error method while the meta-heuristic techniques can be applied to any engineering problems that utilize the evolutionary technique. This chapter deals with the different soft computation tools utilized in order to solve the designed engineering problems. Different soft computation techniques have been newly proposed as well to solve these problems which have been duly described in this chapter. The soft computing techniques have attempted to solve the problem of clustering and routing jointly providing reliable results. Finally, a meta-heuristic optimization based home energy management algorithm has been proposed that aims to schedule appliances of a household to earn economic benefits for the customer.

6.1 Implemented Soft Computing Techniques for Node Placement Problem in Wireless Network

As discussed above, the meta-heuristic soft computing techniques have shown to provide most accurate results related to any engineering optimization problem. These techniques mainly use two steps for optimization namely Intensification and Diversification. The current best solutions and the best candidate for providing the best result for the designed objective function is done by the intensification process while the diversification process explores the entire search space efficiently to find out the possible combination of solutions. One such meta-heuristic algorithm is Cuckoo Search algorithm which has been chosen as the main optimization technique for this work. Cuckoo Search (CS) optimization technique is one of the modern nature-inspired meta heuristic algorithms which was first proposed by Yang and Deb in 2009 [388]. It has been observed that application of CS algorithm in wireless network problems has been sparse in literature. But the ease to use, involvement of lesser number of parameters and quick convergence of the CS algorithm has made it ideal for optimization problems related to wireless sensor network. Moreover, during this application of router placement optimization, CS algorithm has been made to work with binary data in this work in two loops which is a novel approach related to engineering optimization problems. To understand the implementation of CS algorithm, an overview of the algorithm, its solution approach and the different components associated need a detailed study.

6.1.1 Overview of Cuckoo Search Algorithm

The basis of working of the Cuckoo Search Algorithm was inspired by the interesting breeding behaviour of the cuckoo birds which is known as brood parasitism. The cuckoo birds generally lay their eggs in the nest of other birds. However, if the host bird discovers that the eggs do not belong to them, they either throw away these alien eggs or leave their nests to make a new nest elsewhere. This behaviour of the cuckoo birds increases the chances of the survival of the cuckoo's next generation which can be applied to various engineering optimization problems. In order to implement this nature of cuckoo birds in order to produce best case results, three idealized rules have been made to obtain the optimized result which has been stated below:

i. Initially each cuckoo bird is considered to lay one egg at a time and randomly dump it in any nest. A set of certain number of nest is considered where the eggs can be possibly placed

ii. To obtain best results, the nests with the better quality of eggs are carried over to the subsequent generations while others are rejected.

iii. The total number of nests available is pre specified and the probability of alien egg discovery by the host bird is considered to be $Pa \in [0, 1]$. In this scenario, either the nest is discarded or the host bird abandons the nest and this nest is considered to be rejected. A new set of nests is considered again to find out the best case result.

These three rules makes implementation of cuckoo search algorithm simpler and it considers fewer number of parameters considered to other meta-heuristic methods. Some components help to form the basis of implementation of the cuckoo search algorithm which needs a detailed study before being put to use.

6.1.1.1 Components of Cuckoo Search Algorithm

The standard variables that are needed to be considered during implementation of Cuckoo Search Optimization Technique are as follows:

- Host Nest
- Levy Flight
- Cuckoo Eggs
- Nest Discarding Probability.

6.1.1.1.1 Host Nest

The initial populations or the solutions are generated through some random value considerations and are placed in the form of host nests. Considering a minimum value of the parameter, the initial solution to be placed in the host nest is calculated by Equation (6.1) [119] as;

$$nest_{(i)}^{(0)} = x_{min} + rand(0,1) \times (x_{max} - x_{min}) \tag{6.1}$$

Where, $nest_{(i)}^{(0)}$ represents the initial value forparameter of i^{th} nest, x_{max} and x_{min} indicates the maximum and minimum limit of the parameter.

The total number of rows in the host nest matrix equals to the number of nests initially considered while the number of columns indicates the different parameters considered to be optimized. The possible solutions or the cuckoo eggs are updated in iterations through another component known as Levy Flight that forms the heart of the optimization technique.

6.1.1.1.2 Levy flight

Benoît Mandelbrot was the first person that introduced the term Levy flight after the name of a French mathematician Paul Levy [388]. Levy flight is a method of calculation of the step lengths of the animals when they search their food in random or quasi-random manner. The path these animals follow during search of food is a random walk and their next move cannot be predicted. The next location of the walk depends entirely depends upon the current position and the transition probability. Once the animal reaches their desired food, the steps that make up the pathway are chosen to be the best set of solution. This nature inspired theory of Levy flight was utilized in the CS algorithm problem to generate set of new nests or solutions [388]. As mentioned earlier, the process of intensification was performed by Levy Flight to search around the current best solutions through updating the candidate solutions by an idealized step length through iterations. The step length $Levy(\lambda)$ considered to update the current set of solutions is given by equation 6.2 [389].

$$Levy(\lambda) = \left\{ \frac{\Gamma(1+\beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}} \right\}^{\frac{1}{\beta}} \tag{6.2}$$

Where, β is a constant having value in between 0.5 to 1. This generated step length is utilized to find a new set of cuckoo eggs in the next generation that may lead to the solution to a local minimum for the designed problem. The cuckoo search algorithm helps to find the most suitable nest through maximization of the survival chances of cuckoo egg.

6.1.1.1.3 Cuckoo Eggs

The cuckoo eggs that are more similar to the host bird's eggs have the maximum chances of survival and mathematically the solution nearer to the optimal process stays in the optimization process. The randomly distributed initial population of host nest is repeatedly updated by using levy flight method in the iteration cycles and the optimized solutions are aimed to be found through a detailed search process. In this search process new eggs are found out through the mathematical equation given below in (6.3) as [388];

$$nest_i^{(t+1)} = nest_i^{(t)} + s.Levy(\lambda).rand(1).\left(nest_i^{(t)} - nest_{best}^{(t)}\right) \quad (6.3)$$

Here, s is the step size parameter which needs to be chosen carefully so that the optimized solution does not gets fixed at the local maxima or minima and the optimization process converges to a global maxima or minima. A MATLAB command, $rand(1)$, gives random values between zero to one, $nest_i^{(t)}$ is the current position of i_{th} nest and $nest_{best}^{(t)}$ is the position of the best nest.

6.1.1.1.4 Nest Discard Probability

A nest discard probability, $P_a \epsilon$ [0 1], helps to reject a fraction of total number of eggs in the nests which generate poor set of solutions. The best set of solutions amongst the generated eggs is kept and a new set of random solutions replace the solutions of poor quality with lower fitness values [388]. This idea of Cuckoo Search Algorithm (CSA) has been utilized in this work for testing the node placement efficiency and finding out the cost benefits of wireless network implementation.

6.1.1.2 Proposed Implementation of CSA in Testing of Node Placement Efficiency and Cost Benefits

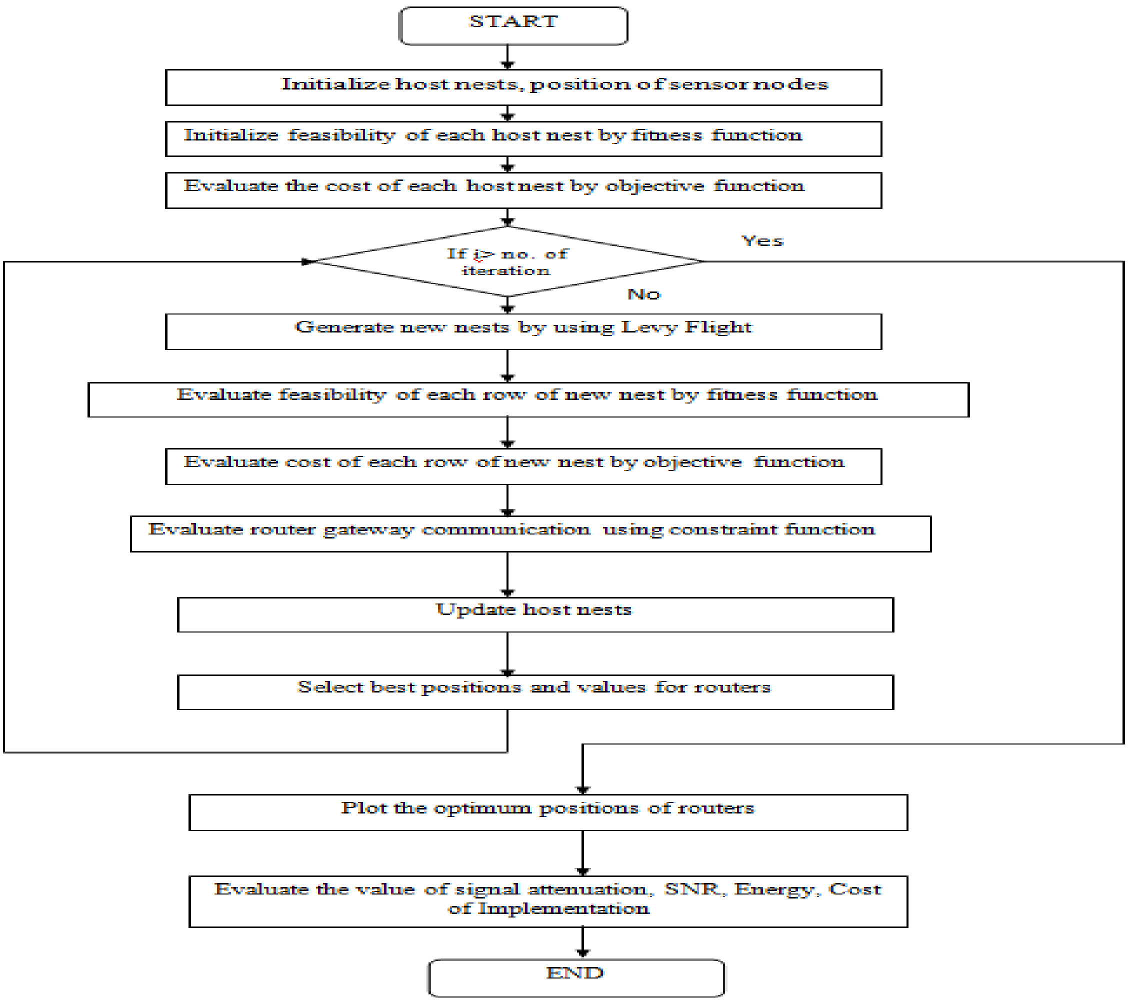


Figure 6.1 Implemented steps of cuckoo search algorithm

The basic concept of Cuckoo Search algorithm has been utilized here to find out the best position of the routers to ensure maximum network coverage and minimum signal crossover. The mathematical formulations proposed in Equations (5.9) and (5.10) have been optimized using Cuckoo Search algorithm. Figure 6.1 depicts the implemented flowchart for the Cuckoo Search algorithm in the problems to choose the optimized positions of the intermediate nodes. The best case results for cost benefits calculation by Equation (5.11) has been found out through the same optimization approach. The number of iterations has been fixed to 100 for this approach, the number of host nests has been chosen to be 50 and the nest discard probability is taken as 0.25 for best case result. The entire programming has been performed in MATLAB 2013A [387] and the results obtained have been presented in Chapter 8.

A novel approach has been presented in this work where Cuckoo Search Algorithm has been implemented in two loops to simultaneously reduce the signal attenuation and optimize the number and position of routers in the network.

6.1.2 Implementation of Cascaded Cuckoo Search Algorithm in Router Placement Problem to Minimize Signal Attenuation

In this work, an improvised version of Cuckoo Search Algorithm known as Cascaded Cuckoo Search Algorithm has been proposed where the engineering problem has been solved through two loops [390]. The signal attenuation has been minimized in outer loop by obtaining the best router positions in the inner loop. The output of the inner loop is utilized as one of the inputs of the outer loop to find out the minimum results of signal attenuation for the designed wireless network. The router placement in the network has been subjected to constraints of presence of other wireless nodes at that selected co-ordinate and area of coverage of individual placed nodes. If these constraints are satisfied during the optimization, the placement of router at a certain co-ordinate is designated to be '1' and the respective value in the matrix 'router position' is set to 1. However, if already a router is positioned at that obtained co-ordinate or if the position lies within the transmission range of another router, the value is taken as '0' and the program is again run to obtain new co-ordinates. The algorithm is repeated until all the values of the matrix titled 'router position' become '1' and the signal attenuation for the obtained router positions is calculated. The algorithm is run several times until the time the signal attenuation is obtained to be minimal for a certain set of router placement positions. This approach helped to jointly optimize two parameters related to router positions and the signal attenuation during transmission in the designed wireless network. This optimization technique ensured that two parameters are simultaneously optimized when one parameter is directly related with the other. The two set of input parameters in the two cascaded loops worked jointly to find out a common solution by optimizing the two parameters. In C-CSA algorithm, the best results are obtained through updating of the cuckoo eggs through Levy Flight algorithm in both the loops to find out the best results. Figure 6.2 shows the flowchart for the implementation of C-CSA algorithm in this particular router deployment problem where the nested loops are well displayed.

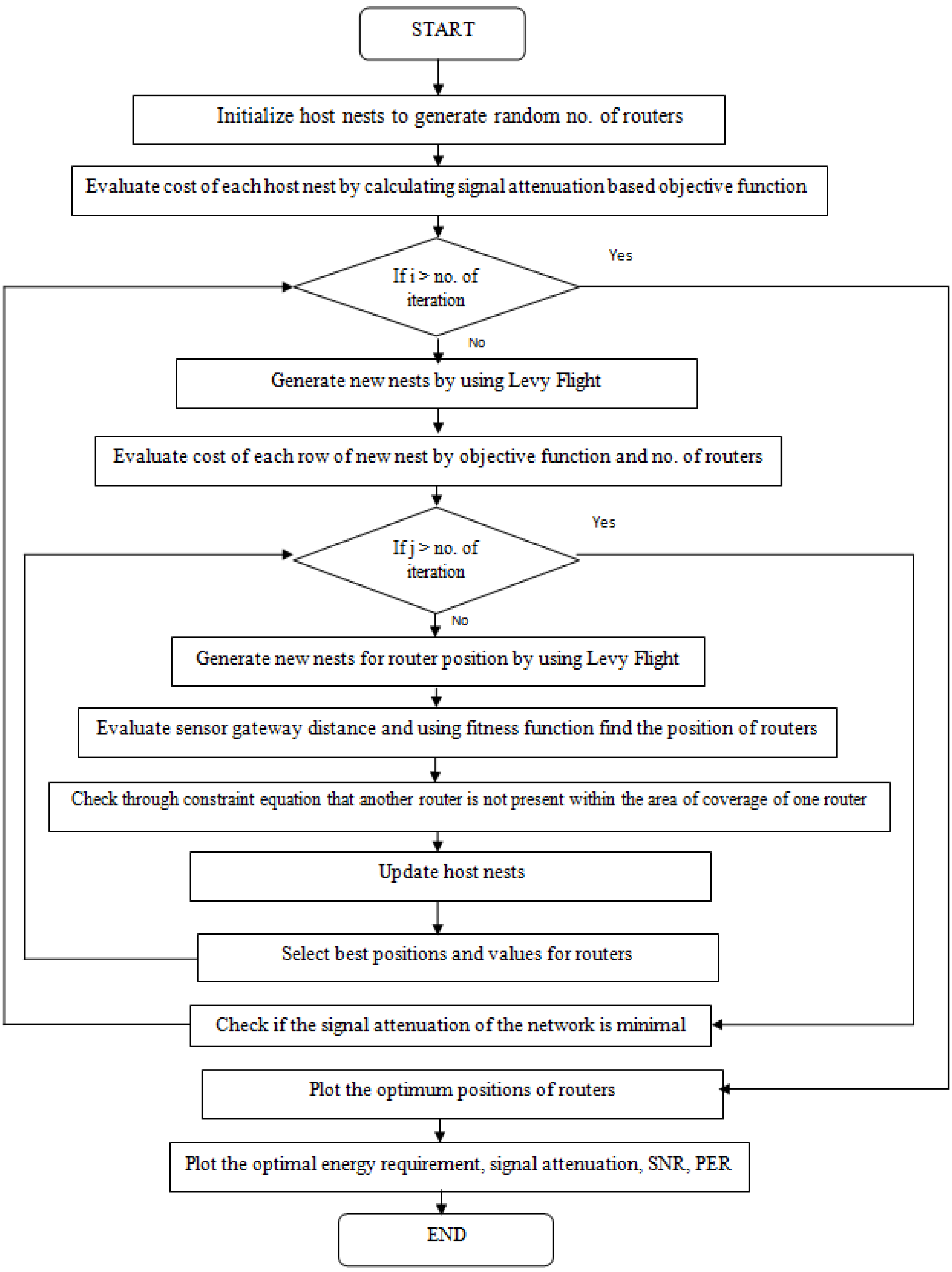


Figure 6.2 Flowchart of cascaded cuckoo search algorithm [390]

The number of iterations has been decided by hit and trial method to allow maximum possible iterations to find out the best case result. Thereby, the number of iterations has been considered to be 200 to obtain the best case results. The simulation program has been run for 30 independent runs and the best results has been obtained for the number of host nests as 50 and the nest discard probability is found to be 0.25 for the best case result. The Levy flight parameters have been varied in the 30 different trial runs to test the best case results and the value of β for application of Levy flight has been found to be 0.5. The optimized router positions are finally determined based on the minimum value of the signal attenuation achieved. Calculation of all the other values with the obtained minimum value of signal attenuation establishes the efficiency and reliability of the network. The implementation of C-CSA has been developed through an in-house developed program in MATLAB. The rules followed in this approach have been described below:

- Initially random number of routers is chosen and the signal attenuation is calculated by help of Equation 5.2.
- After the random placement of the nodes, the value of signal attenuation for each set of nodes is evaluated and the best nests are carried over to the following generations.
- A nest discard probability factor is selected for the algorithm which eliminates a fraction of the available nests having poor solutions and a new set of solutions replaces the poor solutions in the aim to obtain the best optimized solution for the number of routers.
- The number of routers for minimum signal attenuation is taken as an input to the next stage where the intermediate routers between the sensor and the gateway are determined.
- It is then checked if efficient communication pathway for all the sensors till the gateway is established with minimum signal crossover and no uncovered sensor in the network.
- The process is repeated for specified number of iterations until optimized number and position of the routers are obtained subject to minimum signal attenuation.

The data transmission in the designed wireless network based on the positioning of the routers can be determined by choosing the appropriate routing protocol. In this work, two routing protocols based on Open Shortest Path First (OSPF) protocol and Level Based Routing (LBR) routing protocol has been tested to understand the transmission pathway in the designed network.

6.2 The Routing Protocols

The routing protocols helps to determine the path between the source node and the sink node based on the request from the sink node. Proper routing algorithms help to establish proper links between the nodes through efficient utilization of the energy of the nodes. The routing protocol would help to increase the data transmission rates and eliminate the chances of interference. Quick data delivery based on shortest path routing can also be achieved through the choice of right protocol. The operation of the routing protocols is determined based on the established data transmission pathway, network structure, initiator of communications and how the next hop is selected in the forward routing path. In this work the transmission of the data has been tested based on two routing protocols namely Open Shortest Path First Routing (OSPF) protocol and Level based Routing (LBR) protocol [391]. The first protocol aims at data transmission through the shortest available pathway from the source node to the sink node. On the other hand LBR protocol transmits data based on hierarchical levels, thereby utilizes lesser number of nodes while transmitting the data from the source node to the sink node.

6.2.1 Open Shortest Path First (OSPF) Routing Protocol

The Open Shortest Path First (OSPF) finds its application for quick data delivery such as in smart grids that requires quick and real time data delivery [392]. As the positions of the nodes are fixed, the direction of hopping is decided through the intermediate hops from the source to the sink. Dijkstra's algorithm follows this protocol which has been nowadays utilized in Google Maps to find the minimum distances for journey [393]. The working of the protocol has been depicted by the help of the flowchart in Figure 6.3. The position of all the nodes and their distances between one another is fixed and put as input value to the simulation program.

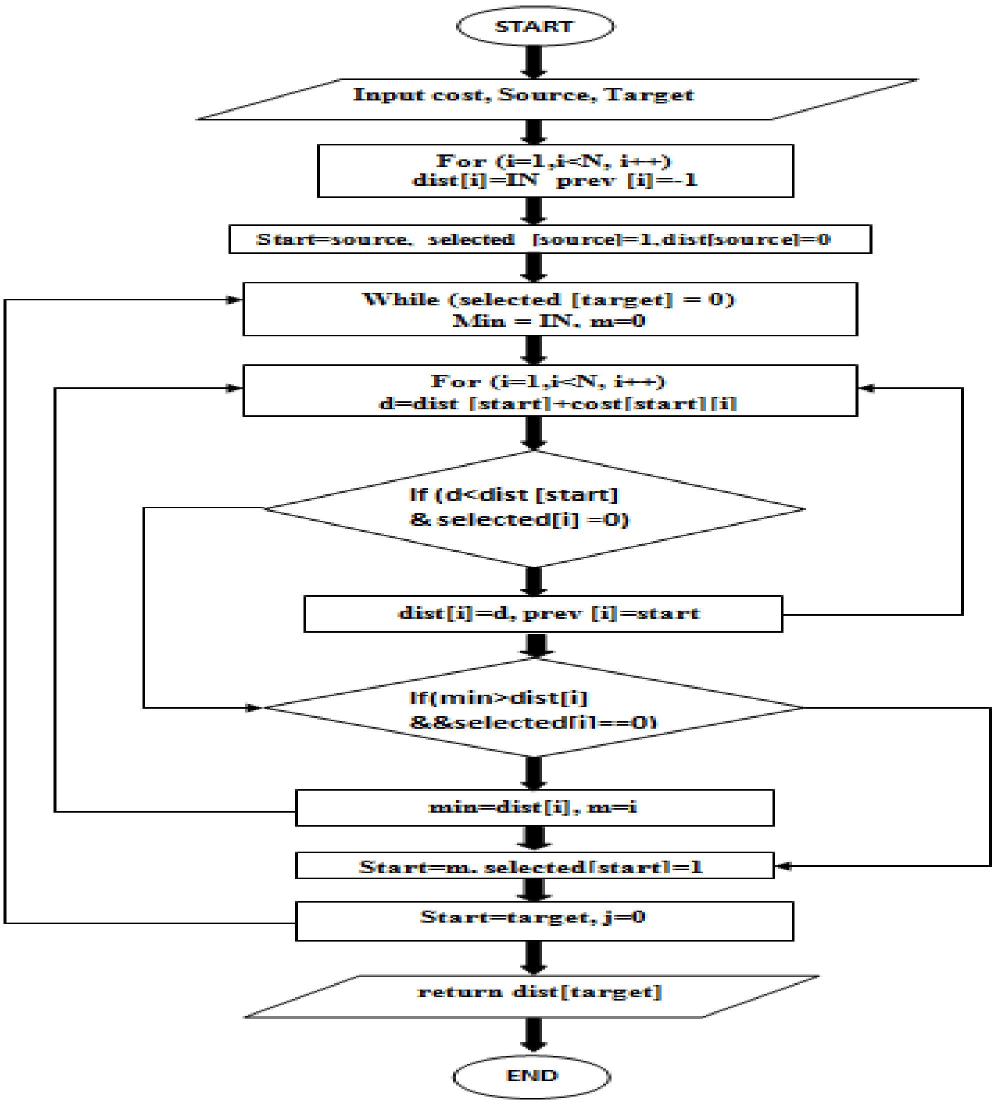


Figure 6.3 Flowchart of OSPF protocol

The steps of the algorithm that operates based on the OSPF protocol has been enumerated below based on the input data about the positions of the nodes in the network and the distances between the nodes.

Step 1: The number of nodes *n,* the source node v_s, destination node v_d and the distances between the nodes $L\ (i, j)$ are taken as input

Step 2: This step is repeated for all the nodes to find the links present between the source node and other nodes. If no link exists, between the source node and the i^{th} node, then $a\ [v_s, v_i] = 0$, *distance* dj=*Infinity*, *path[i]=0* [Invalid path]
Else: *distance* di=$L\ (s, i)$ and $path[i] = v_s, v_i$ (where v_s is the predecessor of v_i)

Step 3: Find the set of nodes that can be reached from the current node i by a link (i,j). Update the distance values of these nodes.
For each such link, the distance value *dj* of node *j* is updated as follows:
new $dj = \min\{dj, di + L\ (i, j)\}$
where $L\ (i, j)$ is the length of each such link (i, j).

Step 4: The node which is at the smallest distance value *dj* among all nodes and is chosen as the next hop for the transmitted data.

Step 5: Steps 3 and 4 are repeated for each such link and is continued till the destination node is reached The shortest path length is determined by repeating the above steps for all possible hops.

Step 6: The shortest pathway along with the shortest distance is evaluated by backtracking.

Step 7: Exit

The other protocol implemented in this work utilizes minimum number of nodes between the sink and the source node. The nodes connected to the sink node directly are considered to be on the same level and likewise the nodes are considered to be placed in hierarchical levels.

6.2.2 Level Based Routing (LBR) Routing Protocol

The path determined based on the Level Based Routing (LBR) protocol is based on selection of the next hop in the hierarchical levels [391]. The nodes in the hierarchical levels are considered to be at different energy levels. Utilization of lesser number of nodes during data transmission ensures that lesser amount of energy is utilized while transmitting the data. Therefore, this algorithm becomes suitable to be utilized in applications which have limited supply of energy and ensures more number of nodes is active for longer periods. For this protocol, the determination of the pathway is started from the sink node. The node closest to the sink is considered to be at the highest energy level and therefore this node is selected as the next hop. Similarly, the process is continued for selecting the hops at next levels till the entire pathway from the sink to the source node is determined. The steps of the LBR protocol have been enumerated below:

Step 1: Input the number of deployed nodes in the network n, source node v_1, destination node v_n and all the distances between the nodes placed.

Step 2: Check if v_1 linked to v_i,
For distance $di = \min\ \{ L\ (1, i) \}$, [length between the destination and the i^{th} node]
path = a$[v_1][v_i]$
Select v_i as the next hop and now this acts as the source node

Repeat step 2 for all the nodes and find the possible links with the source node

Step 3: Check if v_i linked to v_j

New distance $dj = \min\{dj,\ di + L\,(i,j)\}$ [This is the selected hop in the next hierarchical level]

Then path = a[v_1][v_i], [v_j]

Select v_j as the next source node

Else if v_j is linked to previous node, [this means nodes are in the same hierarchical level]

Then L(i,j)= infinity; and the next hop is again searched v_j

Repeat step 3 for the nodes other than the source node

Step 4: The shortest path is chosen based on hierarchical hop and the best pathway is printed.

Step 5: Exit

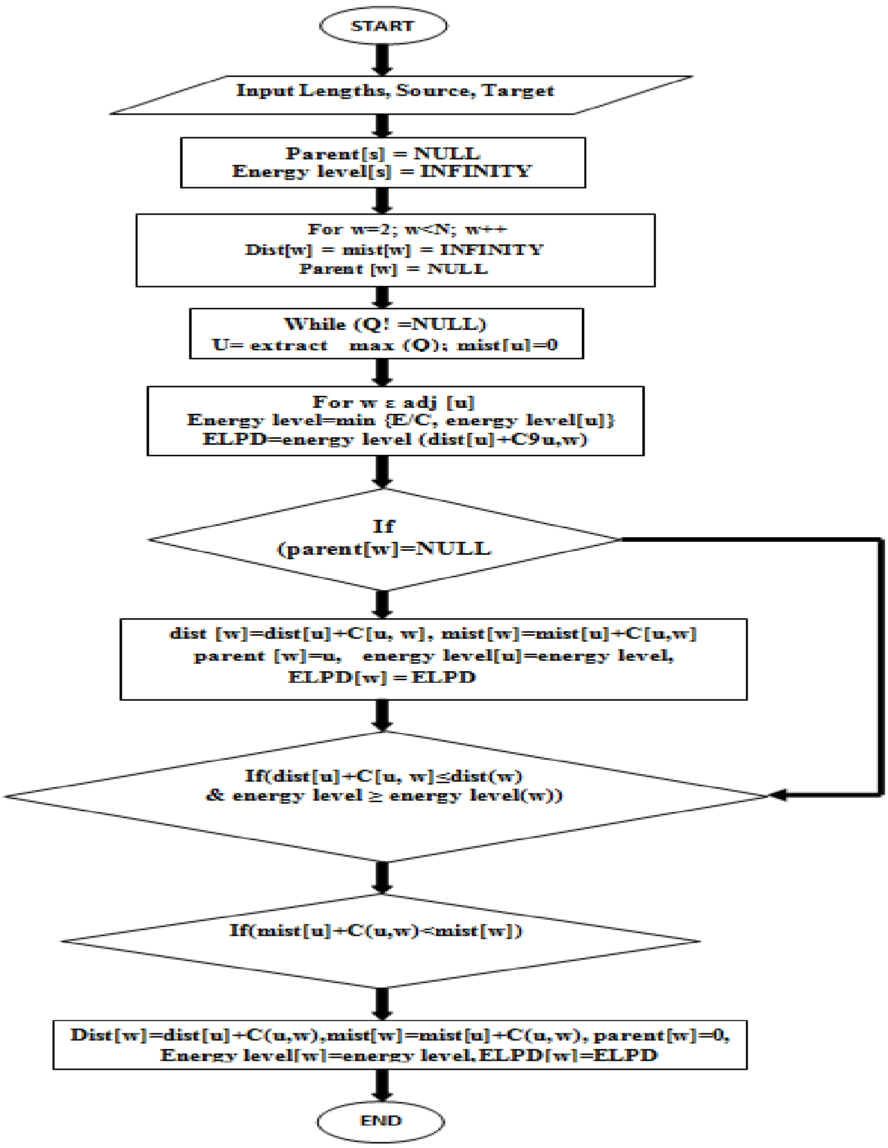


Figure 6.4 Work flow diagram of designed LBR protocol [391]

Figure 6.4 shows the work flow diagram of the LBR protocol. The designed routing algorithm is simulated by help of MATLAB software to determine the routing pathway amongst the deployed nodes in the network.

In the next phase of the thesis work, the clustering process has been given focus while positioning of the cluster heads in the network during transmission of the data. LEACH protocol is one of the most proclaimed clustering protocols of the wireless sensor network which has been utilized in this work for formation of clusters in the network [8].

6.3 LEACH: The Protocol for Clustering

LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol was initially proposed by Heinzelmann et.al in 2000 to elect the cluster heads by random rotation at every round of data transmission based on clustering process [8]. This clustering approach of rotating the cluster heads at every round of data transmission helps to distribute the load amongst the deployed nodes in the network to prevent early node death. It was found in literature that the clustering approach adopted in LEACH algorithm helped to save almost 1/8th of the energy during data transmission and reception in wireless sensor network. The concept of random rotation of cluster heads also helped to eliminate the problems of energy dissipation of the network and extend lifetime of the network. The steps of LEACH algorithm has been discussed below [219]:

- Step 1 (Advertisement Phase)

In the initial phase when the cluster formation has just started, each of the deployed nodes in the network is all candidates of becoming cluster head of the network. The nodes choose a random number between 0 and 1 and if this value is lower than the threshold value calculated by Equation 6.4, then that particular node is allowed to become the cluster head for that round of data transmission. The equation can be written as [219]:

$$ET(n) = \begin{cases} \frac{P}{1-P*(r mod \frac{1}{P})} & if n \epsilon G \\ 0 & otherwise \end{cases} \quad (6.4)$$

For this application, the desired percentage of cluster heads in a certain round of data transmission is denoted by P. To equally share the loads amongst all the nodes in the network, the equation takes care of the fact that the nodes that have become cluster heads in a certain round cannot become cluster heads for next 1/P rounds. The non-cluster head nodes become a part of every cluster and it receives the signal from all the cluster head nodes to decide to which cluster it wants to belong during a certain round of data transmission.

- Step 2 (Cluster Set-Up Phase)

After all the deployed nodes in the network have been associated with one or the other cluster, the cluster members send their data to the sink node via the dedicated cluster head.

- Step 3 (Schedule Creation)

After the clusters have been set up, a schedule for data transmission through the cluster heads is fixed that helps to reduce the chances of data collision and data loss in the network.

- Step 4 (Data Transmission)

In this step, the data sensed by the individual nodes is transmitted to the base station through the intermediate cluster heads according to the schedule pre stated by the sink node in the previous step. In this step, only the cluster members transmitting the data remain in active mode while the other nodes are kept in sleep mode to conserve their residual energy for the consecutive rounds of data transmission.

- Step 5 (Multiple Clusters)

All the clusters formed in the process of data transmission tries to transmit data simultaneously to the sink node that may lead to channel interference. To prevent data loss, the different channels are created based on residual energy of the nodes to avoid data collision and the data transmission is done through the channel with highest residual energy.

- Step 6 (Hierarchical Clustering)

The data transmission from the cluster members to the sink node is done through hierarchical clustering approach when the sink node is far placed. The designed cluster heads chooses a node in the next hierarchical level in order to conserve the energy of them and forward the data to the sink node in an organised manner.

A new algorithm which aims at joint clustering and routing approach has been proposed in this work named as Residual Energy based Distributed Clustering and Routing (REDCR) algorithm. The clustering has been performed based on residual energy of the nodes through LEACH algorithm. In the next step, Cuckoo Search Algorithm has been utilised for selection of optimal number of cluster heads and their positions in the network to ensure a proper and continuous routing path from the nodes to the base station. LEACH protocol has been found to be one of the most efficient clustering algorithms that have been utilized to select the cluster head by rotation. But the positioning of the cluster heads is equally important to ensure that the cluster heads can communicate with most of the nodes in the network. These cluster heads also help to form the intermediate hops between the deployed nodes and the base station. The Cuckoo Search algorithm helps to position the cluster heads in a fashion that it helps to balance the data traffic load amongst the nodes in the network. This hybridization approach has therefore helped to attain the joint objectives of clustering and routing in the designed network.

6.4 The Proposed Integrated Residual Energy Based Distributed Clustering and Routing (REDCR) Algorithm

The newly designed REDCR algorithm utilizes two well-known soft computation techniques namely Cuckoo Search and LEACH algorithm in two phases to jointly attain the objective of efficient clustering and routing in the designed wireless network. Initially the LEACH protocol aims at selecting the cluster heads while the Cuckoo Search Algorithm helps to determine the position of the cluster heads to design an efficient routing pathway. This algorithm aims to transmit the data based on hierarchical clustering which has been described in details.

6.4.1 Principle of Working of REDCR algorithm

Figure 6.5 represents the schematic diagram for the complete working of the REDCR protocol for data exchange between the sensor nodes and base station by positioning the cluster heads in the network [394]. The cluster heads are optimally positioned in the network based on the distance between the nodes and the base station. The cluster heads in the next level of data transmission form clusters amongst themselves and they optimally choose a head node amongst themselves termed as the "super-cluster" head for data transmission through REDCR algorithm.

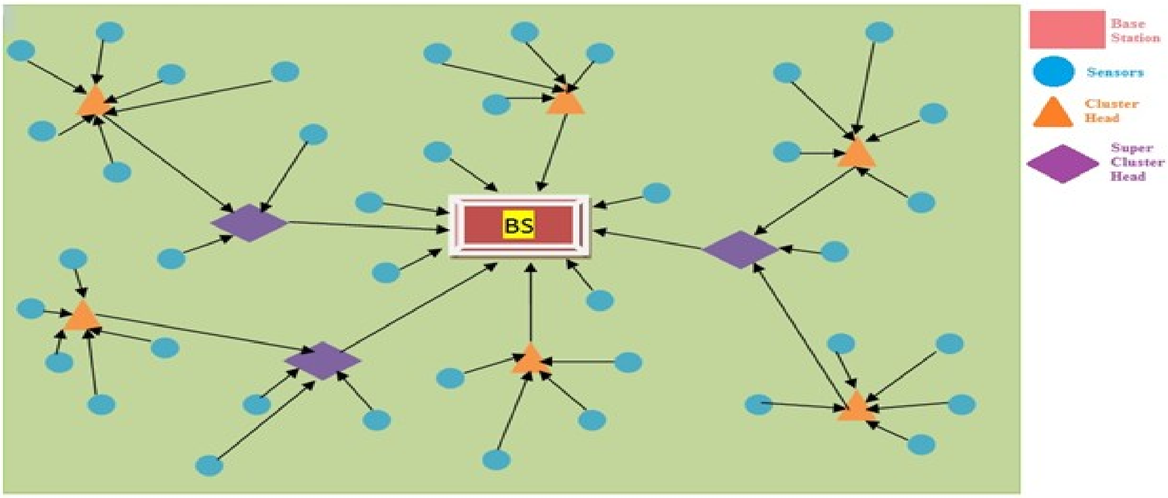


Figure 6.5 Schematic working of the REDCR algorithm

The schematic diagram represents data transmission through the proposed REDCR algorithm. The sensor nodes near the base station (BS) are seen to directly communicate their data to the base station [394]. The sensor nodes placed far away from the base station cannot communicate the data directly to the base station, it being out of the transmission range of the sensor nodes. During this scenario, they utilize their nearest cluster head to aggregate the data and forms clusters amongst themselves. This algorithm also takes care of the fact that more or less equal number of nodes is present in every cluster to balance the energy consumption amongst the cluster heads. Some nodes present in the cluster act as the "super cluster heads" (SCH) which serve as the destination of data aggregation in the next level of transmission from the cluster heads. Some super cluster heads also aggregate data from the sensor nodes scattered in the network which have not been able to become members of any clusters in the network. This approach maximizes the area of coverage of the network and ensures that no node is left out from monitoring. The roles of the nodes to act as cluster heads and super cluster heads are rotated at every round of data transmission thereby balancing the energy consumption of the nodes and improving the time of first node death. The performance of the designed REDCR algorithm related to lifetime enhancement and conservation of residual energy has been tested for two different scenarios. The first problem considers performance analysis based on variation in the number of cluster heads of the network which is pre-stated. The chosen nodes as cluster heads are placed at various positions in the network depending on the residual energy of the channels, average distance between the node and the base station and the network coverage. In the next scenario, the cluster head is chosen amongst the nodes with highest residual energy and they have been optimally placed using Cuckoo Search algorithm for analysing the performance related to the wireless network.

6.4.2 Performance Analysis of Network Lifetime through Cluster Head Variation using integrated CS-LEACH Algorithm

Initially for choosing the cluster heads in the network by LEACH algorithm, the previously stated equation in Eq. (6.4) is remodelled for this problem. The maximum number of permissible cluster heads is pre-stated in the problem and Eq. (5.14) is utilized for selecting the cluster heads in the chosen application area. The cluster head and the super cluster head selection is done by rotation at every round of data transmission by the help of the steps of LEACH algorithm stated in Section 6.2. In the next step, Cuckoo Search Algorithm is utilized to position the nodes chosen as cluster heads in the network by optimizing the fitness function designed in Eq. (5.21). Figure 6.6 represents the integrated implementation of the Cuckoo Search and LEACH algorithm for solving the current problem of the wireless sensor network.

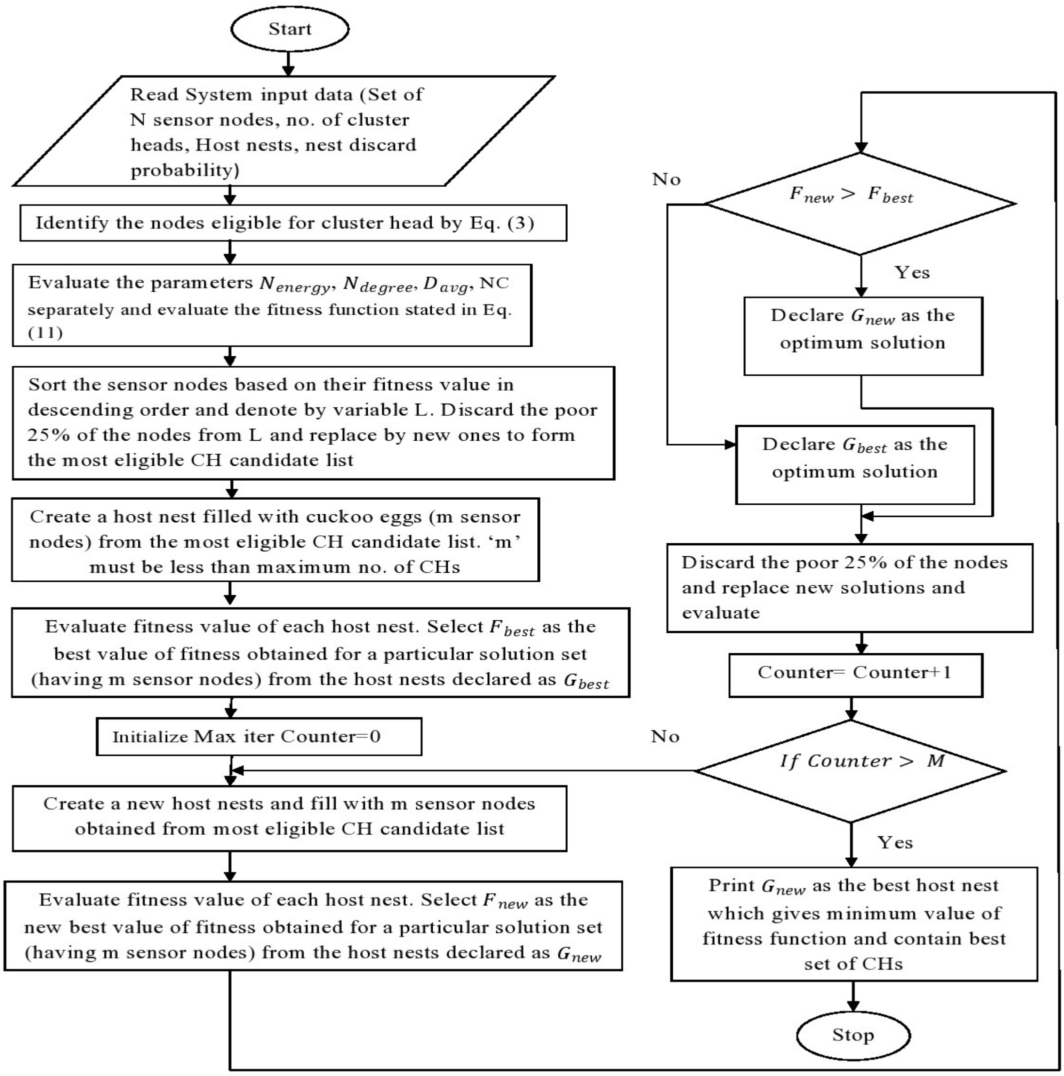


Figure 6.6 The integrated CS-LEACH algorithm for positioning of the nodes selected as cluster heads [394]

For solving of this problem, the number of nodes, *N*, has been varied from 300 to 700 while the number of cluster heads has been pre specified to be 5% or 10% of the total number of sensor nodes for different case studies. The number of rounds of data transmission has been chosen to be 5000 in order to calculate the energy consumption of the network and the results have been compared for variation in number of cluster heads. The obtained results have been compared with other existing conditions keeping the input parameters same [28]. For the cluster head selection part by LEACH algorithm, *P* is the desired percentage of cluster heads in a certain round of data transmission whose value has been taken as 0.1 while value of m_c varies from 0.05 to 0.1. For the cluster head positioning through Cuckoo Search optimization, the number of host nests has been chosen to be 50 while the nest discard probability is taken as 0.25 for the best case result [389]. The entire in house programming has been developed in MATLAB 13 platform [387]. The simulation results obtained for different scenarios which are created by changing the placement of the base station, for varied number of nodes in the network and by variation in the number of cluster heads in the network has been presented with detailed analysis in Chapter 8. The comparative results with other algorithms presented help to present the superiority of the proposed approach in comparison to the works in literature.

The REDCR algorithm has been implemented in the second scenario to choose the nodes based on residual energy of the nodes and optimize the number and position of the cluster heads in every round of data transmission.

6.4.3 Application of REDCR algorithm in Positioning of Elected Cluster Heads based on their Residual Energy

The working of the REDCR algorithm to jointly attain the objective of efficient clustering and routing in the wireless network has been divided into two phases in this work through designing of novel equations. In the first step, the concept of rotation of cluster heads in the network has been aimed through a remodelled equation. The original equation of stated in eq. (6.4) has been modified to design the equations stated in Eq. (5.12) and (5.13) to select the cluster heads in the network based on the residual energy of the nodes in every round of data transmission through LEACH algorithm. The fitness function designed in Eq. (5.20) based on optimal number of hops between sensor nodes and sink node, the number of nodes in a cluster, the residual energy of the nodes, the distance between the sensor and base station and the maximum network coverage is solved using Cuckoo Search algorithm in the second phase of the REDCR algorithm. The application of REDCR algorithm through the proposed approach has helped to design reliable communication architecture for the wireless network through efficient clustering and routing in the network. Figure 6.7 depicts the entire flowchart to optimally choose the number and position of the cluster heads in the network through the implemented Cuckoo Search algorithm. The steps of implementation of the cuckoo search algorithm in the current engineering problem have been shown in details in the flowchart. For the simulation purpose, initially the number of nodes has been considered to be 100 in the network. The number of iterations has been chosen to be 50 for all the chosen scenarios and the obtained results have been compared with existing algorithms.

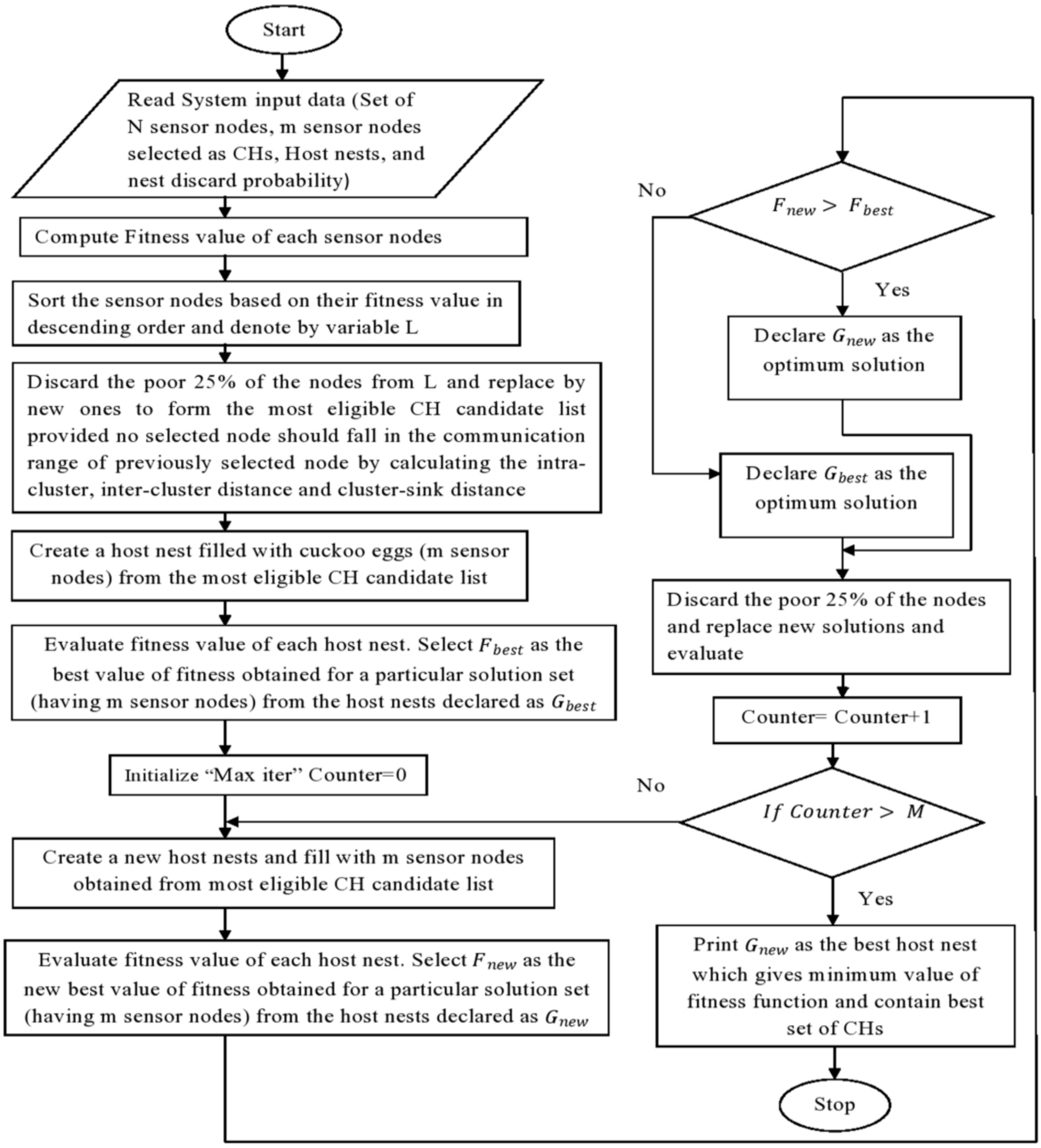


Figure 6.7 Implementation of REDCR algorithm in joint clustering and routing problem of WSN

An in house program has been designed in MATLAB software to optimize the designed mathematical formulations by Cuckoo Search algorithm and LEACH algorithm. The combination of the LEACH and Cuckoo Search algorithm gives a complete shape to the proposed Residual Energy based Distributed Clustering and Routing (REDCR) protocol. The results related to Network lifetime, network stability, network scalability and amount of energy consumption for different case studies has been presented with detailed analysis in Chapter 8.

The ease of utilization of the meta-heuristic algorithms in the different problems related to the wireless network prompted to design a Cuckoo Search based home energy management scheme to minimize the cost of electricity bills amongst the low demand customers.

6.5 Cuckoo Search based Home Energy Management Scheme

The proposed home energy management scheme aims at scheduling the various appliances in a household throughout the day based on the tariff scheme at various times during the day. The implemented Cuckoo Search algorithm aims at minimizing the cost of the electricity consumption proposed by Equation (5.34).The proposed algorithm takes care of the input constraints about the time period of operation of the appliances, the tariff structure and the maximum delay period allowed that does not hamper the comfort of the customers. The steps of the designed energy management scheme have been elaborated as follows:

Step-1: The appliances are initially allowed to randomly get switched at various time periods. The entire 24 hour of a day is divided into 48 equal time periods of half hour interval each. The status of the appliances over the considered 48 time periods are considered as the initial nests while the designed objective is to attain demand side management through proper scheduling of these appliances. In the first step of the designed energy management scheme, the appliances are randomly switched on at the various time periods. The status of the appliances through the designed objective function in Eq. (5.34) helped to calculate the electricity cost subject to the appliance status and the Time of Day (ToD) tariff scheme. A bidirectional communication infrastructure between the appliances and the EMU is set up by the WSN. At each time slot initially chosen randomly, each appliance sends a request to the EMU to get switched on at that instant.

Step-2: On receipt of the starting request, the EMU checks the ToD price at that instant. If it is found to lie within the peak period, a signal is sent from the EMU to shift the working of the appliance to mid-peak period. Similarly, the EMU requests the appliance to shift its working to off-peak period if the request is sent during the off-peak period. If the time instant is found to lie within the off peak period, the appliance is immediately turned or else the algorithm moves to the next step to shift the appliance operation.

Step-3: Depending on the tariff structure, the EMU suggests a time to switch on the device. This introduces a delay d_i during shifting of the appliances which is equal to the difference of the scheduled time suggested by EMU and the start time requested by the appliance. For this considered problem, it has been assumed that the EMU generates a shifting delay for the appliances based on Poisson distribution function [21]. During the peak period, the interval between the switching requests of the appliances is considered to be a negative exponential distribution with a mean of 4 time periods and for mid peak period the mean is taken to be 2 time periods.

Step-4: A maximum waiting time D_{max} (=2hours or 4 time periods) is initially given as input to the energy management scheme taking care of the customer's since customers are never satisfied with large delays. If $d_i \geq D_{max}$ then the EMU directs the appliance to start immediately without taking care of the tariff or else the algorithm moves onto the next step.

Step-5: If $d_i < D_{max}$, a request is sent from the EMU to the appliances to get shifted to a certain hour where the electricity prices are low compared to the current tariff of that hour. The customer comfort zone of time periods acts as the constraint in this step of the algorithm. It is checked if the suggested time period of operation by the EMU lies within the customer specified time periods, then only the appliance operation is shifted or else the appliance is turned on at the last cycle of specified usage interval.

Step-6: The total energy consumption due to operation of the appliances at a certain time period is calculated. If the total energy consumption from all the appliances is found to be less than the pre-stated maximum energy consumption, E_{max} for a certain cycle, then only the appliance operation is shifted to that period. For this problem, E_{max} is specified to be 2kWh. If this condition is not satisfied, the algorithm is sent back to Step 3.

Step-7: The appliance cycle duration for each appliance is given as input at the initiation of the algorithm designed for the EMU. The consecutive time periods after the suggested time period by the EMU for completion of an appliance cycle are switched to '1'. If another time period suggested by the EMU for the same appliance lies within its one cycle, the suggested time period is discarded and the algorithm is sent back to Step-3 of the algorithm to propose a new hour of operation.

Step-8: The maximum number of times an appliance needs to be switched during the course of the entire day is specified at input and the algorithm checks at this step if the condition is satisfied. If not, then steps 2 to 7 are once again repeated to newly state hours of operation for each appliance so that devices are switched on for the pre-mentioned number of times.

Step-9: Initially 50 set of possible solutions are randomly considered consisting of the statuses of the appliances over the 48 hours. The cost of the energy incurred through the possible appliance statuses are calculated for all the possible 50 solutions and a nest discard probability of 0.25 helps to reject the set of poor solutions incurring high costs. The new possible solution sets are readjusted through Cuckoo Search algorithm and the next set of solutions replaces the poor solutions. The entire algorithm is run for 50 iterations to find out the optimal appliance schedule for which the electrical energy cost is minimal.

The appliance schedule for which the energy cost obtained is minimum, satisfying all the boundary conditions, is considered as the best operation scheme and the EMU instructs the customer to schedule the appliance accordingly. The difference in the cost incurred between the initial random operation of the appliances and the operation cycle suggested by the EMU through a CS based home energy management helps to calculate the economic benefits for the customer. The profits obtained through minimization of the energy cost through this Cuckoo Search based Energy Management Algorithm is added to the profit earned through selling of generated power from the rooftop solar panel to calculate the economic cost benefits and payback period related to solar rooftop installation. An in-house program has been designed based on the following algorithm in the MATLAB software [41]. The simulation results presented in Chapter 8 based on this residential energy scheme depicts the appliance shifting, reduction in peak load and minimization of energy cost for one household. The projection of the size of the rooftop solar installation is also performed to enhance the annual profit with low payback periods for low demand prosumers.

The verification of the results obtained through the simulation of the soft computing techniques can be best done through physical implementation of the wireless nodes in real time applications. The wireless nodes have been implemented in the Power Engineering

Department of Jadavpur University has been done to monitor data from different sensors placed at various positions of the department. The packet delivery ratio subject to the original implementation of the wireless nodes has been tested and compared with the results obtained through the soft computation implication of Section 6.1.2. The next chapter therefore deals with the hardware descriptions of the wireless kits that have been utilized to monitor the data and packet delivery ratio in the network. The details of the deployment area and the position of the nodes in the area have also been presented in details to understand the position of the routers in network obtained through C-CSA algorithm. The electrical circuitries employed for monitoring of the data from the different power supplying sources have also been discussed. The physical positioning of the nodes also has helped to study the transmission pathways established through the considered routing protocols. The next chapter also presents the reader with the input conditions considered for efficient design of CS based home energy management scheme in the EMU for efficient shifting of the appliances. An overview of all the hardware set up and input parameters would help to give a clearer picture about the results obtained through these soft computation implementations.

Chapter 7

The Hardware Implementation and the Proposed Network Design

This chapter presents a complete description of the wireless kits utilized for data collection and performance monitoring in the designed wireless sensor network. The physical implementation of the wireless nodes has been thought of in the Power Engineering Department of Jadavpur University Saltlake Campus, Kolkata (22.5733^{0}N, 88.4137^{0}E) to verify the results related to packet delivery ratio obtained through simulations. The data transmission pathway developed through physical node deployments are also tested through application of the two routing protocols in the same network area. Apart from this, the other instruments utilized in data collection and the corresponding circuit diagrams related to data collection from the AC conventional sources, solar panel and wind generator have been discussed. This chapter also presents the entire network design for placement of the sensor nodes throughout the application area to measure data from different sections of the area. The input operational details of the appliances depending upon the customer's choice and the time of day (ToD) tariff scheme applied throughout the day has also been presented in this chapter to understand the participation conditions of the designed home energy management scheme in the EMU.

7.1 The Implemented Hardware Kits for Network Design

Hardware implementations have been done in this work to develop a model set up for measurement of power data from conventional source and non conventional sources simultaneously. The performance of the network related to packet delivery ratio has also been studied through physical placement of the wireless nodes to validate the result obtained through simulation in MATLAB. In order to design a model wireless network that functions for both data collection and network performance monitoring, two kinds of wireless sensor kits have been implemented.

7.1.1 Wireless Sensor Kit involved with Data Collection

The data collection operation from the various deployed sensors has been performed by the wireless sensor kit provided by Sensenuts Pvt. Ltd [395]. This wireless kit is very user friendly since it allows easy access of the various ports of the wireless sensor board. The library for writing the programs in the Sensenuts platform is easy to understand for the amateur students and can be easily modified according to the type of application where it is being used. The provided wireless sensor kits are supplied with power through a 12V DC adapter. Back-up power sources in form batteries are provided with the kits to enable continuous working of the nodes even in case of power failure. The provided wireless kits by Sensenuts Pvt. Ltd [395] have been shown in Figure 7.1.

Figure 7.1 Wireless sensor kit used for data collection [395]

The microcontroller JN5168 is the primary component of the wireless sensor kit that controls the working of the other accessories of the wireless kit. The maximum acceptable voltage of the microcontroller is 2.56V and hence for all the applications the voltage to be fed to the kit needs to be stepped down to this acceptable limit. The voltage given to the kit is scaled down to a voltage of 3.3 volts to power the microcontroller. The detailed pin configuration of the microcontroller used in the WSN kit is shown in Figure 7.2.

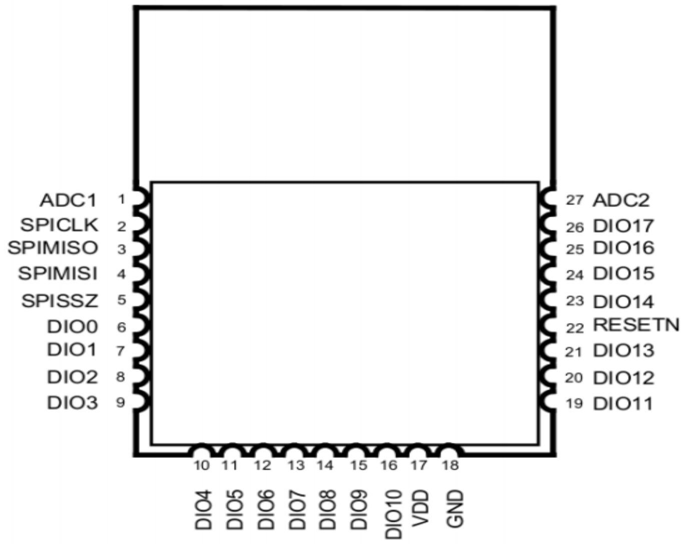


Figure 7.2 JN5168 microcontroller for the WSN kit [395]

The low power consuming microcontroller is provided with a 256kb flash memory and a 32kB RAM with an additional 4KB EEPROM for processing of the collected data. A 32 bit RISC processor is associated with the microcontroller that helps in high coding efficiency and programmable clock speeds. The microcontroller is also provided with a 128bit AES security processor that helps in secure data handling [395]. The microcontroller is interfaced with the other peripherals of the wireless kit like RF module, USB module, LCD module, ADC ports, programming connectors, test LEDs, relay drivers etc. The wireless sensor kit is provided with a transceiver unit that follows IEEE 802.15.4 protocol which works on 2.4 GHz frequency channel. The different ports of the microcontroller allow connection of different analog and digital peripheral devices with the microcontroller that enable data collection from different applications by the wireless sensor kit. These devices can be operated in both low power and high power mode. In the low power mode, the devices can transmit upto an ideal distance of 30metre in indoor environment while in the high power mode the devices can transmit upto 90metres in indoor environment. This dual mode operation makes it ideal to be used for Smart Energy Home Automation according to the need of the application.

The whole WSN board is provided with different junction terminals that support various external components to be interfaced with the board. The different junctions provided with the wireless kit and their specific interfacing functions have been enlisted in Table 7.1.

Table 7.1 Components connected to the different junctions of the Sensenuts WSN board [395]

SL. No.	Junctions	Components Connected
1	J1,J2	Mapped to the pins of Microcontroller
2	J3	ADC2
3	J4	ADC1
4	J5	UART1
5	J6,J17	LCD Port
6	J8	Programmer Port
7	J9	External Pull-up resistor for µC Pin 14
8	J10	Jumper to switch between LED and Capacitor on Pin 14
9	J11	9V Adapter socket
0	J12	3.3V output
11	J14	9V output
12	J16	Jumper for LED connected on Pin 15

Out of the different junctions provided in the microcontroller kit, the two ADCs and the Universal Asynchronous Receiver Transmitter (UART) are associated with the most important functions of data collection and data transmission in the wireless sensor node. The software coding developed to programme the different kits is fed into the wireless kit by help of the programmer through junction J5. The LED connected at J16 continuously blinks till the program is burned onto the WSN kit. The two 4 channel ADCs are connected at junctions J3 and J4 to interface the several I/O devices with the wireless network circuit. The output terminals of the different sensors are connected with the ADC terminals and these sensors are calibrated, in the scale of 2.56V acceptable by the microcontroller, in the Human User Interface software to display the original values measured by the sensors. There are mainly 3 pins with each junction port associated to ADC port. The configuration of the ADC module is shown in Table 7.2.

Table 7.2 Pin configuration of ADC of the WSN kit [395]

Pin No.	Connections
Pin 1	V_{cc}
Pin 2	G_{nd}
Pin 3	ADC

In J5 a Universal Asynchronous Receiver Transmitter (UART) is interfaced which has been used for the serial communication between the output and the WSN kit. There are four pins in the junction for making the connection and the various pin configurations for it is described below in the Table 7.3.

Table 7.3 Pin configuration of UART of the WSN kit [395]

Pin No.	Connections
1	Vcc
2	Gnd
3	UART Rx
4	UART Tx

A variety of sensors and transducers simultaneously collect data from the conventional and solar power sources through the ADC terminal. The data collected from the different sensors by this wireless kit needs to be efficiently transferred to the control station for real time monitoring by the UART terminal. A different set of wireless kit is next installed to monitor the network performance related to packet delivery ratio in the designed wireless network.

7.1.2 Description of the Wireless Kit Monitoring the Network Performance

The wireless sensor kit involved with monitoring of the network performance has been provided by PervCom Pvt. Ltd [396**]** which has been depicted in Figure 7.3. This kit enables proper tracking of the data being delivered and evaluates if all the transmitted packets are received at the control station. Missing of any data packet may result in fatal conditions of the application being monitored.

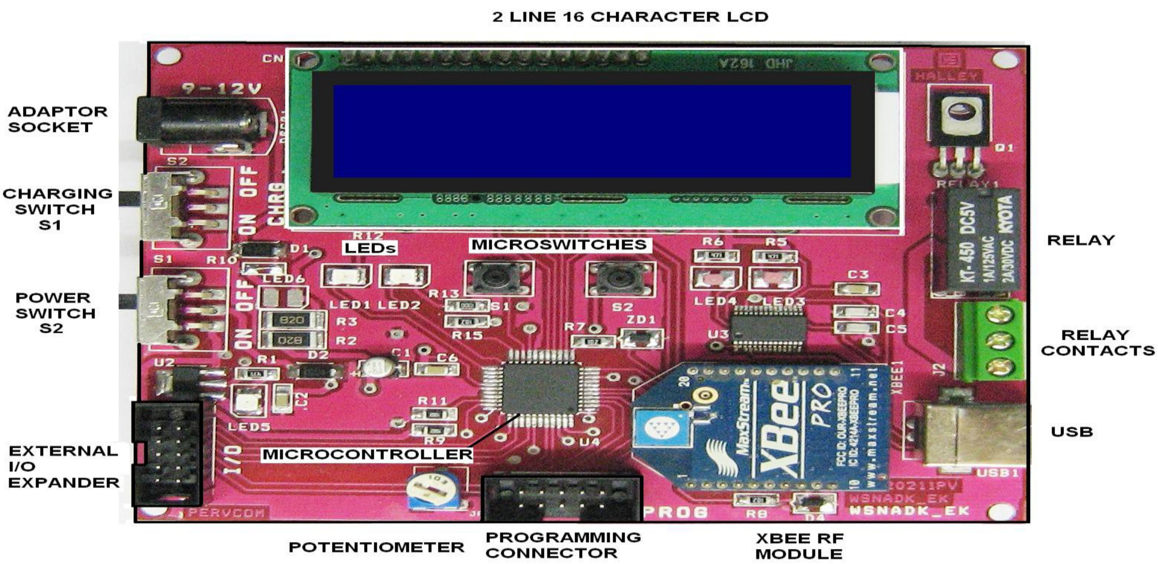


Figure 7.3 Wireless sensor kit involved with performance monitoring [396]

ATMEGA324PA is the 44 pin microcontroller that forms the central controlling unit. This microcontroller is a microcontroller of the AVR family and is one of the most compatible microcontrollers for the wireless sensor kits [396]. This microcontroller consists of a 32kb flash memory where the hex code of the program is burnt. The size of the EEPROM is 1kb and SRAM is 2kb for the installed microcontroller. A crystal clock oscillator of 16 MHz is associated with the microcontroller. The flash memory can read or write the memory upto 10000 times. The serial communication with the PC for exchange of programming and storing of data in the control station is performed by the help of USB converter IC FT232R [396]. The programmer device to store the designed program in the microcontroller is performed using a FRC cable through a virtual serial RS 232C port. The external I/O expander is used to connect these performance monitoring devices with the data collecting devices to evaluate the number of packets successfully delivered. A detailed description of the components that form a part of the wireless sensor board has been enlisted in Table 7.4. The radio transceiver associated with the wireless kit is the ZigBee module that facilitates data transmission in the wireless kit throughout the application area. The communication protocol therefore associated with these kits has been presented in details in the next subsection.

Table 7.4 Main components of PervCom WSN board [396]

Sl. No.	Components	Description
1.	ATMEGA 324PA microcontroller	A 44pin microcontroller having 32kb flash memory and additional features of 1kb EEPROM and 2kb SRAM,. This microcontroller has a clock frequency of 16MHz
2.	Alpha-numeric LED display board	2*16 LED display
3.	Chip 7805 converter	A voltage regulator that helps to maintain 2.3-5.2V i/p voltage to microcontroller from 12V i/p to board.
4.	ZIGBEE module	RF transceiver module that communicates in 2.4GHz frequency channel
5.	Charging switch S1	Helps in charging the batteries while node operation is off
6.	Power switch S2	Power supply to board
7.	FRC connector	Helps to connect the programmer for burning the program and ADC to the output analog signal
8.	ADC input	4 channel input that converts the analog signals into 7 bit digital outputs
9.	Potentiometer	Helps in varying the voltage across the 10k resistance range
10.	B-type USB port	The port through which gateway is connected to CPU
11.	Adaptor Socket	Power Supply socket from mains
12.	Micro-switches	2 micro-switches present to test proper hardware operation through LED switching
13.	LEDs	2 LEDs present to test proper I/O operation
14.	Relay and relay contacts	Used to control the low power signal

7.1.3 The Communication Module

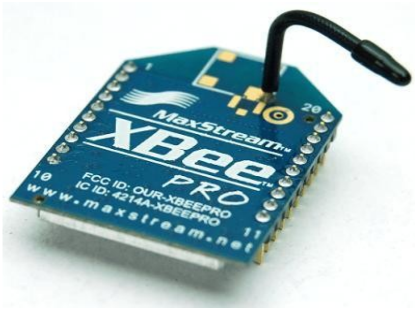


Figure 7.4 ZigBee transceiver in WSN kits [396]

ZigBee module is a very well known communication protocol that can operate in 868 MHz, 915 MHz, and 2.4 GHz frequency bands for data transmission in the network [397]. This communication module operates based on IEEE 802.15.4 standard that is ideal for low power and low range communications. The low cost, low power and easy to use features of the ZigBee module makes it suitable to be used as the transceiver in the wireless sensor modules. Figure 7.4 depicts the ZigBee module called ZigBee Pro (also known as Xbee Pro) which has been installed in the following wireless kit. The working range of this used module is ideally 30m indoors and 90m outdoors considering line of sight data communication. But due to presence of several obstacles in the path of communication and interference with radio frequency waves, the range of transmission for these modules gets reduced.

The wireless sensor kits serve as the backbone of the communication architecture to sense, process, transmit & receive data based on some well established protocols. The different electrical measurement instruments and set ups prepared also needs a brief description to give the readers an idea about how the data was collected through hardware implementation.

7.2 Data Monitoring Hardware Implementation

For the considered hardware set up, different electrical instruments have been used to simultaneously collect data from the conventional power sources and the solar panel. The two sources being different in nature in term of production of AC and DC power, different hardware circuits had to be made to accomplish the objective. The data collected by the different sources have been collected by the wireless kits interfaced with the circuit in the form of analog data. This collected data is converted into digital data for transmission in the network by the help of the Analog to Digital Converter (ADC) associated with each wireless sensor kit. The wireless kits feed the collected data into the base station where the original measured analog data is displayed according to previously made calibrations.

7.2.1 Monitoring Data from Conventional Power Supply Sources

Measurement of the voltages and current related to the present load across the conventional AC power supply sources has been done by utilizing the voltage and current transducer in the circuit. The AC voltage supplied by the conventional power source is measured by an AC voltage transducer which converts 0-220V AC supply to 0-5V DC. The wireless kits accept the voltages in DC form and hence utilization of the voltage transducer becomes necessary.

The circuit diagram for the measurement of the AC conventional supply voltage is shown as below in Figure 7.5.

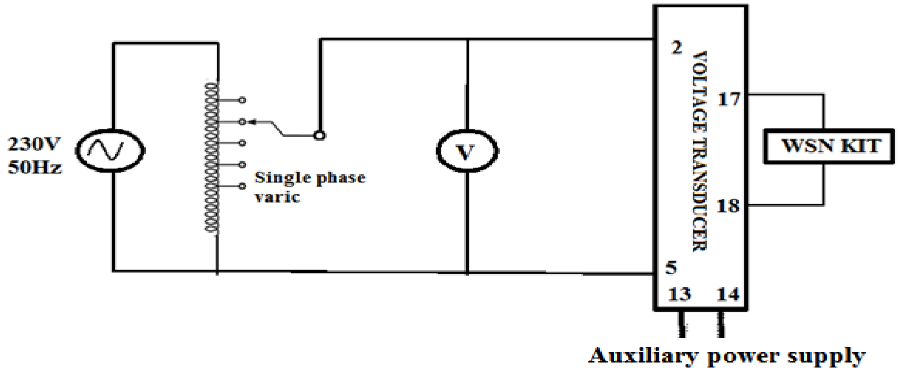


Figure 7.5 Circuit diagram for the measurement of the AC conventional supply voltage

The function of AC voltage transducer is to convert the AC voltage into DC voltage. Thereby an intermediate circuit consisting of the AC voltage transducer is required in between the AC supply and the WSN kit employed to measure the voltage. The input voltage from the conventional AC supply is given to the pins 2 and 5 of the voltage transducer through a variac. A variac is an auto transformer that helps to control the voltage input to the voltage transducer. This in turn helps to calibrate the voltage transducer being used in the control station to display the original measured voltage in the control station. The voltage transducer being a passive transducer, an auxiliary supply is needed to be given to the transducer for its operation at the terminals 13 and 14 of the transducer. The DC output from the pins 17 and 18 are of the range of 0-5V which are needed to be stepped down before being fed into the WSN kit as the maximum acceptable voltage of the WSN kit is 2.56V. This is fed to the control station where the original collected data is calculated according to a pre specified formula and then displayed in the control station. The voltmeter connected in parallel with the original AC supply helps to measure the actual AC voltage so that an analysis related to the error in measurement can be made. The circuit diagram for the measurement of the AC conventional supply current is shown in Figure 7.6 below.

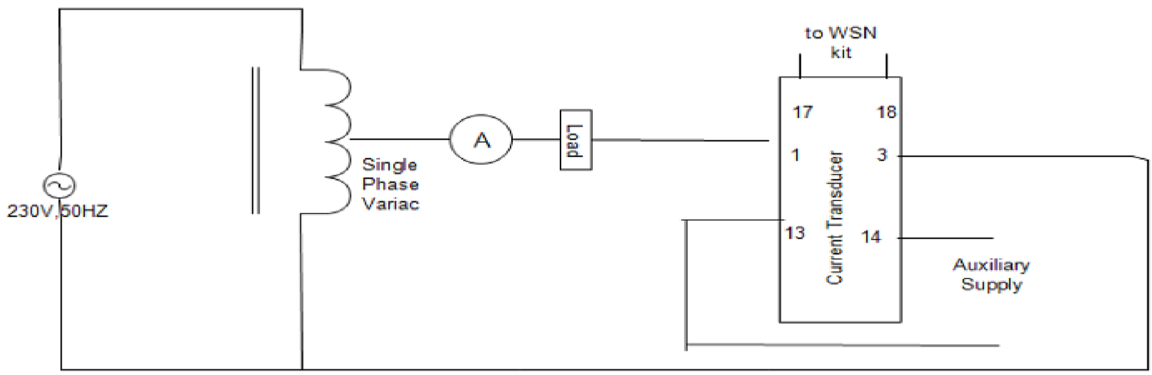


Figure 7.6 Circuit diagram for the measurement of the AC conventional supply current

Similar to the process of voltage measurement, the current obtained from the conventional AC supply is measured using the AC current transducer. The AC current transducer can measure upto 0-5A AC current and give a DC voltage output of the range of 0-5V. This circuit involving the current transducer is placed in between the original supply and the WSN kit as the WSN kits accept only DC voltages. The current transducer is placed in series in the circuit unlike the voltage transducer and hence the input to the current transducer is given through the pins 1and 13. The current transducer is also a passive transducer that requires auxiliary power for its operation and is given through the pins 13 and 14. The output of the transducer for a maximum of 5V DC is taken from the pins 17 and 18 and is stepped down to the acceptable voltage limit before being fed to the WSN kit. The variation in the testing load helps to vary the supply current in the circuit thus aiding in calibration of the transducer. The collected data in digital form is fed to the control station where the original analog data is displayed according to the pre stated calibrations. In applications where the supply AC voltage and current is high, potential transformers and current transformers are used additionally used along with the voltage and current transducer respectively to step down the inputs to the acceptable limits of the transducers.

The step down transformer (LM 2596) used to step down the transducer DC output into acceptable voltage limits of WSN kit is shown in Figure 7.7. LM2596 is the step down transformer used in this work which can take an input of 4-40V dc and steps down to give an output of 1.5-35V DC output. This is a low ripple DC converter to step down the DC voltage according to the need of the WSN kit.

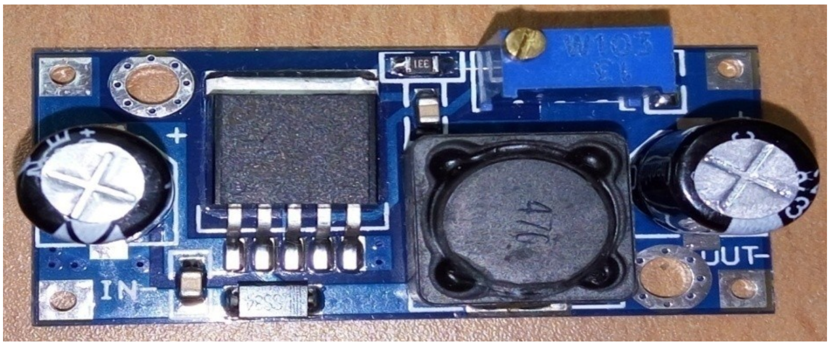


Figure 7.7 Step down transformer (LM2596) [398]

The circuit arrangements for measurement of data from the solar panels is different since the output from the solar panels is high DC voltages which needs to be handled properly before being fed into the wireless sensor kit.

7.2.2 Wireless Network Arrangement to Measure Data from Solar panels

Due to rapid depletion of the conventional power sources, currently the renewable power sources have come up as an alternative to every fields related to energy supply. Solar power is the most common resource amongst the renewable power sources that has found applications in almost every field. The solar radiations falling on the solar cells are directly converted into electrical power making its installation favourable in areas where Sun is available. In this considered application of power measurement in the university campus, the power generated from the solar panels at the roof of the building has also been measured along with the performance monitoring of the solar panels. The 3.2 KW solar panels used in this application was able to provide a maximum DC voltage output of about 80 V. However, the solar insolation received yielded a maximum output of 66V. The circuit diagram for collection of DC voltage output from the panels by WSN kit is shown below in Figure 7.7.

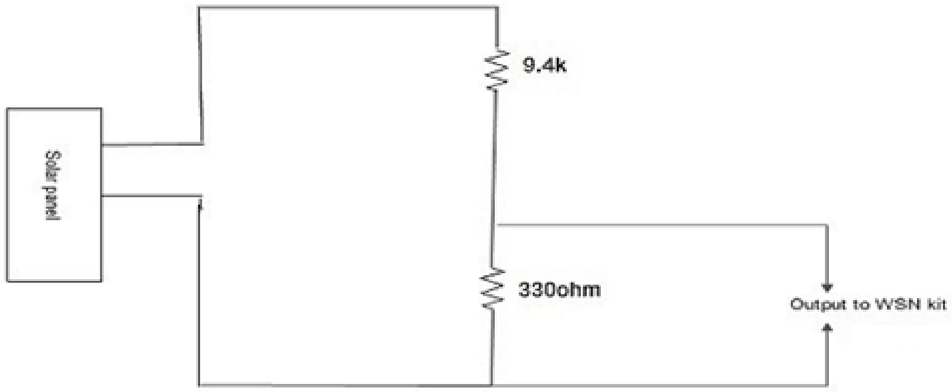


Figure 7.8 Depiction of solar voltage measurement

The DC voltage output from the solar panel is stepped down to the maximum permissible voltage limit of the microcontroller kit by the help of a designed potential divider circuit. Two resistances of values 9.4kΩ and 330Ω make up the potential divider circuit and the voltage measured across the 330Ω resistance is fed to the WSN kit. Figure 7.9 shows the physical implementation of the wireless kit to collect data from the terminals in the panel at the control station providing the solar panel voltage output.

Figure 7.9 Physical implementation of wireless kits to measure voltage

The data collected from the different sensors in the application area are stored in the control station where the DC voltage inputs to the microcontrollers are displayed. Based on the calibration data of the different sensors, the original analog value is obtained from the control station. The network map of the entire area along with the positions of the sensors and the utilized hardware kits needs a detailed overview to understand the problem related to the optimized positions of the routers through the MATLAB programming.

7.3 Network Map for Physical Placement of Hardware Kits and Performance Monitoring

The entire hardware implementation of the wireless kits to collect data and check the network performance has been done in the Department of Power Engineering, Jadavpur University, Saltlake Campus. For the considered sensor node deployment, the simulation through C-CSA is utilized to calculate the best router positions in the network based on minimal signal attenuation by the mathematical formulation in Equation (5.1). Based on the results obtained, the routers are physically placed in the suggested positions and the data delivery in real time scenario is examined. The deployed nodes in the chosen area for data monitoring has been depicted in form of a block diagram in Figure 7.10.

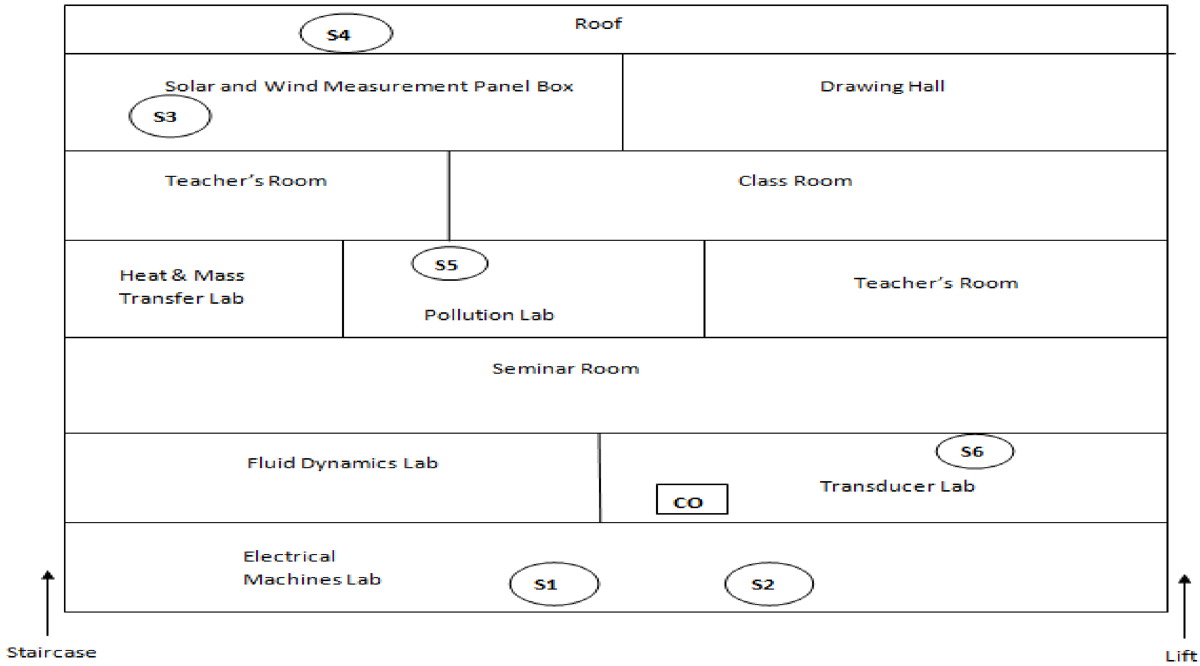


Figure 7.10 Diagram of the working area for practical router placement

For this work, the Department of Power Engineering has been considered as 2-D deployment area divided into a (15×15) unit square grid. The length and width of the building being almost same in dimension, the grid length and breadth represents the building length and height respectively. Six sensors have been deployed throughout the building to collect the power related data from different parts of the building. The co-ordinates provided to the nodes are based on the grid dimensions that have been properly scaled with the actual height and length of the building. Six sensors are responsible to collect data from different parts of the building. The original height and length has been scaled down accordingly and coordinates has been associated to individual sensor positions. The wireless sensor kits that are attached to the individual sensors are termed as tag and denoted by *S1, S2, S3, S4, S5 and S6*. These tags have been associated with co-ordinates (8,1), (10,1), (2,13), (5,15), (6,10), and (12,5) respectively. The gateway or the co-ordinator node helps to store the collected data in the control station and is denoted by C0. This node has been fixed in the transducer lab at the co-ordinate (9, 4). The tags *S3* and *S4* are associated with measuring the data from the solar panel installed at the rooftop of the building while all the other sensor nodes measure the voltage and current levels at different floors of the building. The transmission range of the building is low in case of these ZigBee based devices in the indoor environment and has been considered to be equal to 3 units for the considered grid. This low range of the devices is a constraint for ZigBee based applications but the features of a low interfering network makes it suitable to be used in indoor environment.

While performing the experiments with original hardware kits, there was a limitation related to the availability of the kits in the network. The same types of kits were programmed differently to collect, transmit and store data in the chosen monitoring network. Therefore, in a small scale testing through hardware implementation, six nodes were programmed to collect data from the various positions and one gateway node was associated with data storage in the control station. The number and position of the routers are evaluated based on minimization of the signal attenuation and accordingly planned to be planted at the obtained positions to study the network performance. Sensenuts Pvt. Ltd. provided the wireless sensor kits used here as tag, router and gateway [395]. The wireless kits provided by PervCom Pvt. Ltd were entrusted with the duties to study the network performance related to the packet delivery success ratio for the various sensor nodes employed in the network. All the sensor nodes were provided with one such kit that monitored the amount of data packets sent while one kit fixed at the base station evaluated the percentage of the data packets successfully received at the base station. The hardware implementation was done to establish authenticity of the results obtained by mathematical analysis. This would help to design hassle free wireless communication architecture for household applications involving demand side management schemes.

7.4 Participating Conditions of High Power Appliances in Home Energy Management

The entire cycle of 24 hours of appliance operation has been considered to start from 6AM on one day and the cycle completes on 6AM on the next day. This entire 24 hour duration is considered to be divided into 48 equal time periods of 30 minutes each. Based on this division, the operation cycle from 6.00 -6.30 A.M on the first day has been considered to be time period '1' while time period '48' represents the operation cycle from 5.30-6A.M on the next day. The specifications related to the power rating of the appliances and the time periods for which the appliance operates once started are enlisted in Table 7.5. The customer's choice for the time of the day when they want to run the appliance and the number of times the appliance is switched on is also given preference for this application of residential energy management which has also been displayed in the table.

Table 7.5 Operational details of the appliances

Name	Power Rating	Cycle Duration	No. of times operated in a day	Time of operation
Microwave Oven	1.34 kW	0.5hr	6	1-36
Induction Oven	1.26 kW	2hr	3	13-34
Air Conditioner / Room heater	1.19kW	1hr	6	17-48
Computer	0.4 kW	1.5hr	4	19-40

The Time of Day (ToD) tariff scheme is not yet popular in INDIA for the residential customers but the increased addition of the modern appliances to every house would result in such type of tariff scheme for different periods in the near future. The industrial sector had initially undertaken this type of tariff scheme to manage the production during different time of the day so that they are not charged with high electricity charges. Later, this tariff scheme was prevalent in the commercial sector but the day is not far away when it will be applied to the domestic sector to manage the usage of the modern appliances in the homes distributed in the entire society. The load consumption pattern mostly prevalent in the residential sector all over India has been shown in Figure 7.11 based on which the tariff structure is set.

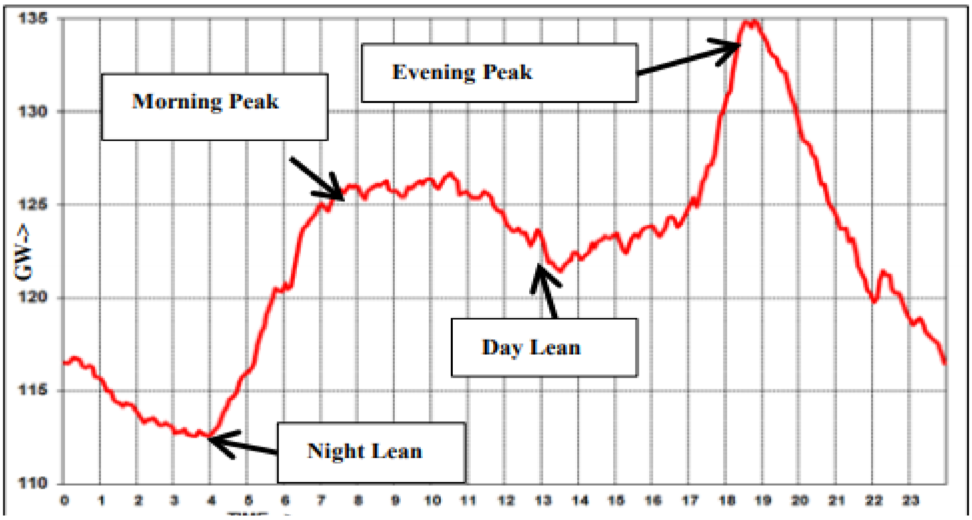


Figure 7.11 A typical all India daily load curve for residential customers [399]

For residential customers, it has been seen that the maximum load demand is between 5PM to 10PM during which most of the modern appliances such as the microwave oven, computers and air conditions are used along with other appliances such as washing machine, dishwashers, etc. Therefore, this time of the day is considered as the peak period of operation for the residential customers which corresponds to time period '8' to '20' of the designed intervals. The mid peak period of the day when the load is quite less among the residential customers is considered from 6A.M to 10A.M in the morning and 4PM to 8PM in the evening. The night time from 8PM in the evening on the 1st day to 6A.M in the morning of the next day is the time when the load is least amongst the residential customers is termed as the off peak period which is represented by the time periods 29 to 48. The ToD tariff considered for the peak period is Rs 8.73/kWh, for the mid-peak period is Rs 6.60/kWh and for the off peak period is Rs 4.97/kWh which has been depicted in Figure 7.12.

The tariffs chosen for the peak, mid peak and off peak periods are taken from Calcutta Electric Supply Corporation (CESC) tariff chart for different kinds of load based customer in the urban sector [38]. The price during the peak period is chosen as the highest price given by CESC as the energy demand is highest amongst the residential customers in this period. Accordingly, the minimum price offered by CESC has been chosen as the off peak period price while the present per unit price for the customers has been chosen as the mid peak period price. Based on the ToD tariff scheme, the designed home energy management scheme helps to shift the operation of the appliances from the periods of high power demand to periods of low power demand. Thereby, the appliances operating in peak periods are shifted to mid peak periods while the appliances operating in mid-peak periods are shifted to the low peak periods subjected to the input constraint of time period of operation. The appliance shifting based on this home energy management scheme helps to efficiently control the operation of appliances to reduce the electricity energy cost of the customers.

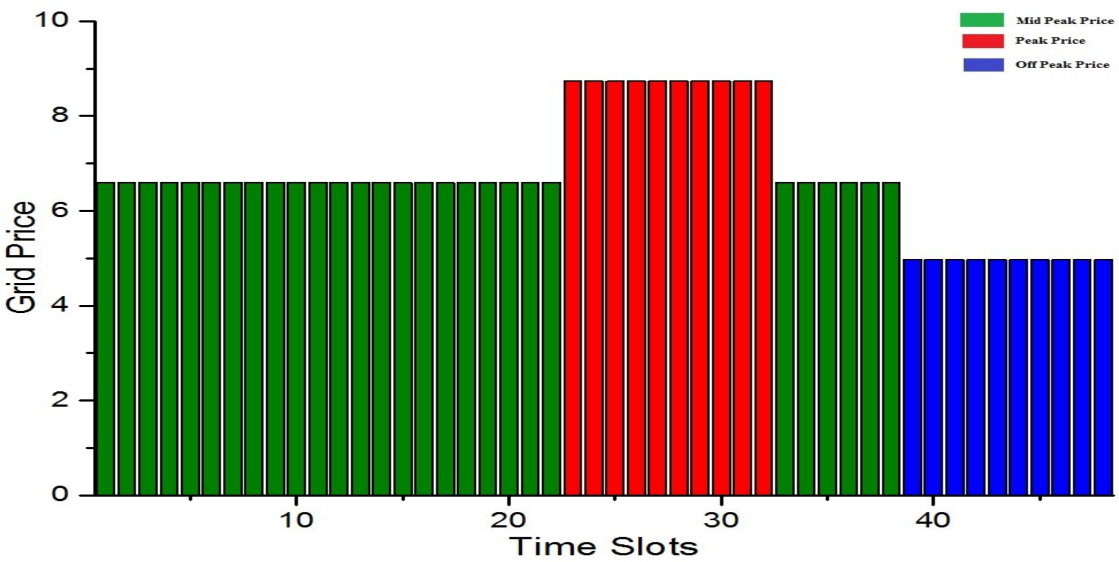


Figure 7.12 Time of Day (ToD) tariff scheme considered for residential customers [400]

The results related to the software simulations and the hardware implementation for the various considered problems of the wireless sensor network applications have been presented in the next chapter. The results related to node placement obtained through software and hardware implementations have also been compared to study the efficiency of the designed algorithm. The study of lifetime enhancement through the designed algorithm also helps to implement the wireless network in different fields. The home energy management scheme involving rooftop solar installation and wireless network as the controlling infrastructure has provided economic benefits which are presented in the next chapter as well.

Chapter 8

Results and Discussion

The results related to the various implemented soft computation techniques and hardware implementations have been depicted in this chapter. The monitored data and the different routing protocols employed to transmit data from the source to sink is visualized in the control station. The routing pathways determined through the discussed protocols have been depicted in the control station to understand the differences in the operation of the protocol. Simultaneous monitoring of the data from two different sensor nodes often leads to error in monitoring due to interference in the network. The soft computation technique based on C-CSA has helped to identify the best positions related to router placement in order to improve the performance parameters of the network. Statistical studies and comparisons with other approaches in literature have proved the efficiency of the design approach. The hardware implementation studies have further helped to verify the results obtained through the soft computation techniques. The efficiency in router placement and the comparison of the cost benefits earned through two different network topologies further helped in choosing the ideal network architecture. The improvement in network lifetime and the reduction in node energy consumption have also been studied through a newly proposed REDCR algorithm that involved both LEACH and CS algorithm. The results related to efficient selection and placement of cluster heads and also through variation in the cluster heads in the network have been analyzed in this chapter. The implementation of the wireless network as the control unit to schedule the appliances in the proposed home energy management scheme involving Cuckoo Search algorithm has helped to provide significant cost benefits as has been described in this chapter. Installation of the renewable sources in form of rooftop solar panels further adds to the economic benefits by selling of the generated energy to the traditional grid. These approaches further have helped to propose a future smart grid network scheme for monitoring of wide areas such as university campus through efficient placement of routers throughout the network. All the in house programs have been developed in MATLAB 13.0 software and the simulations have been carried out in the computer with Intel i5 3.10GHz processor and 4GB RAM. The graphical user interface (GUI) set up in the control station needs to be considered first where the real time data monitored is visualized to detect the abnormalities related to data loss due to interference or node deaths. These are first identified in the control station for taking the required measures.

8.1 Data Monitoring in Control Station and Study of Different Protocols

The control station GUI is set up using the JAVA based software where the data collected from the different sensors are displayed. Based on proper calibration in the control station, the original data is displayed after the corresponding DC value is fed into the control station. The site map is recreated in the control station and all the data monitored from the different sensors in the application area helped to give proper idea about the application data. The MAC addresses of the different nodes helped to identify the node from which data is being monitored and also the faulty nodes in the network.

8.1.1 Visualization of Data in Control Station

In a sample experimental set up, the voltage and the current transducer was utilized to collect the data related to the conventional AC voltage and AC current as shown in Figure 7.5 and Figure 7.6. The microcontroller kit accepts only upto a DC voltage of 2.56V which is fed into the control station GUI software where the respective scaling for the measured parameters is done. The scaling of the AC voltage and current transducer with respect to their corresponding DC voltage output that is fed into the WSN kit has been shown in Table 8.1. The original AC voltage input of 0-230V has been scaled with a DC voltage output of 0-2.56V which corresponds to the scaling of 1V AC input to give an output of 0.0108V DC from the transducer. Similarly, 0-2.5A AC current has been scaled with 0-2.56V DC voltage output which relates 0.1A of AC current input to give an output of 0.096V DC from the transducer.

Table 8.1 Scaling of AC voltage and current transducer

DC voltage input to WSN kit (V)	AC voltage input(V)	AC current input(A)
2.4	230	2.5
2.1	201.25	2.1875
1.8	172.5	1.875
1.5	143.75	1.5625
1.2	115	1.25
0.9	86.25	0.9375
0.6	57.5	0.625
0.3	28.75	0.3125

The DC voltage output from the transducers is fed directly to the WSN kit which stores the same value in the control station. Thereby, the control station displays the DC voltage output from the transducers in the control station along with the medium access control (MAC) address of the node involved with the collection of the data. Based on the scaling done in the control station, the actual measured value of the voltage and the current can be retrieved and displayed in the control station if the scaling formula is previously fed into the control station. Figure 8.1 shows the control station display panel that displays the DC voltage output from the transducers. The left panel of the control station displays the continuously monitored real time data as received from the packets sent continuously to the control station. The instantaneous value of the data being monitored is displayed in the latest data section while the node ID displays the MAC address of the node monitoring the sensors. In the data displayed in a certain time instant in Figure 8.1, it can be seen that the DC voltage output from voltage transducer is 2.2664063 whose equivalent AC input voltage at that instant must be 217.2V. The AC voltage measured at that instant was 218V which corresponds to an error of about 0.3%. Similarly, the DC voltage output from current transducer is 1.565625V whose equivalent AC input current is 1.63A recording an error of only 0.6% for the measured AC current. These errors can be attributed to the low resolution of the wireless kits; however it was well within the experimental limits of 2% signifying the monitoring framework to be quite an efficient one [391].

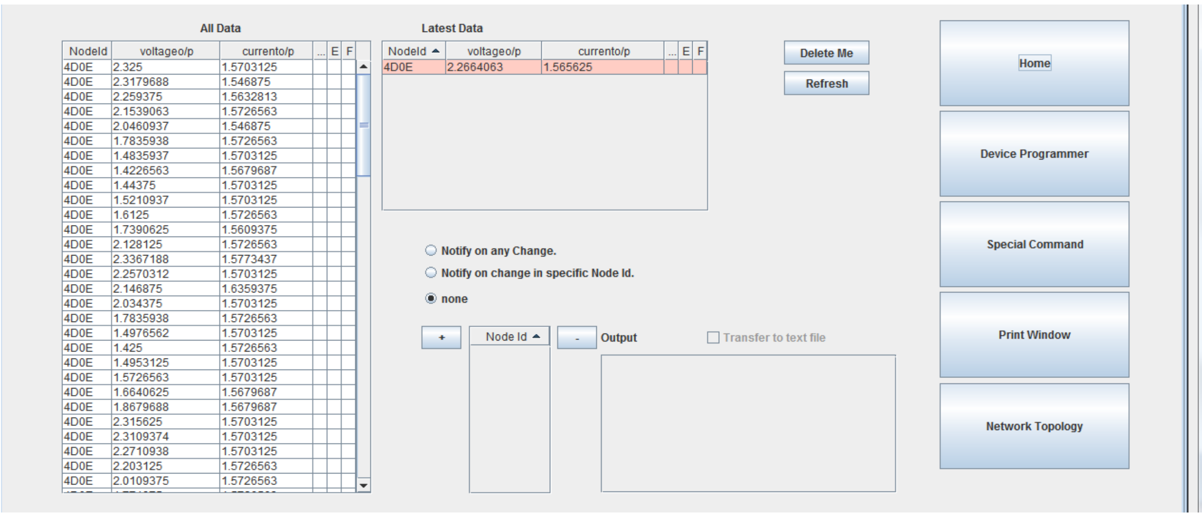


Figure 8.1 Voltage output of current and voltage transducer obtained in the control station

The control station suite also displays the different routing pathways adopted through the employed nodes based on the routing protocol implemented while transmitting the data from the tag to the control station.

8.1.2 Data Communication Architecture for Different Protocols

Based on the theoretical study of the two routing protocols namely Open Shortest Path First (OSPF) protocol and Level Based Routing (LBR), the solutions of the network pathways through the employed nodes have been depicted through red lines in Figure 8.2 and Figure 8.3 respectively. The figures depict the individual nodes MAC addresses as well as the distances between each other during physical placement of the nodes. The data has been collected by node *N1* (MAC address: 4DOE) and sent to the sink node *N5* (MAC address: 0000) once following the OSPF protocol and then following LBR protocol.

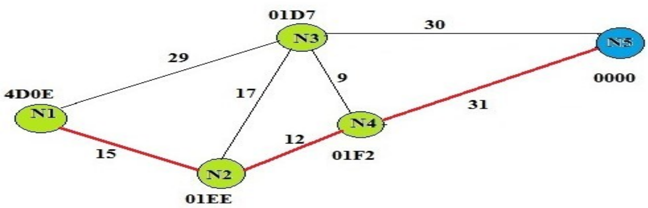


Figure 8.2 Solution of the network map using OSPF protocol

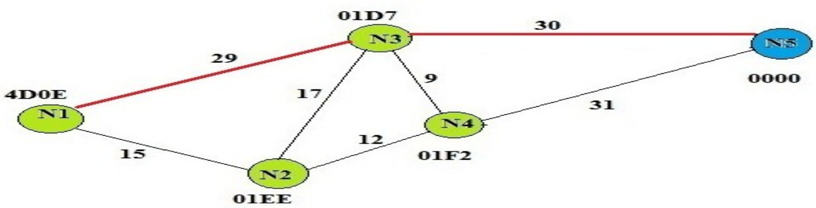


Figure 8.3 Solution of the network map using LBR protocol

The predicted network pathways through theoretical study have been tested through physical implementation of the nodes. The topologies displayed in the control station due to application of OSPF and LBR have been shown in Figure 8.4(a) and 8.4(b) respectively. These match the predicted results of Figure 8.2 and Figure 8.3. The gateway node being only one in any designed wireless network is represented by address 0000 and is placed at the top of the hierarchy of the transmission pathway. The data is collected by node *N1* (MAC address: 4D0E) from conventional AC power source was transmitted according to the pathway shown in Figure 8.4(a) following OSPF protocol and Figure 8.4(b) following LBR protocol [391].

Figure 8.4 Display of pathway: (a) using OSPF protocol; (b) LBR protocol

Table 8.2 displays the available pathways in this network for data transmission along with the total distance to be covered from the source to the sink through these pathways.

Table 8.2 Available pathways in the network [391]

Source Node	Destination Node	Available Pathways	Distance to be covered (in metres)
N1	N5	N1→N3→N5	**59 (LBR)**
N1	N5	N1→N2→N3→N5	62
N1	N5	N1→N2→N4→N5	**58 (OSPF)**
N1	N5	N1→N2→N3→N4→N5	72
N1	N5	N1→N3→N4→N5	69

It can be observed from the displayed solution pathways the pathway *N1→N2→N4→N5* is chosen using the OSPF protocol since it covers the minimum distance of 58 metres. Whenever a node in the designed pathway fails, the next shortest pathway in terms of distance is chosen for data communication. Using the LBR protocol the pathway *N1→N3→N5* is chosen since it involves transmission in three level hierarchies. It can be seen that the pathway chosen is a longer pathway of 59 metres. Both the nodes, *N3* and *N4*, are considered to be in the same level since both are connected to the sink node *N5*. But node *N3,* being closer to the sink node *N5,* has higher amount of energy and hence chosen as the next hop in the next level of transmission. Similarly, *N3* to *N1* distance is possible with a single hop, so this pathway is chosen to conserve energy. Real time applications require quick data transmission and therefore OSPF protocol is preferred in such applications to transmit distance through shorter distances. In applications where energy is limited and involves limited number of nodes to cover the entire application process, LBR protocol is preferred to involve lesser number nodes leading to huge energy savings. Multipath architectures have been preferred in case of both the protocols to allow data transmission even if one of the nodes fails. The limited transmission range of the nodes in the indoor network scenario requires implementation of intermediate nodes to form the transmission pathways.

The applications have been performed in the indoor network scenario which is subjected to interference due to signal crossovers or walls and other obstacles within the indoor area. This necessitates detection of the interference in the control station to check the error related to the data monitoring and undertake suitable control measures.

8.1.3 Interference Detection in Wireless Networks

The interference caused during simultaneous monitoring of data from two different sources has been demonstrated in Figure 8.5. The output map shows two tags indicated by *E52* and *E53* that collect data from two sources. The node *E52* is dedicated for collecting data from the solar voltage panels while the node *E53* collects data from the conventional AC source. Both the sensor nodes look to forward the data through the same transmission channel involving the router node *R2*, thereby resulting in interference. Figure 8.5 depicts a certain instant when the data monitored by tag *E53* is not measured due to interference. At this instant, the sensor node is found to become inactive while data is collected only from the other node.

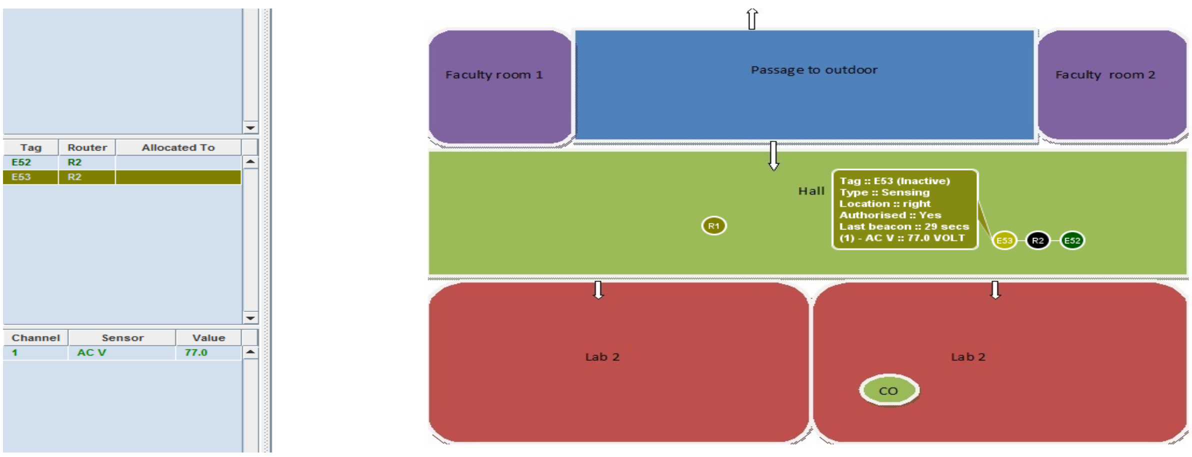


Figure 8.5 Interference detected in control station [381]

Several readings were taken during the experiment when the separate tags are associated with the measurement of AC source voltage and DC source voltage. Table 8.3 depicts the observation table showing both the actual measured voltages and displayed voltages in the control station along with the errors being calculated. A constant error of about 2-4% is found throughout which is caused due to the scaling error of the sensor kit. The low resolution of the wireless kits does not allow better scaling of the output data. As seen from the Table 8.3, in some observed values the error is found to be high in comparison to other values which can be attributed to the interference occurring in the network. The tag E52 collecting DC voltage data is found to suffer interferences in two such instants resulting in errors of 11.7% and 9.2% while *E53* collecting data from AC voltage suffers similar interferences resulting in errors as high as 14.4% and 10.6%. The data collected at these instants are not transmitted to the control station by the wireless nodes and hence cannot be visualized in the control station. Hence, large errors are observed in the output and proper control measures are needed to be taken in order to enhance the performance of the network.

Table 8.3 Observed and actual AC and DC voltages during interference [381]

Sl. No.	AC & DC Voltages					
	E52 Tag Data			E53 Tag Data		
	Actual DC voltage (V)	***Observed DC voltage (V)***	***Error (%)***	***Actual AC voltage (V)***	***Observed AC voltage (V)***	***Error (%)***
1.	7.38	7.2	2.43	60	58	3.33
2.	7.91	7.68	2.91	90	77	**14.44**
3.	9.26	8.16	**11.88**	120	115	4.16
4.	11.16	10.8	3.22	140	138	1.42
5.	14.59	14.16	2.95	180	161	**10.56**
6.	15.82	14.4	**9.09**	200	194	3

Optimized node placement based on C-CSA algorithm has been undertaken as the solution measure to improve the performance related to minimization of signal attenuation and packet error ratio.

8.2 Optimized Node Placement in Wireless Sensor Network

A newly designed optimization technique based on utilization of cuckoo search optimization in cascaded loops has been used in this work to minimize the signal attenuation in the network and then to decide the position of the routers in the network simultaneously. The router placement strategy adopted through the C-CSA technique has been then utilized to study the parameters related to the network performance. The results obtained through the proposed techniques have then been compared with the results obtained through other algorithms keeping the initial input parameters constant. The performance of the algorithm based on variation of number of nodes has also been studied in this work. Statistical study of the proposed algorithm helps to establish the efficiency of the performance of the proposed engineering optimization technique. The efficiency in the router placement obtained through the proposed technique based on coverage of the network area and minimization of the signal overlap has been tested through this designed algorithm. The cost benefits obtained through deployment of the nodes in applications of wide area monitoring have also been tested through design of wireless network based on star and mesh topology.

8.2.1 Optimization and Placement of Routers in the Network

For the considered problem, a network area has been chosen which has been represented by a grid of dimension 15×15 square unit and the range of transmission for the wireless sensor nodes has been considered to be 3 units for all the nodes. The positions of the sensors and the gateway have been previously pre-fixed in the considered simulation model. The program based on C-CSA has been made to run for 200 iterations to obtain the best case solution. Figure 8.6 represents the results related to the optimized number of routers and their positions in the chosen simulation domain. Twenty sensor nodes have been initially considered to be present in the considered network area and accordingly the positions of the routers have been determined based on the condition that each sensor must choose at least one intermediate router to forward the sensed data to the control station.

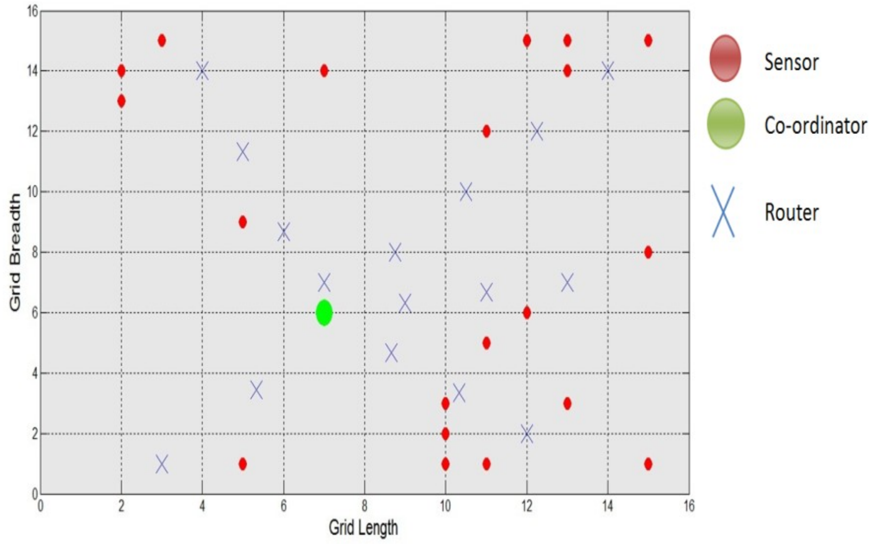


Figure 8.6 Plot of router positions in the simulated domain area [390]

Considering the primary aim of signal attenuation minimization in the network, the routers are positioned in the network well within the range of transmission of the nodes. While positioning the routers, care is taken so that no router comes within the coverage area of another router and all the sensors are well covered through router placement. The optimization curve plot for the number of routers against number of iterations has been depicted in Figure 8.7 [390]. It can be seen that the algorithm reaches to an optimized result in the 38th iteration while the optimal number of routers have been found to be 16 for the considered test case. The optimized number of routers ensures that the routers employed in the network are not more than required and not too less. If the routers were more, it would have introduced signal attenuation in the network while lesser number of routers leads to poor communication links in the network.

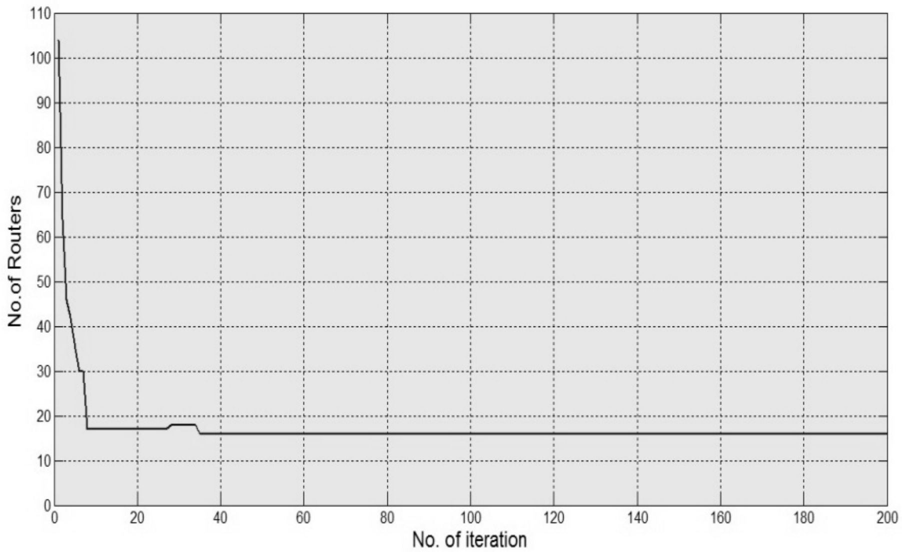


Figure 8.7 Number of routers vs number of iterations

The placement of the routers is deemed to be an efficient one if the primary objective of the reliable data delivery with minimized signal attenuation is achieved. Thereby, study of the performance of these network parameters is necessary to ensure efficiency of the cascaded approach.

8.2.2 Signal Attenuation Minimization in the Network

The proposed technique is implemented to find out an optimal solution for minimized signal attenuation based on the objective function designed in Equation (5.1) [390]. Figure 8.8 depicts the results related to signal attenuation in the network in comparison to the number of routers. It can be seen that the minimum signal attenuation level of 87.63 dB has been obtained in case of this considered simulation model for the 16 number of routers. This signal attenuation is attributed to the presence of the thick walls and other obstacles in the network along with the attenuation suffered due to presence of other electromagnetic waves in the network.

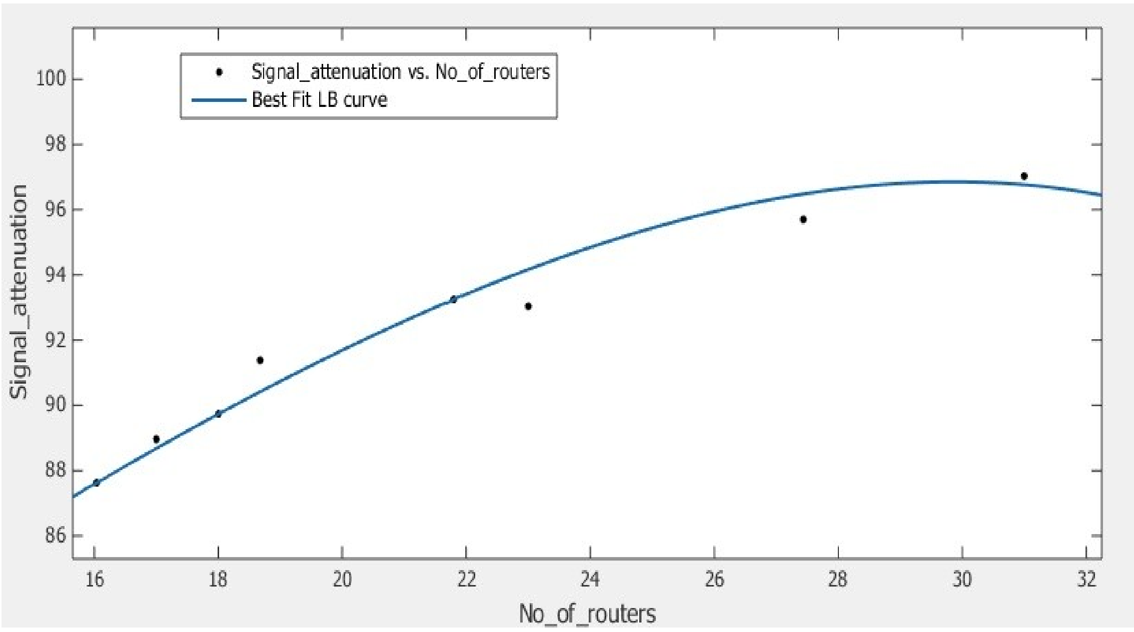


Figure 8.8 Signal attenuation vs number of routers

The other parameters, such as the energy required for each data packet transmission, signal to noise ratio (SNR) and the packet error ratio, that determine the network performance are all dependent on the signal attenuation in the network. Equations (5.4) to (5.6) are thereby evaluated based on the minimal signal attenuation value obtained to determine performance of all the other related parameters in the network.

8.2.2.1 Study of Other Performance Related Parameters

The designed objective functions have been made to run for 50 different trial modes to find out the best case results related to the optimization based on Cascaded Cuckoo Search Algorithm. The results for minimum signal attenuation, signal to noise ratio, packet error ratio and data transmission energy have been obtained for the same considered simulation domain consisting of 20 sensor nodes. The best, worst and average case results related to these parameters evaluated based on the previously designed equation have been represented in Table 8.4.

Table 8.4 Comparison of best case, worst case and average result for various parameters for 50 trial runs

Parameters	Best Case	Worst Case	Average Case	Mean	Standard Deviation
Number of routers	10	22	14	14.36	2.405
Signal Attenuation	78.8947	92.4623	84.1964	84.9102	3.3579
Signal to Noise Ratio	43.1053	29.5377	37.8036	37.101	3.3769
Energy for Data packet Transmission/ Reception (μJ)	3.36	9.17	5.01	5.34	2.235
%Packet Error Ratio	1.68	9.67	3.89	5.58	2.696

The presence of the several thick walls, metallic obstacles and the electromagnetic waves have significant effects on the signal attenuation of the network and thereby the signal attenuation has never been obtained to be zero which is the ideal case. But with decrease in number of involved routers in the network, the signal attenuation has considerably reduced. After an optimal number of solutions are achieved, it has been seen that further decrease in number of router would add to the signal attenuation since proper communication links would not be established. In the considered network architecture, care has also been taken so that the nodes can go off to sleep mode in their idle state to conserve their battery power. Elimination of signal crossover further reduces the energy consumption in the network that may have resulted due to excess data collision in the network. Thereby, minimization of the signal attenuation has helped to reduce the energy required for transmission of each data packet which is desirable for wireless data transmission. The Signal to Noise ratio (SNR) of the network determines the quality of the communication network and for all the trial runs it is found to be higher than 20dB which is necessary for a good communicating network. The Packet Error Rate (PER) of the network reduces with reduction in signal attenuation of the network since the chances of data loss reduces in case of a good communication network. For all the trial runs in this experimental set up, PER has been found to be within the experimental limits of 10% as found in previous literatures when signal attenuation is less than 100 dB [307]. However, for the 50 trial runs considering the same sensor deployment, most runs have given 14 as the optimized number of routers required to design the communicating network for this case. The signal attenuation, energy for packet transmission, SNR and PER with respect to this optimal number of routers for most cases has been found to be around 84.1964dB, 5.01μJ, 37.8036 dB and 3.89% respectively which is quite satisfactory for a communicating medium.

The values of the different network performance related parameters obtained through variation of the number of nodes from 20 to 60 in the same application area have been presented in Table 8.5. It can be seen that the number of intermediate routers required increases with increase in the number of sensors in the network. The rate of increase in the number of routers however decreases since one router is capable of collecting data from more than one sensor in the network. As the density of the sensors increases in the chosen application area, the sensors need to be very closely placed denoting that many of them may communicating through the same router. This leads to signal crossover in the network due to several sensors communicating through the same channel. This affects the SNR of the network and also leads to extra energy consumption. The signal crossover thereby increases the Packet Error Ratio of the network which is achieved to be highest in case of 60 sensors. These results establish the fact that overcrowding of the nodes in a small application area needs careful placement of nodes to keep the signal attenuation minimum.

Table 8.5 Comparison of parametric values for varied number of sensors in the area

Parameters	**20 sensors**	**30 sensors**	**40 sensors**	**50 sensors**	**60 sensors**
Number of routers	14	16	19	21	23
Signal Attenuation (dB)	84.1964	90.1892	94.9576	97.2603	99.1012
Signal to Noise Ratio (dB)	37.8036	31.8108	27.0424	24.7397	22.8988
Energy for Data packet Transmission/ Reception (in µJ)	5.01	6.26	7.09	8.30	9.59
%Packet Error Ratio	3.89	8.30	12.84	17.86	21.37

The positions of the routers obtained through this optimization technique have also helped to establish a proper framework for data communication between all the sensors and the gateway. A statistical study based on normality tests, parametric and non parametric tests for 50 independent runs of the algorithm further establishes the suitability of the proposed algorithm in the node placement problem of wireless network.

8.2.2.2 Statistical Study of Various Measured Parameters

The statistical study of the different network performance related parameters obtained through C-CSA over the 50 trial runs has been carried out using the histogram, normal probability and Quantile-Quantile (Q-Q) plots to understand the efficiency of the algorithm in terms of uniformity. The plots help to determine the fact that the rule of central tendency has been followed by execution of the algorithm through 50 independent trial runs [401]. Shapiro-Wilk test and Kolmogorov-Smirnov test are the two different normality tests that helped to determine if the values obtained follow normal distribution curve through the course of the trial runs [401].

8.2.2.2.1 Determination of Statistical Distribution over 50 trials

The most commonly used statistical plot is the histogram plot that displays the frequency of occurrence of a certain phenomenon over a course of time and estimates if the values obtained lie within a specified range [401]. Figure 8.9, 8.10 and 8.11 plot the histograms for the obtained results for the number of routers, energy required during data transmission and packet error ratio over the 50 trial runs [390]. The results of the histogram plot depict that the highest number of times the number of required routers has been obtained to be 14-16, while the maximum counts for transmission energy of each data packet and packet error ratio is obtained at 5.01µJ and 3.89% respectively. The overall histogram plots follow the rule of statistics, where the maximum data concentration is near the center and reduces towards the extreme. The values of the different parameters with maximum count are therefore chosen to be average case values obtained through optimization by C-CSA algorithm.

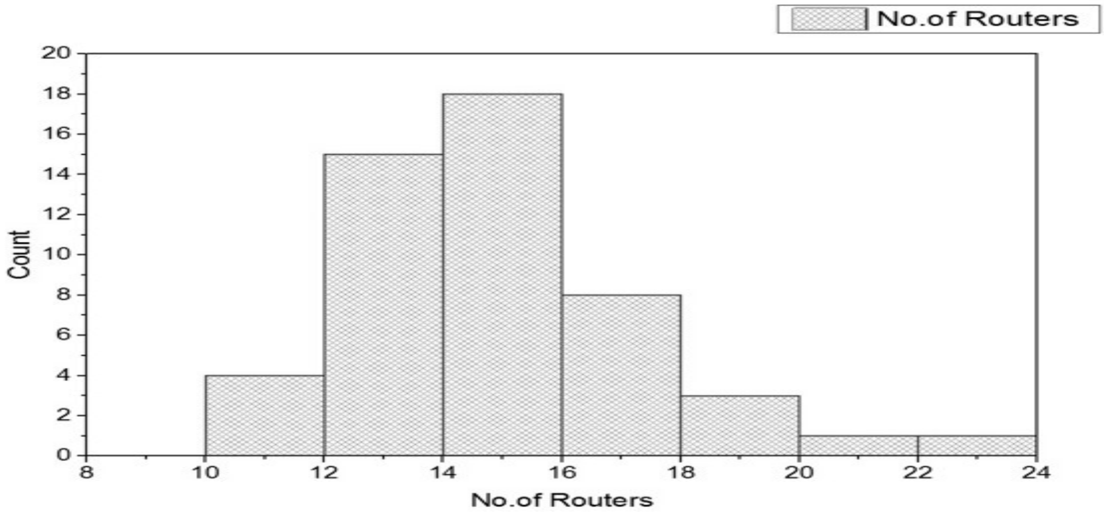


Figure 8.9 Histogram plot of number of routers

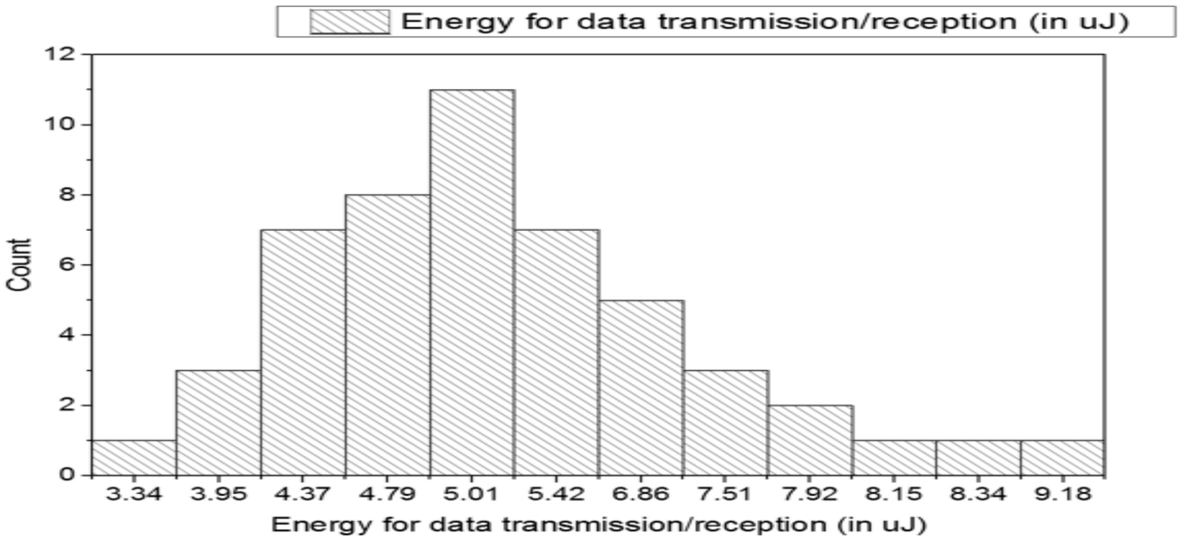


Figure 8.10 Histogram plot of energy for data transmission/reception

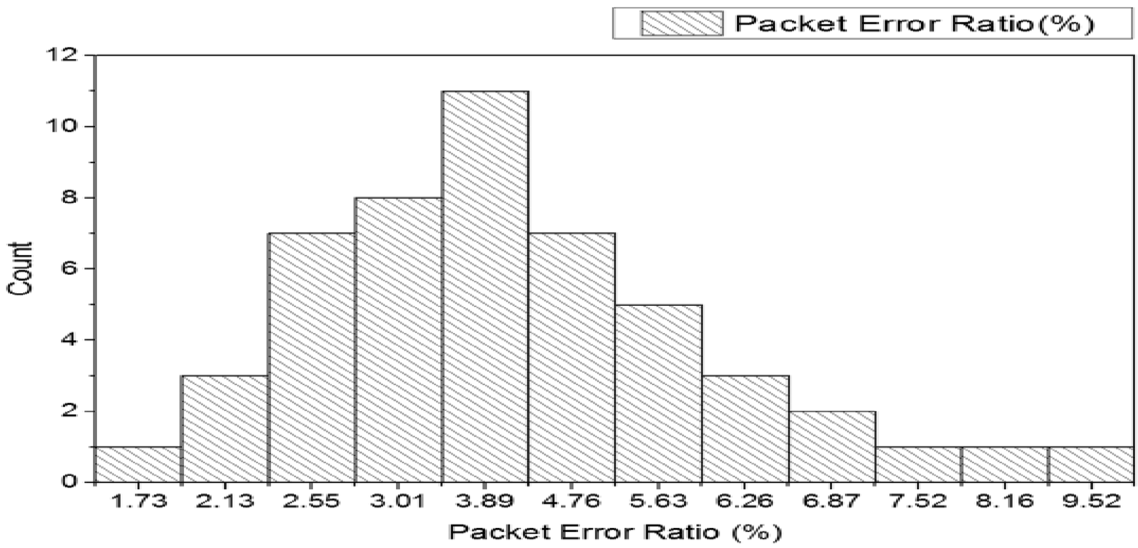


Figure 8.11 Histogram plot for packet error ratio

The Quantile-Quantile plot (Q-Q plot) is another important tool for statistical analysis that helps to plot the percentile of data obtained through C-CSA that follows the normal distribution data [401]. A 45 degree reference line is drawn through the origin of the graph with the expected normal value and the obtained values at the two axes. If the two sets of data come from the same distribution, the points roughly fall on the reference line. A Q-Q plot helps to plot the percentiles of the data with respect to the normal distribution data. The Q-Q plots for the signal attenuation and the SNR of the network has been depicted in Figure 8.12 and 8.13 respectively [390]. The mean and standard deviation for signal attenuation has been achieved to be 84.9102 dB and 3.3579 dB respectively. In case of SNR, the mean and standard deviation is found to be 37.1017 dB and 3.3769 dB respectively. It can be stated that most of the values following the central tendency have given a value close to the mean through the Q-Q plot proving the precision of the C-CSA algorithm.

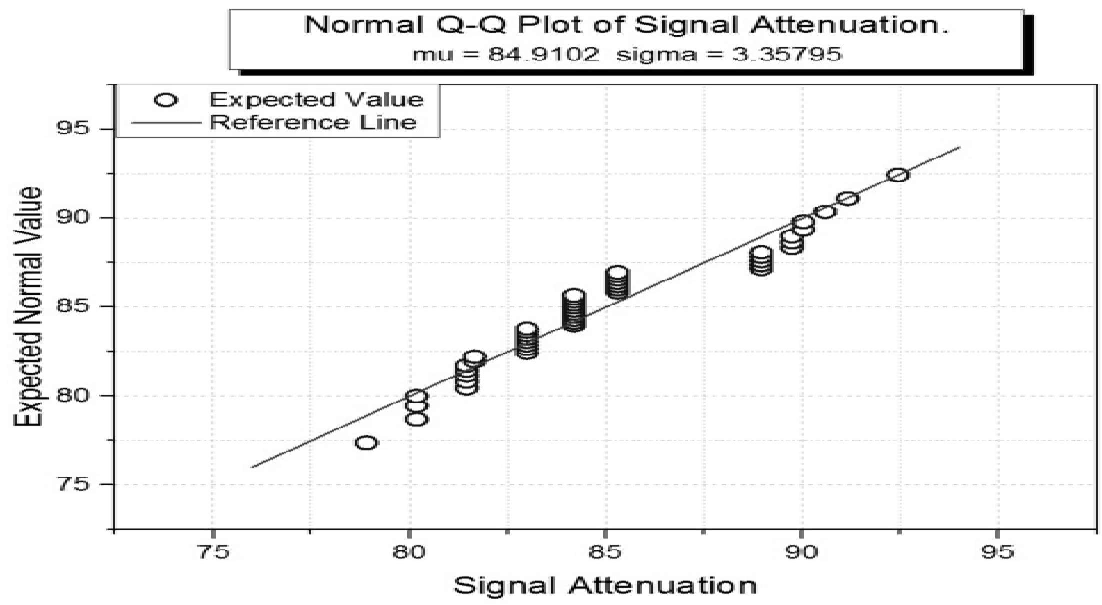


Figure 8.12 Q-Q plot for signal attenuation

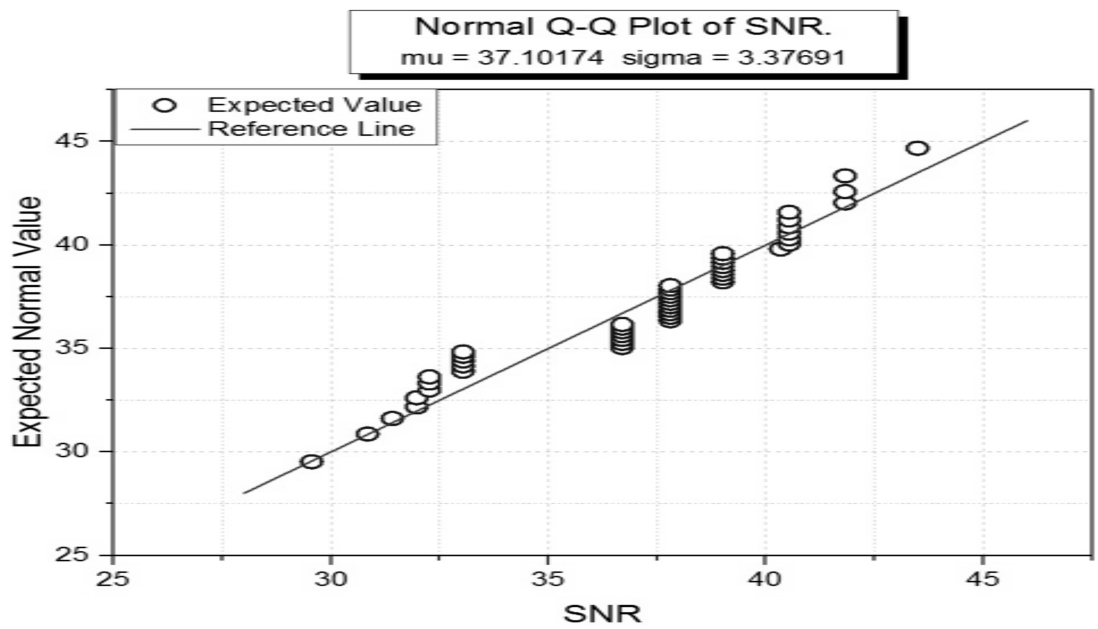


Figure 8.13 Q-Q plot for SNR

The normality tests performed for the different parameters using C-CSA help to determine if the set of output values obtained over the entire range of input values has followed any normal distribution curve.

8.2.2.2.2 Normality Tests for Different Parameters using C-CSA

To determine if the designed parameters follow any normal distribution curve, Normality tests are performed on the proposed C-CSA technique. Initially a confidence level 'α' is set to determine whether the data is normally distributed or not. Shapiro-Wilk test is one of the primary normality tests used very commonly in statistical analysis [401]. A parameter named $'p-value'$is estimated over the range of the output data set and if this value is smaller than *'α'*, then it can be said that the data is not normally distributed (Garcia et al. 2009). Another normality test known as Kolmogorov-Smirnov Goodness of Fit Test (K-S test) compares the set of output data with a known distribution and determines if the values belong to the same distribution [401]. The KS-test has the advantage that it has to make no assumptions about the distribution of data. Similar to the Shapiro-Wilk test, if the $'p-value'$obtained based on the comparison is smaller than the chosen value of *'α',* it can be said that the values have not been derived from that distribution. Table 8.6 represents the $'p-values'$ obtained from the Shapiro-Wilk test and Kolmogorov-Smirnov test individually over 50 individual runs of C-CSA [390]. The parameters that rejected normality has been represented by '*' and the values within the brackets is the $'p-value'$. For experimentation, the value of *'α'* has been considered to be 0.05 level as found in other literatures which means the results related to normality obtained over 50 trial runs can be stated with 95% confidence.

Table 8.6 'p-value' obtained by Normality tests for safe use of parametric tests using C-CSA algorithm (α=0.05)

Parameters	Shapiro-Wilk Test	Kolmogorov-Smirnov Test
Number of routers	*(0.0169)	(0.138)
Signal Attenuation	*(0.0031)	*(0.039)
Signal to Noise Ratio	*(0.0042)	*(0.043)
Energy for Data packet Transmission/ Reception	*(0.038)	(0.142)
Packet Error Ratio	*(0.0048)	*(0.044)

It can be seen that for all the parameters Shapiro-Wilk test have rejected normality while Kolmogorov-Smirnov test rejected normality in case of signal attenuation, SNR and PER. As the sample size is relatively small, Shapiro-Wilk test was found to be more suitable. The results establish the fact that the output data was entirely dependent on the input set up and the optimization technique that aided in minimization of the objective function. When the normality has been rejected through these tests, non-parametric tests were needed to be performed to compare the performance of the proposed algorithm with other existing algorithms.

8.2.3 Comparison of C-CSA with other Algorithms

The implemented C-CSA technique has helped to place the router nodes in a fashion that fulfills both the objective of efficient clustering from multiple nodes in the network as well as designs an efficient routing path from all the sensors to the gateway. To understand the superiority of the proposed technique, the results related to the different network performance parameters obtained by C-CSA have been compared with the results of available research works based on clustering and routing algorithms.

8.2.3.1 Performance Comparison for C-CSA with other Clustering Algorithms

The performance of C-CSA based on the packet error ratio in the network has been compared with few existent works in literature namely Hyper-geometric Energy Factor based Semi-Markov Prediction Mechanism, Cluster Head Selection approach for Collaborative Data Processing (CHSCDP), Hybrid Energy-Efficient Distributed clustering (HEED) and Centralized Low Energy Adaptive Clustering Hierarchy (LEACH-C) algorithms [305]. Figure 8.14 depicts the comparison results related to the percentage of packets successfully delivered considering variation in the number of nodes in the same network area. The results depict that the meta-heuristic approach involving C-CSA has provided a network design that helps in higher percentage of packets being successfully delivered in comparison to all the other existing approaches for a varied range of 10 to 100 sensors establishing the supremacy of the proposed algorithm.

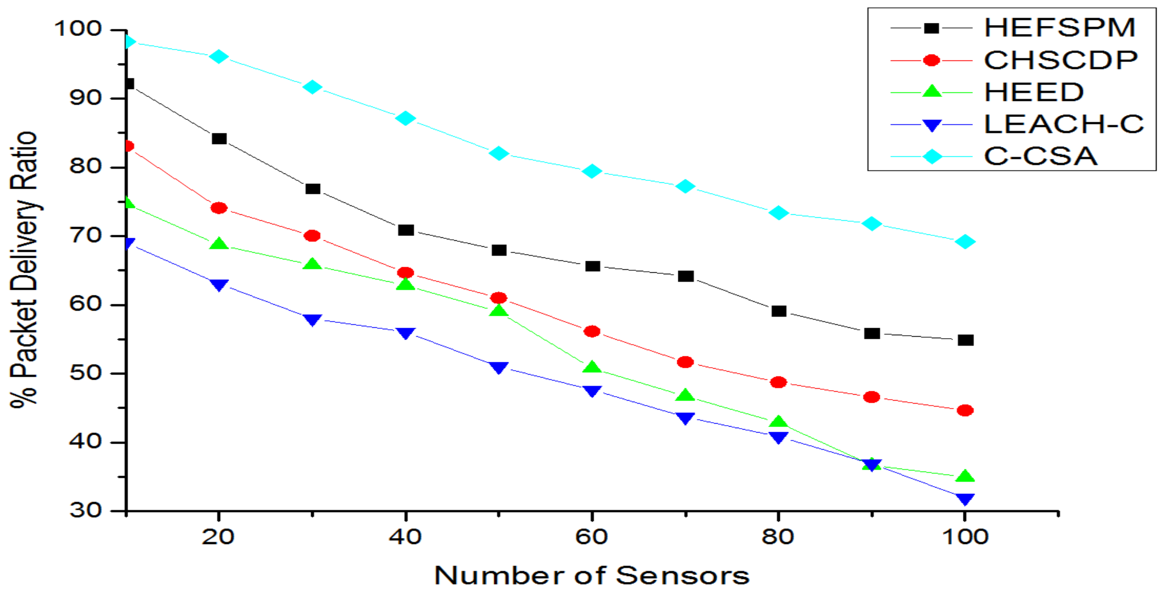


Figure 8.14 Packet delivery ratio comparison with other clustering algorithms for variation in number of nodes

A non parametric test using Friedman ANOVA test [401] was performed to evaluate the performance of C-CSA algorithm in to CHSCDP, HEFSPM, HEED and LEACH-C algorithms in terms of packet delivery ratio. This parametric test helped to find the extent of differences found in the output value of a certain dependent variable across different attempts or with different experimental conditions. For this experimentation purpose, 10 different experimental conditions based on varied number of nodes have been undertaken to perform the comparison study. Based on the extent of the differences in the output value, the Friedman-ANOVA test provided a ranking value to all the different soft computation techniques considered. It has been depicted in Table 8.7 [390].

Table 8.7 Non-Parametric tests to determine efficiency of C-CSA by Friedman ANOVA test

Algorithm	Ranking
LEACH-C	4.9
HEED	4.1
CHSCDP	3
HEFSPM	2
C-CSA	1

The results obtained from the C-CSA technique have earned this algorithm the lowest ranking value amongst all the techniques proving its performance to be the best. The 'chi-square' value using the Friedman ANOVA test has been obtained to be 39.26 and the 'p-value' has been obtained to be 6.0978×10^{-8} which is much less than the level considered (α=0.05). This proves C-CSA is proved to be the best algorithm among the considered set of techniques and the variation in the output with difference in the experimental condition is minimum for this technique. A post hoc analysis helped to determine the superiority of the performance of C-CSA technique individually with the other techniques based on the packet delivery ratio. Mann-Whitney test has been preferred in this work and the corresponding p-value and the mean rank presented in Table 8.8 in reference to the algorithms helped to determine the extent of improvement obtained through this C-CSA technique in comparison to other techniques [390]. The 'p-value' obtained for C-CSA with respect to all the algorithms is less than the level considered (α = 0.05) that claims with 95% confidence that C-CSA performs better than each of the algorithms. The lowest mean rank obtained in comparison to LEACH-C algorithm depicts that performance of C-CSA is best in comparison to this algorithm while the improvement is least in comparison to HEFSPM algorithm.

Table 8.8 Post Hoc Analysis through Mann-Whitney Test for C-CSA (α=0.05)

C-CSA vs	Mean Rank	Z	Exact 'p-value'
LEACH-C	5.5	3.74174	5.413×10^{-6}
HEED	5.8	3.51877	7.576×10^{-5}
CHSCDP	6.5	2.98432	0.0015
HEFSPM	7.3	2.38718	0.01471

The statistical studies based on normality test, parametric tests, non parametric tests and post-hoc analysis have established the efficiency of the proposed Cascaded Cuckoo Search Algorithm and its superiority over other clustering algorithms available in literatures. The accuracy of the algorithm in comparison to other routing algorithms available in literature was further studied based on different experimental instances.

8.2.3.2 Comparative Results for C-CSA with other Routing Algorithms based on Variation of Nodes

The results obtained through Cascaded Cuckoo Search Algorithm for node placement problem in wireless network have been compared with the results obtained by previously implemented routing algorithms namely Energy Efficient Maximum Lifetime Routing (EEMLR) and Ad-hoc On-Demand Vector (AODV) algorithm [310]. To compare the performance of the algorithms on the same base, the input parameters have been taken as available in the literature [310]. The area of application has been considered to be 500×500 metre^2, packet size to be 500 bytes and the channel frequency for transmission is 2.4GHz. Figure 8.15 provides the comparative results in terms of energy consumption per link while transmission or reception occurred for the three algorithms AODV, EEMLR and C-CSA considering varied number of nodes [390]. It has been seen that the energy consumption while transmission or reception occurred has increased in case of all the algorithms whenever the number of nodes has increased leading to excess data traffic. However, the energy consumption for the router placement is found to be lowest through C-CSA for all the cases.

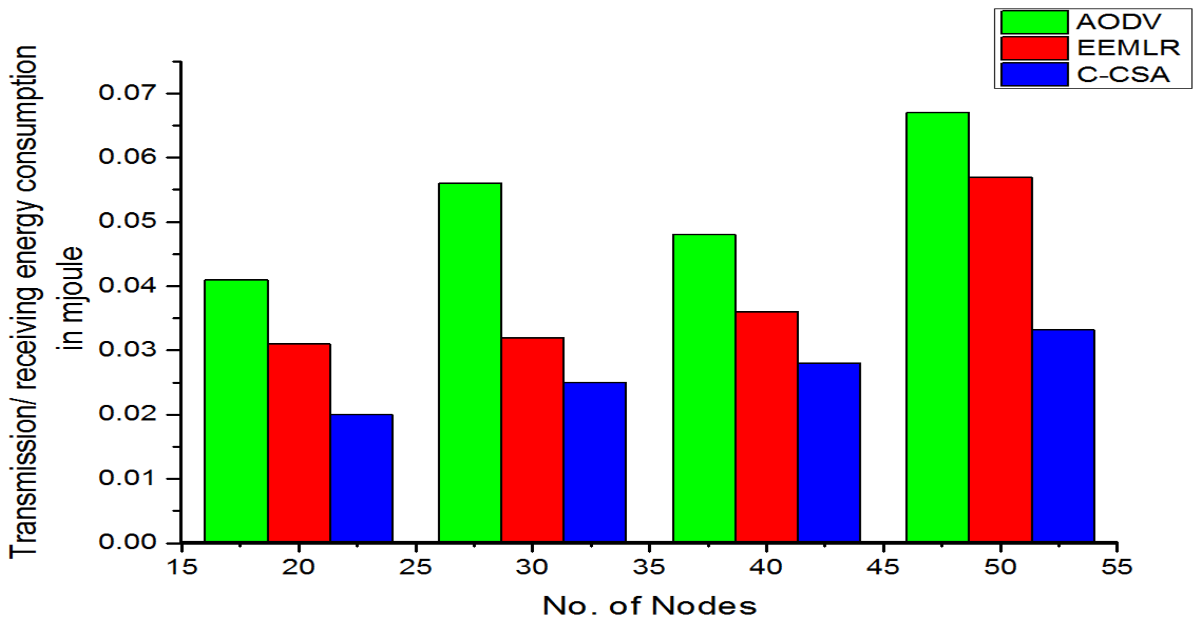


Figure 8.15 Comparison of transmission / receiving energy consumption with number of nodes

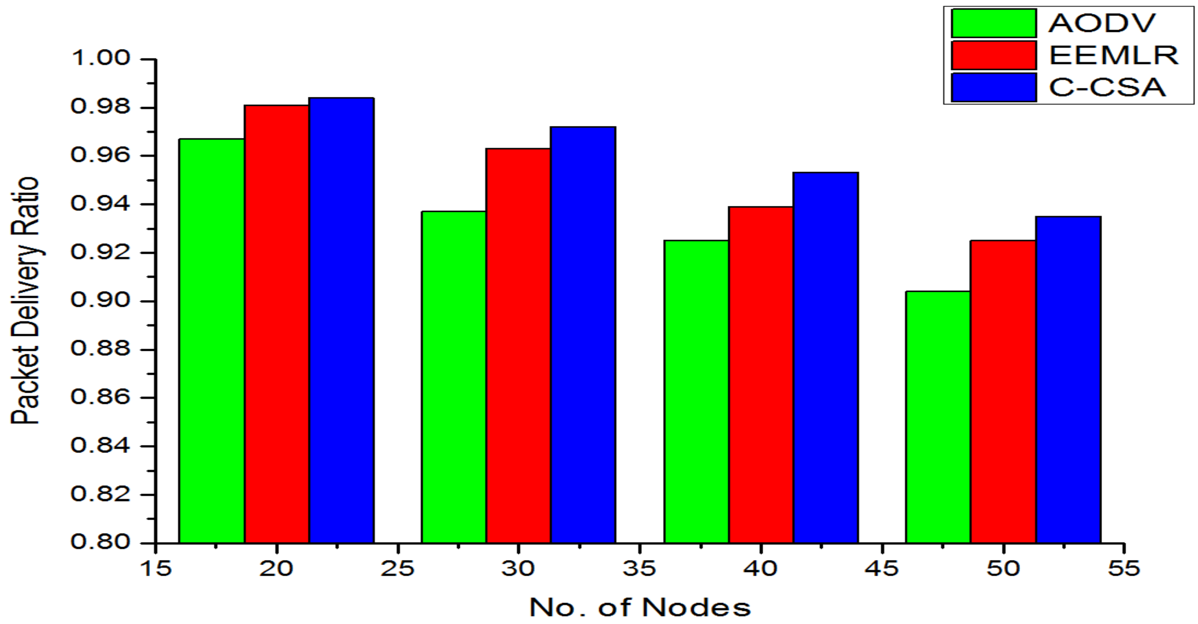


Figure 8.16 Comparison of packet delivery ratio with number of nodes

The comparative results based on the packet delivery ratio for all the three above mentioned algorithms have been represented in Figure 8.16. The results show that the packet delivery ratio obtained through the node placement by C-CSA technique has provided the best results in comparison to the other two routing algorithms for all the instances with varied number of sensor nodes. For instance, when 20 sensor nodes have been deployed in the network, C-CSA algorithm shows only 1.6% packet drop in comparison to AODV which shows 3.3% packet drop and EEMLR algorithm having 1.9% packet drop. The packet drop ratio has increased with increase in number of sensor nodes in the network but the incremental slope is least for the C-CSA technique.

Addition of nodes in the network may lead to nodal transmission delay which also needs to be taken care of while designing the node placement strategy. Figure 8.17 therefore depicts the transmission delay that may be incurred in the network for variation in number of nodes and routing through the three mentioned techniques [390]. The results of transmission delay obtained through these three routing algorithms depict that the transmission delay generated in case of C-CSA is the least for all variation of nodes from 20 to 50.

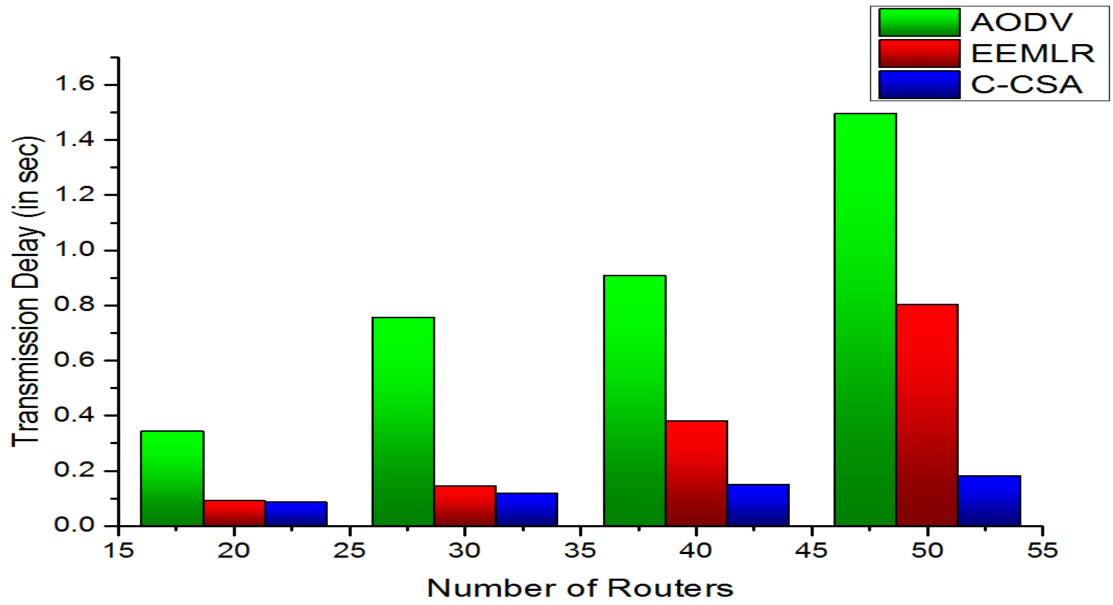


Figure 8.17 Comparison of transmission delay with number of nodes

The comparative results based on the different network parameters such as energy consumption, packet delivery ratio and the transmission delay established the supremacy of the performance of C-CSA algorithm in comparison to other routing algorithms. The proposed node placement technique based on C-CSA algorithm enabled clustering of data from more than one sensor in the placed router and also established the routing pathway. The statistical analysis based on the 50 trial runs has proved the accuracy of the algorithm in terms of all the considered network parameters. The time required for a single iteration has been found to be 43.57 second for the C-CSA technique. Considering the fact that this technique finds the optimal result though performing two optimizations in the inner and outer loop, the time required for iteration is quite low. In order to verify the results obtained through the soft computation technique, a physical placement of routers in an actual real time application was planned to detect the packet losses in the network. The hardware implementation was done in the Jadavpur University Saltlake Campus, India by identifying the best positions of the routers with the designed objective function.

8.2.4 Hardware Implementation of Wireless Sensor Network

In a small scale application involving the physical placement of the nodes, six sensor nodes were programmed as tags to collect data from the different sensors monitoring the power consumption from conventional AC sources, DC power from solar panels and the data related to temperature and humidity of the environment. These tags are placed at different floors of the Power Engineering Department, Jadavpur University. The six sensor nodes acting as tag are represented by *S1, S2, S3*, *S4, S5* and *S6* and have been depicted in Figure 8.18. The gateway represented by *C0* has been fixed at one of the floors to which the sensors transmit the data to store in the control station. The simulation results by C-CSA algorithm based on minimal signal attenuation has helped to identify the best positions for router node and the routers are placed at the positions achieved through simulation. Two kits have been involved to test the packet delivery ratio and verify the results obtained through simulation.

8.2.4.1 Network Design through Physical Placement of Routers

The simulation results obtained through C-CSA technique suggested 7 routers were required to establish the communication architecture based on minimal signal attenuation in the network. The original dimensions of the building of the Power Engineering Department were scaled into a (15×20) square unit grid. Accordingly the deployed sensor nodes were given their respective co-ordinates and the positions of the routers in the simulation domain were obtained based on the co-ordinates. Based on the initial scaling, the positions for the physical placement of the router nodes in the building are identified and the wireless nodes are placed to study the network performance. The range of all the deployed nodes has been taken as a constant of 3 units and the data transmission packet size is 500 bytes. Figure 8.18 depicts a model representation about the physical placement of the nodes in the different sections of the building. Seven routers which selected as the optimal solution are placed at the positions decided by the soft computation technique that helped to collect data from the six deployed sensor nodes and establish a pathway till the gateway or co-ordinator. The routers placed in the chosen area have been designated as *R1, R2, R3*, *R4*, *R5, R6* and *R7* as shown in Figure 8.18. This figure also depicts transmission pathways from each sensor to the gateway. The data transmission in the network takes place through the available shortest path determined by the Open Shortest Path First (OSPF) protocol [392]. The different parameters mentioned earlier that determine the network performance have been evaluated based on the simulation parameters which are all realistic data relative to this hardware implementation. It can be seen that there are six floors in the building and each floor adds up 6dB of signal attenuation as found from literature [307]. Thereby, the total signal attenuation for the designed network has been calculated to be 76.5729dB which can be considered to be relatively low considering the presence of thick walls and other Wi-Fi routers in the network [307]. The equivalent SNR for the designed network has been achieved to be 45.4271dB which is quite good for a communicating network [307]. The energy consumption for data transmission in the network relative to the effective signal attenuation has been found to be as low as 2.93µJ [307].

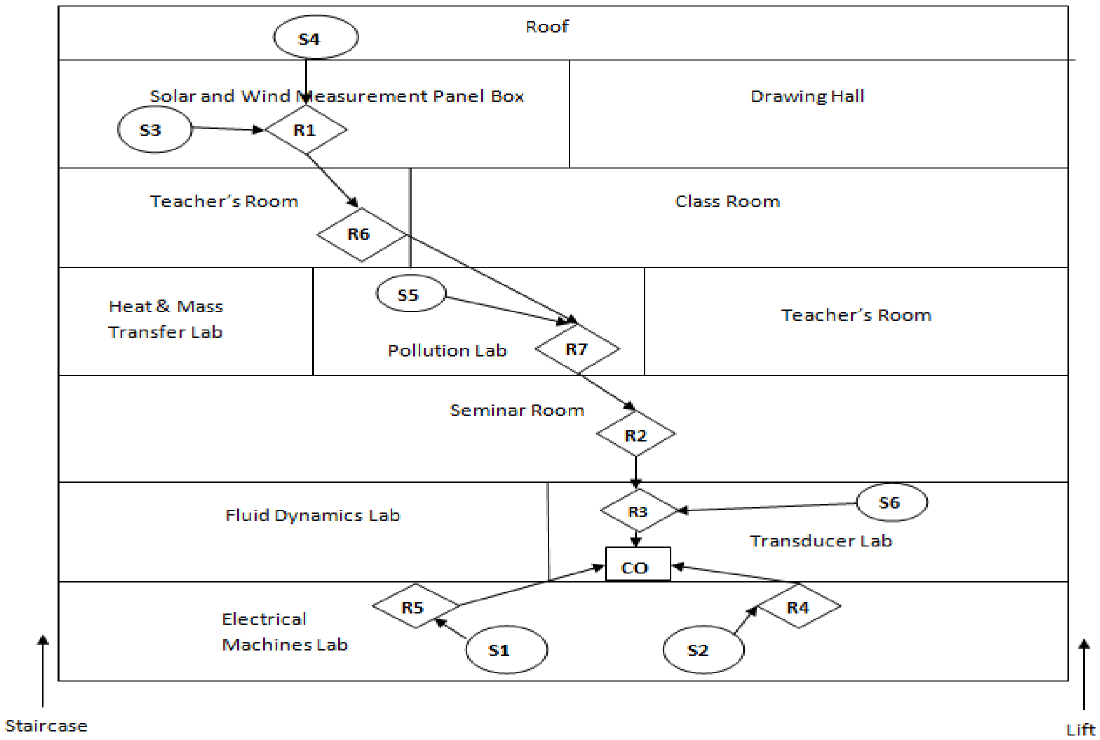


Figure 8.18 Data transmission network architecture in Jadavpur University Saltlake Campus, India

In order to establish the reliability of the algorithm in terms of efficient node placement, the packet error ratio was calculated in the simulation domain and was effectively monitored during the hardware implementation.

8.2.4.2 Study of Packet Delivery Ratio in Hardware Operation

Based on the simulations performed through C-CSA algorithm, the packet error ratio corresponding to the resulting signal attenuation has been displayed in Figure 8.19. It can be seen from the simulation results that the designed network shows an average of 1.4% PER for the communication architecture framed throughout the network. The results related to the signal attenuation and packet error ratio have been calculated from Equation (5.2) and (5.8).

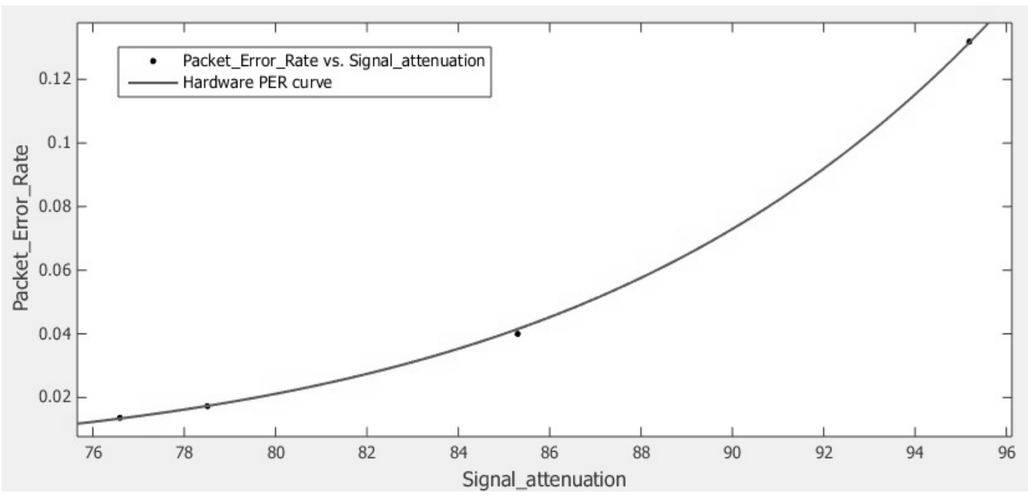


Figure 8.19 Simulation result for PER vs signal attenuation for the hardware implementation of WSN in Power Engineering Department, Jadavpur University

As stated earlier, in order to verify the results obtained through this algorithm, two hardware kits were employed to study the packet delivery ratio between the sensor and the gateway in the network. One wireless kit was placed in unison with the tag collecting the data while the other kit was associated with the gateway to measure the percentage of data packets successfully delivered. The packet error ratio corresponding to the individual deployed sensors in the network has been illustrated in Table 8.9. It has been considered that 50 data packets are being sent at a time and loss of 1 packet corresponds to 2% packet error ratio for the considered hardware kits.

Table 8.9 Packet delivery success ratio for the various hardware implemented sensors

Transmission Pathway	Packet Delivery Success Ratio
S1→G	100%
S2→G	100%
S3→G	96%
S4→G	96%
S5→G	98%
S6→G	100%

As seen from the model network design in Figure 8.18, it can be seen that two of the sensors, *S1*and *S2*, are just one floor away from the gateway node while the node *S6* is placed close to the gateway, thereby suffering lesser signal attenuation. The packet error ratio being directly dependent on the signal attenuation is found to be zero for these three sensors. All the other sensors being away at considerable distances from the gateway are subjected to much higher signal attenuation due to data transmission through multiple walls, floors and metallic structures leading to more packet drops in the network. The average packet drop of the network, considering a total of 300 packets being communicated to the gateway from the available 6 sensor nodes at a particular instant, is found to be 1.67% considering a total of 5 packets are dropped in the network. This result obtained from the hardware implementation matches the soft computation result. Higher resolution kits would have helped to achieve more accurate results relative to packet losses.

Figure 8.20 Wireless sensor kit showing 100% packet delivery

Figure 8.21 Wireless kit Showing 4% PER during transmission

The LCD panel attached with the hardware kits provided by PervCom Pvt. Ltd. displays the packet delivery success ratio of the kits at every second of data transmission. Figure 8.20 and Figure 8.21 displays the moments for the different sensor nodes which display 100% delivery ratio and 96% delivery ratio respectively.

A newly designed parameter namely Router Placement Efficiency has been tested for the results obtained through the proposed C-CSA in comparison to works based on different soft computation algorithms. This parameter helps to find out how efficiently usage of lesser number of nodes has helped to achieve the objective of minimal signal crossover and maximal network coverage for the planned wireless sensor network.

8.2.5 Comparative Analysis of Router Placement Efficiency for Different Algorithms

The results for the optimized number of routers required to establish a reliable routing network considering deployment of 20 and 40 sensor nodes in the application area have been evaluated using the proposed C-CSA algorithm. The obtained result have been compared with a similar work of node deployment using Cultural Algorithm (CA) obtained from literature [402] and has been presented in Figure 8.22.

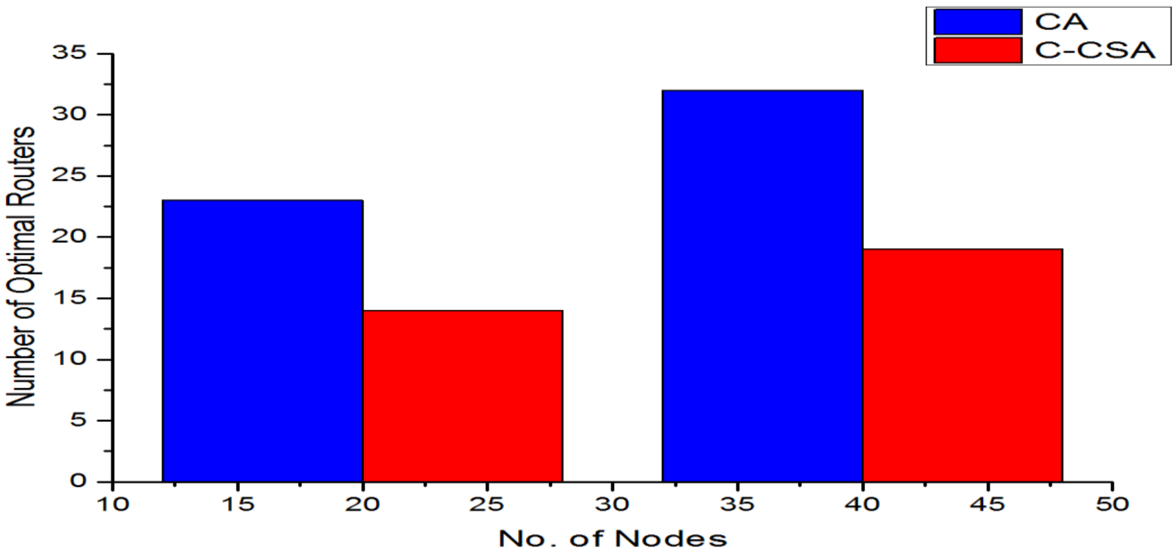


Figure 8.22 Comparison in terms of number of routers deployed for C-CSA with cultural algorithm

The results suggest that the optimal number of routers required in establishing the network connectivity for 20 sensor nodes have been found to be 23 and 14 for CA and C-CSA respectively. The number of intermediate routers for deployment of 40 nodes in the network has been found to be lesser in case of C-CSA compared to the results through CA. The result related to the newly designed parameter “Router Placement Efficiency” has been tested using C-CSA, CA and Genetic Algorithm (GA) algorithm [403]. The designed network performance related parameter takes care of the fact that no node is left unmonitored and there are minimal signal overlaps in the proposed network design.

Table 8.10 Study of router placement efficiency through different soft computation techniques

Sl. No	Property	Using CA	Using C-CSA	Using GA
1	Sensors	20	20	20
2	Active Routers	20	16	22
3	Gateway	1	1	1
4	Inactive Routers	3	1	3
5	Out of range sensors	1	0	2
6	No. of overlaps	1	0	1
7	Total Number of Nodes	44	38	46
8	No. of iterations required to converge	91	38	148
9	Router Placement Efficiency	0.82	0.947	0.804
10	Computational Time	1.199×10^3 s	345.756 s	1.43×10^3s

The comparative results for router placement efficiency displayed in Table 8.10 show that the router placement efficiency has been obtained to be 0.947 for C-CSA technique which is highest amongst all the considered optimization techniques. It has been observed that no sensor is left out from monitoring using the C-CSA technique while one sensor is left out using CA and two sensors for Genetic Algorithm. The number of overlaps in the network designed through C-CSA has been found to be zero which is ideal for minimizing the signal attenuation in the network. The number of routers required to establish the communication architecture has been found to be least using C-CSA algorithm but still the efficiency of the router placement has been found to be highest. Optimal choice of the number of routers through C-CSA ensures that least number of routers remain inactive in the network thereby reducing the energy consumption in the network and decreasing the architectural cost. The highest router placement efficiency subjected to C-CSA ensures that a reliable architecture with minimum signal overlap and maximum network coverage is achieved. The cost analysis of the node placement in the wireless sensor network for wide area applications helped to find the best suited network design for a particular application involving a certain number of sensors.

8.2.6 Cost Efficient Node Placement in Wireless Sensor Network

The cost of the network architecture is one of the important parameters that must be taken care of while designing of the wireless network architecture. The engineers would only accept a proposed wireless network design as a monitoring tool for any application only if the proposed design also earns them certain economic benefits. Cost benefit analysis in terms of battery replacement in case of the different network designs and variation in size of deployment area has been studied to choose the best fit design particularly for its implementation in the developing urban sector. In view of this, two different network topologies namely star topology and mesh topology have been chosen to place the nodes in the application area that helps to determine the perfect network design for a particular application. In case of star topology the sensor nodes can directly communicate with the gateway and thereby are programmed to work in high power mode. In the high power mode, the range of these nodes extend upto 90metres but involves usage of higher energy while data transmission. However, the size of the application area still gets limited to a certain size through this topology. The other network design considering the mesh topology can be extended upto any limit since the entire communication architecture between the placed sensor nodes to the gateway is established by placement of intermediate routers. The nodes in this case are operated in low power mode to avoid excess energy dissipation and have a maximum transmission range of 30metres. In order to evaluate the positions and number of the intermediate routers in the mesh topology and to calculate the cost benefits, the initial parameters considered for the simulation set up have been enlisted in Table 8.11.

Table 8.11 Initial value of the parameters for cost benefit analysis

Parameter	Value
No. of sensor nodes (N)	20-60
Size of the Network	100x100 m^2
Base Station Location	Centre (50, 50)
E_{elec} (Energy Dissipated per bit data transmission) [219]	50nJ/bit/round
ε_{fs} (amplification co-efficient in free space) [219]	10pJ/bit/m^2
ε_{mp} (amplification co-efficient for multi-path transmission) [219]	0.0013pJ/bit/m^4
Packet Size [219]	4000bits
Battery Charge Rating [384]	2400 mAh
Battery Cost, B_c (for set of 4) [384]	Rs 270
Initial Investment Cost/node (I_{nC}) [396]	Rs 24000
Extra Annual Node Maintenance Cost [396]	Rs 1,00,000

For evaluating the cost benefits, the size of the network and the number of sensor nodes deployed has been kept constant for both the considered networks design. Four batteries constitute the energy supply source for each of the considered wireless nodes. The battery considered in the application is made by Duracell and the price and the cost of such batteries are considered for evaluation of the annual running cost of the network [27].Based on the initial parametric settings, the evaluation for the various performance parameters and the annual running cost of the network for Scheme 1 and Scheme 2 has been performed.

8.2.6.1 Selection of Appropriate Network Topology based on Cost Benefit Analysis and Network Run Time

Table 8.12 presents a comparative performance study based on the network design through Scheme 1 and Scheme 2. The application area for both the network designs has been evaluated to be 100x100 m^2while the base station has been considered to be at the centre of the application area at the co-ordinate (50, 50). Scheme 1 refers to the star topology node arrangement with the nodes operating in high power mode while Scheme 2 refers to the mesh topology where intermediate routers are placed to set up the communication architecture.

Table 8.12 Performance comparison of design scheme 1 & 2

Parameter	**Scheme 1 (with high power sensor nodes)**	**Scheme 2 (with low power nodes and intermediate routers)**
Number of nodes	50	56 (includes 6 routers)
Average Signal Attenuation	84.61dB	62.12 dB
SNR of the Network	37.39dB	59.88 dB
Total Energy consumed for data transmission for 1sec	14.7J	12.782J
Run Time of Network	48.97hrs	63.088hrs
Annual Running Cost of Network Architecture based on Battery Replacement	Rs 2414947.927	Rs 2099733.67

Considering the star topology in Scheme 1, no additional nodes are placed in the network to ensure reliable communication architecture. Therefore, it can be seen that only 50 nodes are employed in the network that directly communicate with the base station. However, operating in high power modes these nodes incur higher energy dissipation for transmitting data through larger distances. The signal being transmitted over such large distances is certain to suffer signal attenuation due to presence of several obstacles resulting in lower signal to noise ratio (SNR) of the network. The initial energy supplied by each 1.5V; 2400mAh battery has been calculated to be 12960J. As suggested before, four such batteries make up the total energy supply source for all the nodes employed in Scheme 1 or Scheme 2. Considering the nodes are in continuous operation to transmit real time data, the average energy consumption through Scheme 1 has been found to be 14.7J in one second. Based on the initial energy supplied by the batteries to a node, it can be calculated that at this rate of energy consumption the network developed through this design can run upto 48.97 hours.

Scheme 2 involves network design through mesh topology and thereby six intermediate routers are required to establish communication architecture with minimum power decay and signal attenuation. This indicates that total of 56 nodes were employed in the entire application area that utilized wireless sensor network as the monitoring tool. The reduction in signal attenuation helped to reduce the energy consumption during packet transmission to 12.78J in each second. In comparison to the star topology in Scheme 1, it was found that the signal attenuation was largely reduced to 62.12dB which in turn improved the SNR of the network to 59.88dB. The improvement in the SNR of the network suggested an improvement in quality of the communication architecture. The improvement in the SNR of the network states that the quality of the communication network for data transmission has been enhanced considerably. Considering the same batteries to run the node as in Scheme 1, the run time of the network through the implemented mesh topology has been found to increase to 63.08 hrs based on battery power. Considering the network to run continuously over the course of a year, the annual running cost for the two implemented schemes are tested. It has been found that the annual running cost for a battery based wireless network incurs an annual cost of Rs 2414947.927 Scheme 1 while for Scheme 2 it is found to be Rs 2099733.67. Considering the extra initial investment costs and the annual maintenance costs for the additional routers based on the values mentioned in Table 8.11, the economic benefits over a year for Scheme 2,calculated by Eq. (5.8) has been found to be Rs 98480.54. These cost savings and increment of the lifetime of the network proves the utility of multi-hop multi-path mesh topology to develop communication architecture for wide area networks.

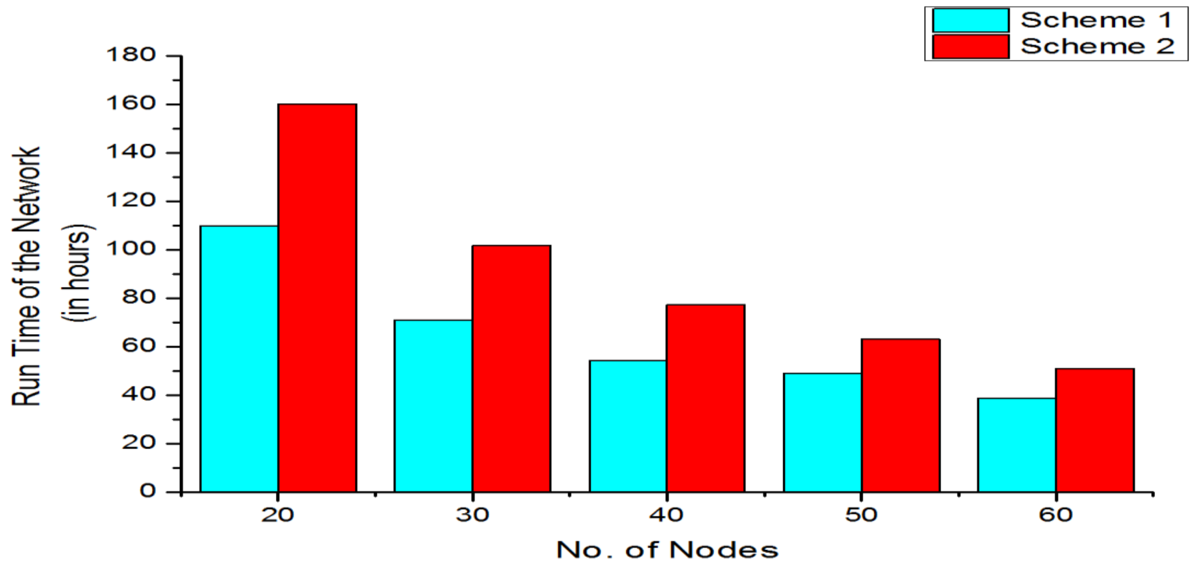


Figure 8.23 Comparison of network run time for scheme 1 and scheme 2 by variation in number of nodes

The network *Run Time* of the network for Scheme 1 and Scheme 2 has been compared for variation in the number of nodes in Figure 8.23. It has been observed that for both the schemes, the duration of the network operation time decreases with deployment of higher number of nodes. This can be related to the fact that with increased number of nodes in the same deployment area, the chances of data collision increases thereby affecting the energy dissipation in the network. However, the *Run Time* of the network has been found to be high for all the cases, the difference being most prominent in case of 20 nodes in the network.

Based on the run time of the network and the number of additional intermediate nodes required to set up the communication architecture in the mesh topology, the economic comparison between Scheme 1 and Scheme 2 has been carried out based on Equation (5.8). The number of nodes has been varied from 20 to 60 in the considered application area of size 100x100 m^2 and the cost differences achieved between Scheme 2 and Scheme 1 has been displayed in Figure 8.24. The results display that the profits have attained to be a maximum of Rs149447.74 in case of a network consisting of 60 nodes. Thereby, data transmission through mesh topology has been identified as the best design proposal for network with such node density. The profits earned through network design by Scheme 2 have shown a gradual increase with the increase in the number of nodes in the network. However, it was found that when the number of nodes was less and the nodes were well connected with the control station through star topology, Scheme 1 was economically beneficial earning a profit of Rs 70678.30 over Scheme 2. The choice of network design therefore completely depends upon the engineers to decide based on their priority between network performance and cost benefits.

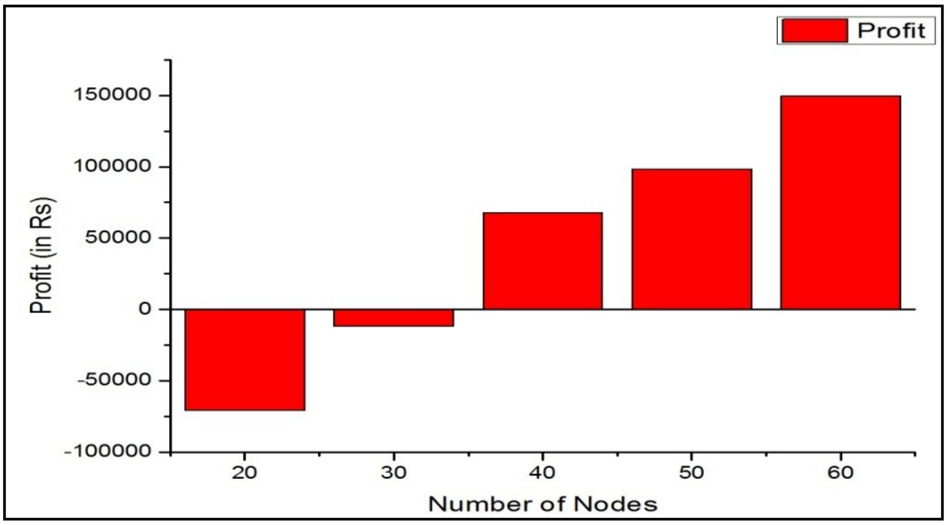


Figure 8.24 Economic analysis for Implementation of scheme 2 by variation in number of nodes

The analysis of the network performance and the economic gains obtained through the network design through Scheme 2 was tested with the variation in the size of the application area of the network.

8.2.6.2 Network Performance and Economic Gains for Variation in the Size of the Application Area involving Scheme 2

The developing countries like India, China and Brazil have focused on development of residential conclaves over large areas nowadays. These residential conclaves include a large number of households all equipped with the modern day appliances. Thereby, monitoring of the load in all the households in such conclaves becomes essential to ensure proper load distribution amongst all the customers. The network performance subjected to the network design through introduction of intermediate nodes based on the different parameters and the effect of increase in size on the network has been studied and presented in Table 8.13. The varied network sizes chosen for the case studies are 100×100 m^2, 200×200 m^2, 300×300 m^2 and 500×500 m^2. The number of nodes involved with monitoring of the area has been initially considered at a constant of 50 for all the network sizes and the base station is considered to be positioned at the center of the network.

Table 8.13 Effect on network performance with increase in network size

Area of the Network	**100×100 m^2**	**200×200 m^2**	**300×300 m^2**	**500×500 m^2**
Intermediate Routers	6	12	16	23
Signal Attenuation	62.12	62.98	74.0740	77.2890
Energy Consumption/link	0.0083J	0.0127J	0.023J	0.0358J
SNR of the network	59.88	59.02	47.93	44.7110
Packet Error Ratio	6.5%	6.58%	8.04%	8.6%
Convergence Iteration Number	21	32	47	78
Computational Time of the Algorithm	1101sec	2247sec	4156 sec	18372 sec

The results depicted in Table 8.13 suggest that with increase in the size of the application area of monitoring, the number of intermediate routers required to cover up the application area need to be increased. The addition of the intermediate nodes adds up to the installation cost of the monitoring network. However, it can be seen that the best network performance for 50 employed sensor nodes related to signal attenuation, SNR and Packet Error Ratio have been obtained to be the best in case of smaller network sizes of 100×100 m^2 and 200×200 m^2**.** When the network area size has been increased to 500×500 m^2, the data in the network gets transmitted over larger distances resulting in higher signal attenuation due to possible increased obstacles in the path. The energy consumption across each link increases to 0.0358J compared to the other cases with lower application area. Although the signal attenuation has relatively increased in case of larger network, the SNR of the network has been still found to be 44.7dB which is relatively higher than the minimum requirements of a good communicating medium. The computational time of the algorithm in the MATLAB software is observed to increase with increase in the application area and the number of employed routers. The constraints applied to this problem checks the links established between all the nodes and the gateway at every step. This increases the complexity of the program when the number of nodes increases in the application area.

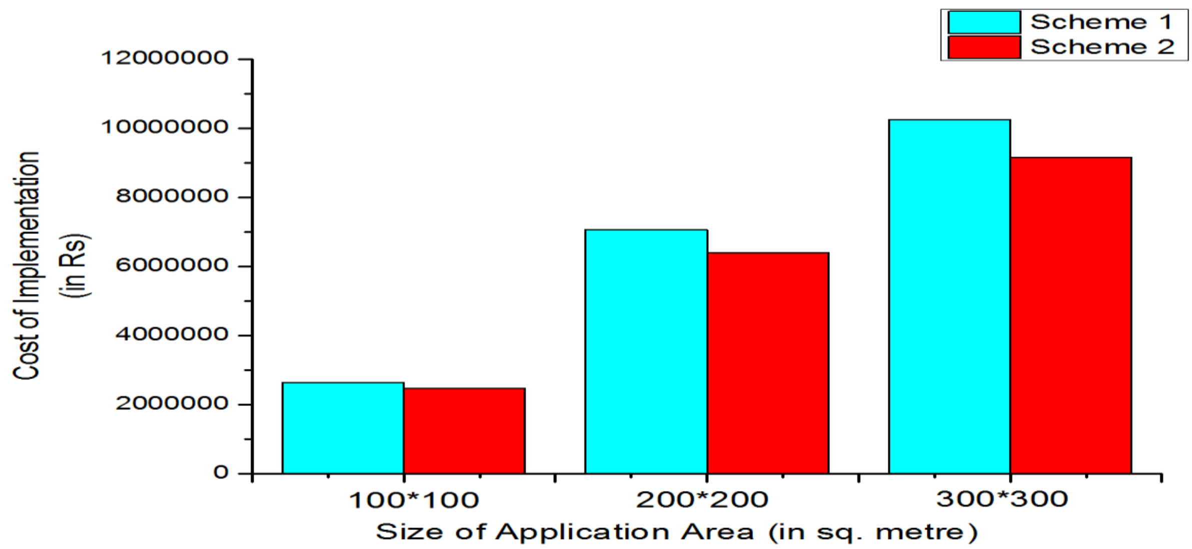


Figure 8.25 Analysis of expenditure for network design of different sizes through scheme 1 and scheme 2

The expenditure analysis involving Scheme 1 and Scheme 2 for implementation of this wireless network has been tested for varied network sizes and is presented in Figure 8.25. The results suggest that the architectural cost of the network increase for both the schemes when the network size is gradually increased from 100×100 m^2 to 300×300 m^2. The overall observation suggests that the expenditure for implementation of the network over a year has been found to lesser for Scheme 2 for all the network sizes consisting of 50 sensors. The profit of installation of the network architecture through Scheme 2 is found to have increased from Rs. 98480.5414 to Rs. 1090601 for increase in size of application area from 100×100m^2 to 300×300m^2. The comparison for the architectural cost for network size of 500×500m^2 was not possible since for such wide networks, the sensors failed to communicate directly with the base station through star topology in Scheme 1. As the distance between the deployed sensors and the base station is sure to exceed the maximum transmission range of the sensor nodes, the network design through intermediate placement of routers was the only possible solution in this case.

In the next part of the work, the results obtained for lifetime enhancement of the network through REDCR algorithm, has been analyzed to understand the efficiency of the proposed protocol in wireless network design.

8.3 Lifetime Enhancement of Wireless Sensor Network

Residual Energy based Distributed Clustering and Routing (REDCR) algorithm was designed as a part of this work with the aim to enhance the lifetime of the network based on joint clustering and routing approach. This proposed protocol was applied to different scenarios of wireless network implementation to study the efficiency of the REDCR algorithm. The obtained simulation results and the data analysis presented in this section would make a better understanding about the positives of the REDCR algorithm. The initial parametric settings undertaken for the simulation purpose and for comparison with other existing approaches have been enlisted in Table 8.14 [23].

Table 8.14 Initial simulation parameters for REDCR algorithm

Parameter	Value
No. of nodes (N)	100
Size of the Network	200*200 m^2
Base Station Location	Centre (100, 100) Intermediate (150, 50) Corner (200, 200)
E_{elec} (Data Aggregation Energy)	50nJ/bit/round
ε_{fs} (amplification co-efficient in free space)	10pJ/bit/m^2
ε_{mp} (amplification co-efficient for multi-path transmission)	0.0013pJ/bit/m^4
Initial Energy	0.5J
Packet Size	4000bits
No. of Cluster Heads	10% of N
No. of rounds of Data Transmission	2000
Weight Factors : w_1, w_2, w_3 *and* w_4	0.4, 0.3, 0.15, 0.15
Probability of a node being cluster head (p)	0.1
Number of host nests	50
Number of iterations/round	50
Nest discard probability	0.25
Maximum Number of Cluster Heads (M)	0.1 of N

The main determining parameters that have been considered in this work to evaluate the performance of the wireless network based on REDCR algorithm are Residual energy, Network Lifetime and Network Throughput. The analysis of the Residual energy of the nodes helps to give an idea about the amount of energy consumed by the nodes while transmission or reception of data occurs in the network. Based on the residual energy of the nodes, the load is distributed amongst the clusters equally and the number of nodes to be part of the clusters is also determined to enhance the longevity of the network. It is well taken care that the nodes that are part of the clusters are more or less equal in number for all the clusters. The assessment of the network lifetime can be done from the half life concept which considers the number of rounds till which half of the nodes employed dies out. It is obvious that if the number of rounds for 50% node death is increased, it will ensure that the entire network lifetime is increased. The evaluation of the network performance has been done considering different test cases and thereafter the performance of the proposed REDCR algorithm has been compared with other existing algorithms.

8.3.1 Evaluation and Analysis of Network Performance for Different Sink Node Placement

The network performance of the wireless network has been studied based on the results obtained for network residual energy, network lifetime and network throughput for different positions of the sink node. Here, the two considered test cases considered position of the sink node at the center (100, 100) and at the corner (200, 200). The obtained results have been compared with some previously used algorithms, namely Energy Proficient Clustering Technique (EPCT) [312], Distance-Based Multi Hop Clustering and Routing (DBMCR) [278], Multi Hop Clustering and Routing (MCR) [275] and Stable Election Protocol (SEP) [274]. The initial parametric settings has been considered same for all the algorithms and it is considered that 100 sensor node have been deployed in the application area all having initial energy of 0.5J.

8.3.1.1 Considering Initial Energy of Nodes as 0.5J and BS at 100×100 co-ordinate

The amount of residual energy in the network has been evaluated after 1300 rounds of transmission and the comparative results with REDCR algorithm has been depicted in Figure 8.26 [394].

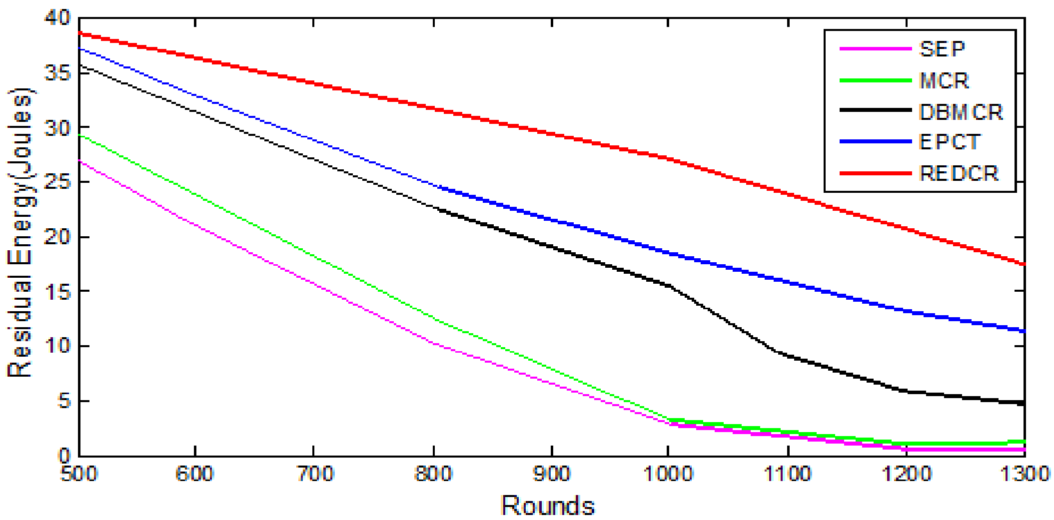


Figure 8.26 Residual energy of network for initial energy of 0.5J and BS at centre

The results prove that the proposed REDCR algorithm shows availability of a total of 18.2J of energy in the network from the initial available 50J and is capable of carrying out data transmission for more rounds. Two of the algorithms, namely SEP and MCR, are found to have no energy left after the 1300 rounds of data transmission. The residual energy left for

DBMCR and EPCT algorithms is observed to be less compared to REDCR algorithm. The energy left for DBMCR algorithm is about 5J while about 11.3J of energy is only left for EPCT protocol. The improvement in residual energy through REDCR algorithm is credited to the proper load distribution amongst the nodes achieved through this algorithm. The nodes employed in the network have the ability to switch to sleep mode sometimes when not in operation conserving their energy.

The comparative results based on the aforementioned algorithms for the network lifetime of the designed wireless network have been portrayed in Figure 8.27. This has been analyzed based on the evaluation of the number of rounds until which 50% of the node death occurs. It can be observed that 50% node death for REDCR algorithm has occurred after 2241 rounds while for all the other protocols the half node death has occurred quite earlier. Proper positioning of the cluster heads through the CS algorithm and ensuring that there are no left out nodes undertaken in this algorithm help to enhance the network lifetime through REDCR algorithm.

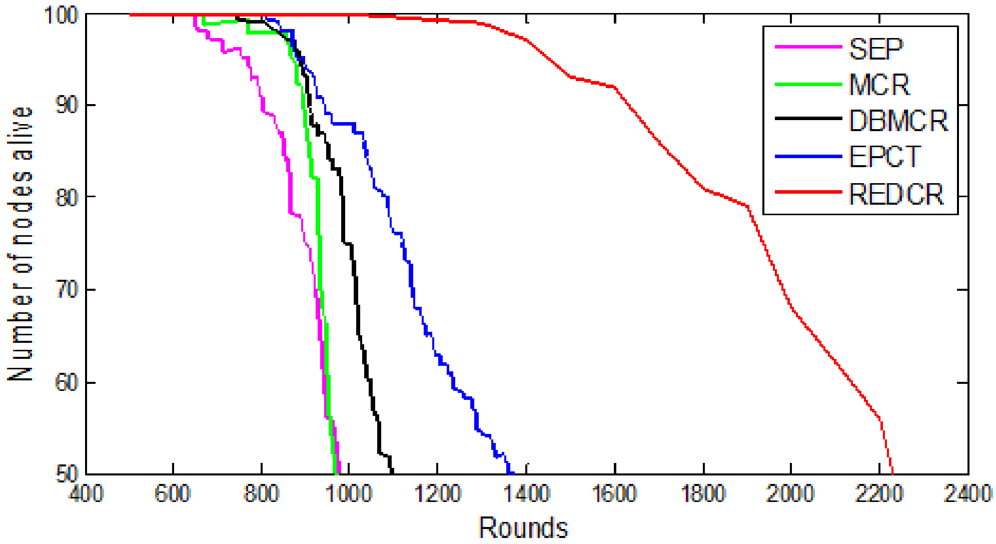


Figure 8.27 Network lifetime in terms of 50% node death for initial energy 0.5J and BS at centre

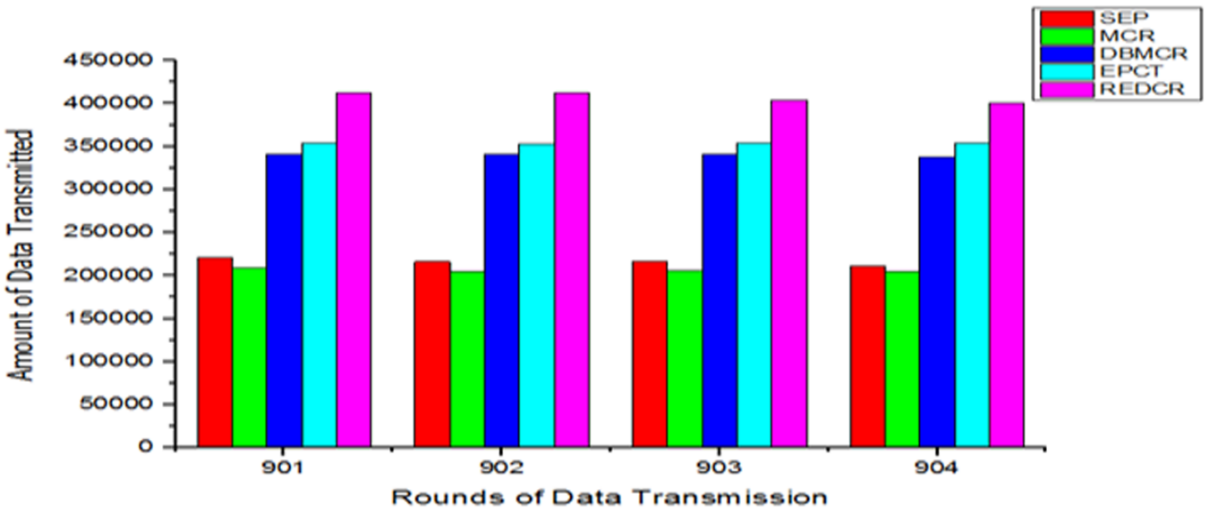


Figure 8.28 Network throughput after 900 rounds for BS at centre

The network throughput of the network corresponding to the data received at the base station placed at the center was evaluated for four consecutive rounds. The obtained results were compared with SEP, MCR, DBMCR and EPCT protocols and have been depicted in Figure 8.28 [394]. It can be observed from the results that the throughput of the network was more or less stable for the proposed REDCR protocol and is more for all the rounds in comparison to the other protocols. This is due to the fact that more number of nodes was alive after 900 rounds of data transmission in comparison to the other protocols which helped in higher volume of data transfer. However, the process of rotation of cluster head induced a relatively small delay during data transmission.

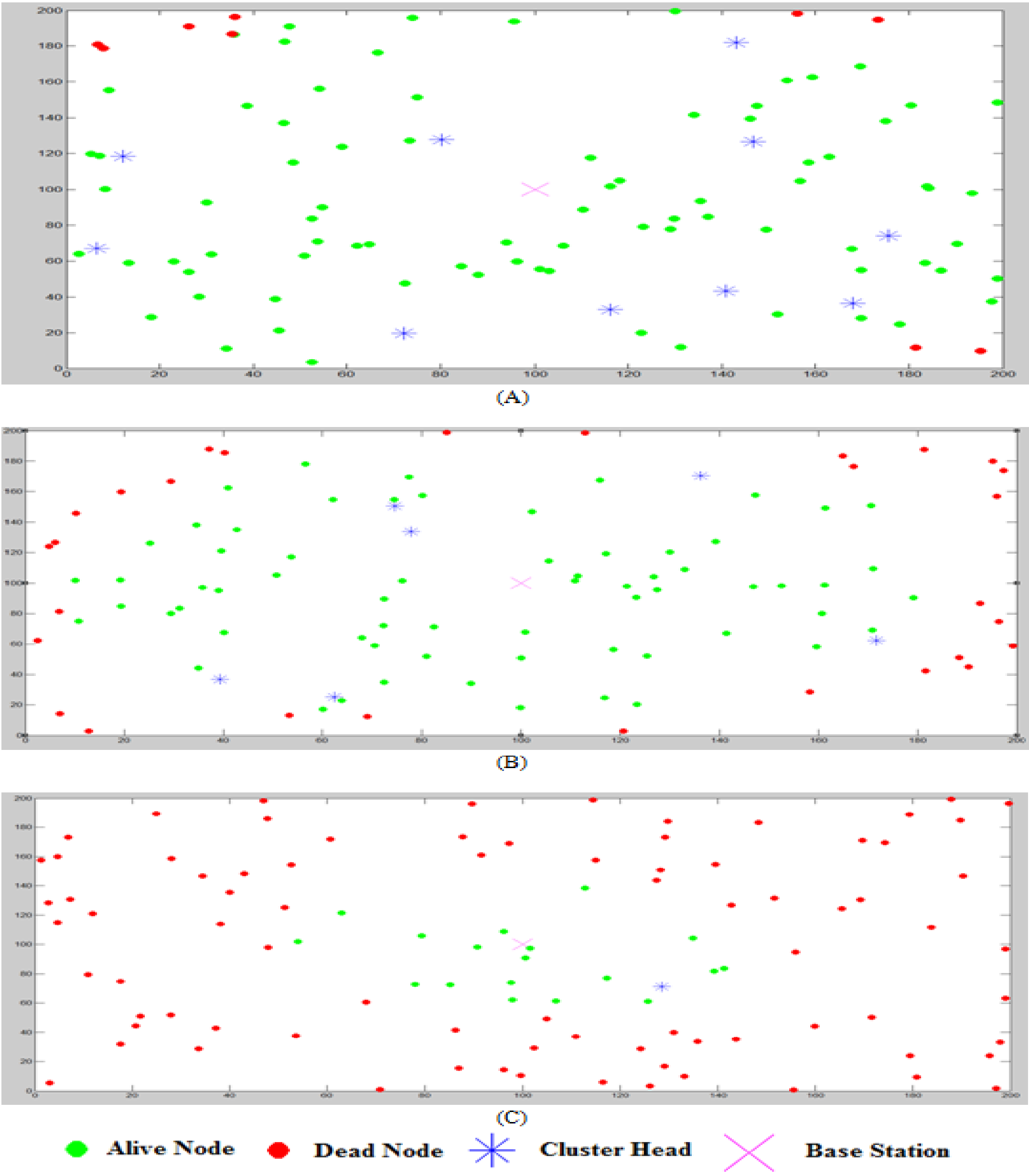


Figure 8.29 (A), (B), (C) Dead and alive nodes for 1500, 2000 and 2500 rounds of data transmission respectively for initial energy 0.5J and BS at centre

Figure 8.29(A), (B) and (C) depict the network condition with dead nodes and alive nodes after 1500, 2000 and 2500 rounds of data transmission respectively considering initial energy of nodes at 0.5J and base station at the center. At the end of 2500 rounds, the nodes that are placed near the base station are found to be active to directly communicate their collected data to the base station without the necessity of forming large clusters. The number of cluster heads in the network has thereby decreases and are found to be all placed near the base station. From the three diagrams, it can be better observed that the node die out starts from the periphery especially from the four corners because of their distance from the sink node. As the data from these nodes need to get transmitted through larger distances, larger amounts of energy get consumed for these nodes resulting in early node death. Considering higher rounds of data transmission, the other nodes die out to reduce the area of coverage and finally the area around the base station remains active.

The same parameters that determine the network performance was again evaluated for the base station (BS) placed at the corner at the co-ordinate (200,200). It has been considered that 100 sensor nodes were employed in the application area and the results related to the network performance has again been compared with EPCT, DBMCR, MCR and SEP protocol.

8.3.1.2 Considering Base Station at 200×200 Co-ordinate

Initially all the nodes are considered to have 0.5J of energy when employed in the wireless network to transmit data. A comparative study of REDCR protocol with EPCT, DBMCR, MCR and SEP protocol has been made with respect to the amount of residual energy of the network.

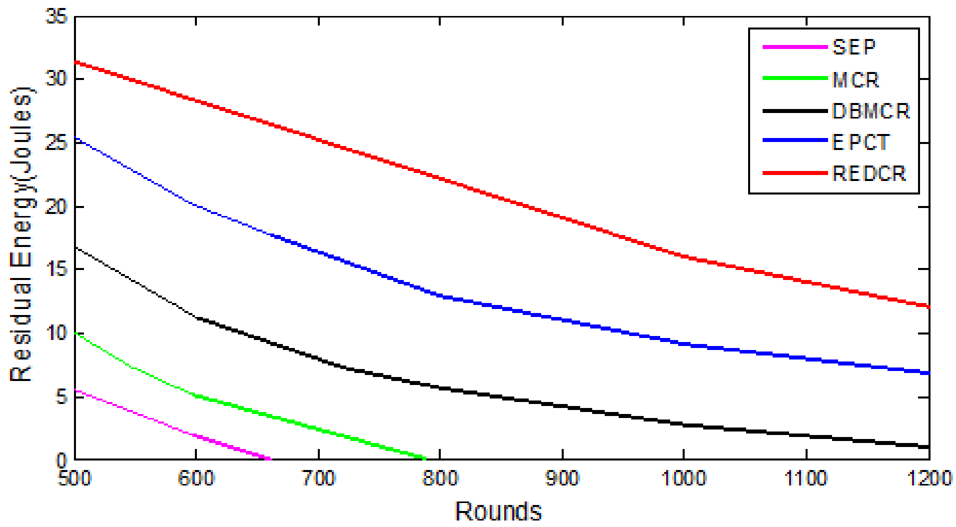


Figure 8.30 Residual energy of network for initial energy of 0.5J and BS at corner

The results displayed in Figure 8.30 help to study the residual energy of the designed network at the end of 1200 rounds. The network designed through REDCR algorithm is found to be left with 12.44J of energy after 1200 rounds to continue data transmission for more rounds. It has been seen that the energy of the networks related to SEP and MCR protocols have exhausted after 670 rounds and 780 rounds of data transmission respectively. The amount of energy left over for the network design through DBMCR and EPCT protocol is considerably low compared to the network design through REDCR protocol. The balanced load distribution amongst the nodes through rotation of cluster heads and ability of the nodes to remain in sleep mode when not in operation helps to conserve the energy of the nodes through REDCR algorithm. The energy left over is lesser in case of sink node at the corner at the same instant since the energy consumption is unequal for the nodes due to the sink node being at one corner.

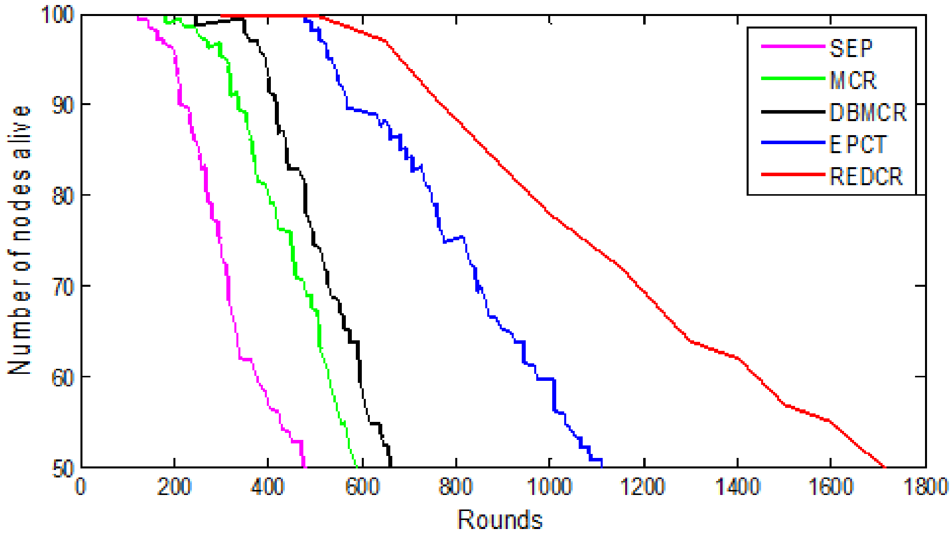


Figure 8.31 Network lifetime in terms of 50% node death for initial energy 0.5J and BS at corner

The results of network lifetime for the designed network based on REDCR algorithm is evaluated by calculating the rounds for 50% node death. The comparative results with the EPCT, DBMCR, MCR and SEP protocol have been represented in Figure 8.31.It can be seen that the network lifetime obtained is highest for REDCR protocol since this approach also takes care of the fact that all the sensors take part in cluster formation. This ensures more number of nodes to remain eligible to become cluster heads thus allowing better load balancing to enhance the network lifetime. However, the network lifetime for base station at corner is found to be lesser than the previous case, since data from some of the nodes need to be transmitted through larger distances when the sink node is positioned at one corner.

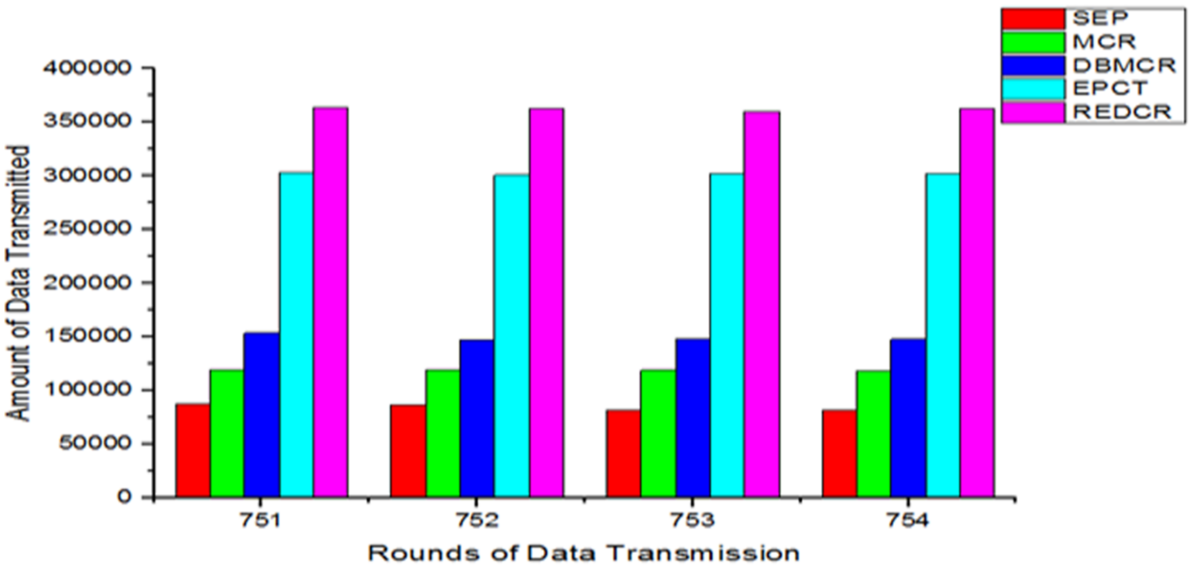


Figure 8.32 Network throughput after 750 rounds with BS at corner

Comparison of the network throughput at the end of 750 rounds for four consecutive rounds for the considered protocols has been displayed in Figure 8.32. For all the consecutive rounds, an overall average of 350518 bits of data has been transmitted through the REDCR algorithm. The amount of transmitted data packets have considerably increased for REDCR protocol in comparison to the other considered protocols. Considering the fact that the number of nodes alive is more compared to the other protocols and there are no left out nodes in the network, the amount of data transmitted is more in case of REDCR protocol.

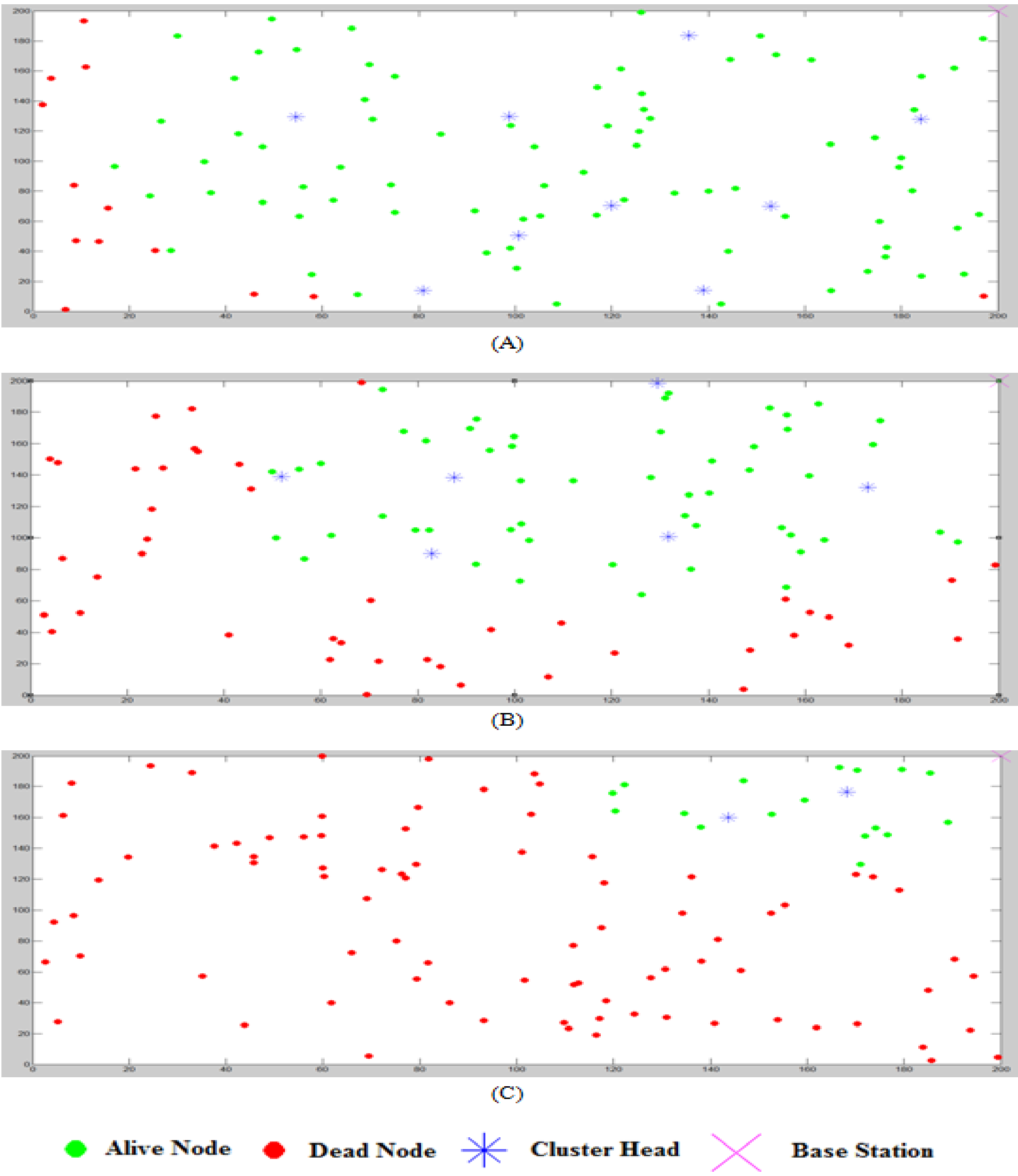


Figure 8.33(A), B), (C) Dead and alive nodes for 750, 1500 and 2250 rounds of data transmission respectively for initial energy 0.5J and BS at corner

The dead nodes and the alive nodes in the network at the end of 750, 1500 and 2250 rounds of data transmission have been portrayed in Figure 8.33 (A), (B) and (C) respectively considering base station is placed at the corner of the network and the deployed nodes have an initial energy of 0.5J. In the progressive rounds, it can be seen that the nodes placed at the farthest distance from the base station die out first while the other nodes progressively die out in successive rounds. This leaves with only 5 nodes near the base station being active at the end of 2250 rounds while all the other nodes have died out. As the residual energy of the nodes has reduced below the threshold energy of the nodes required for data transmission, the far away nodes are considered to be dead and they cannot continue data transmission till the base station. The quantity of the nodes dying out increases with increase in number of data transmission rounds.

An analysis about the percentage improvement in performance of network lifetime, network throughput and residual energy of the nodes for the proposed algorithm for different positions of sink in the wireless network helped to ascertain the efficiency of the proposed algorithm. A comparative study of network stability and network scalability with other algorithms is studied to establish the effectiveness of REDCR algorithm.

8.3.2 Improvement in Performance of Proposed Algorithm with other Algorithms

The wireless sensor nodes used for monitoring have been found to use batteries as the source of energy during their duration of operation. However, replacement of these batteries at all application environments is not always possible. This necessitates conservation of the energy of the nodes that enhances the network lifetime of the network. Therefore, a numerical analysis of the improvements achieved through this proposed REDCR algorithm in comparison to other considered protocols have been done to choose the apt routing protocol for wireless network implementation in real life scenarios.

8.3.2.1 Numerical Analysis of the Performance Enhancement of Wireless Network

The percentage improvement in the residual energy conservation of the networks obtained by REDCR algorithms in comparison to SEP, MCR, DBMCR and EPCT algorithm has been enlisted in Table 8.15 [394].

Table 8.15 Analysis of improvement in conservation of residual energy

Protocol	Location of BS (m^2)	Initial Energy (J)	Improvement by proposed REDCR protocol
SEP	100 × 100	0.5J	92.78%
MCR			90.16%
DBMCR			68.74%
EPCT			35.23%
SEP	200 × 200	0.5J	253.92%
MCR			198.24%
DBMCR			92.67%
EPCT			38.24%

The random rotation of the cluster heads at every round of cluster head selection through LEACH algorithm has enabled proper balancing of network loads amongst the nodes in the network. Appropriate positioning of the cluster heads have helped to develop a transmission pathway from the sensor nodes to the gateway with least conservation of energy that has enabled improvement of residual energy by an average of 35.23% and 38.24% in comparison to EPCT protocol for position of the base station at the center and at the corner of the application area respectively. The observation table suggests that the improvements have been found to be quite remarkable in comparison to SEP, MCR and DBMCR algorithms when the base station has been found to be placed at the corner of the application area.

Due to large improvements in the residual energy of the nodes in the network, the increment in the network lifetime for the proposed REDCR algorithm has been achieved to be highest in comparison to SEP, MCR, DBMCR and EPCT algorithm. The results related to the percentage improvement in network lifetime depicted in Table 8.16 suggest that the REDCR algorithm has helped in improvement by 12.83% and 54.45% in comparison to EPCT algorithm for base station at the center and at the corner respectively. The improvement is marked when considering the base station at the corner since the joint clustering and routing approach undertaken in REDCR algorithm has helped in establishing energy efficient data transmission pathways. Thereby, the improvement is found to be massive in comparison to other routing algorithm considering the base station at the corner. The enhancement has been found to be about 260.16% for SEP algorithm and about 192.1% for MCR protocol. This scale of improvements in the network lifetime makes the algorithm suitable for wireless network design of wide area networks.

Table 8.16 Prolonging of network lifetime by analysis of rounds for 50% node death

Protocol	Location of BS (m^2)	Initial Energy (J)	Improvement by proposed REDCR protocol
SEP	100 × 100	0.5J	128.72%
MCR			130.63%
DBMCR			103.65%
EPCT			12.83%
SEP	200 × 200	0.5J	260.16%
MCR			192.10%
DBMCR			157.76%
EPCT			54.45%

Table 8.17 Improvement of network throughput through cluster head placement

Protocol	Location of BS (m^2)	Initial Energy (J)	Improvement by proposed REDCR protocol
SEP	100 × 100	0.5J	93.34%
MCR			97.67%
DBMCR			21.63%
EPCT			13.84%
SEP	200 × 200	0.5J	290.12%
MCR			192.24%
DBMCR			147.76%
EPCT			15.53%

Increase in the network lifetime and conservation of the residual energy of the network helps to keep alive maximum number of nodes for longer duration. This has helped in enhancement of the network throughput as well by the REDCR algorithm as represented in Table 8.17 since most of the nodes remain active to transmit their data to the gateway node. The proper placement of the cluster heads through the REDCR algorithm helped to create efficient transmission pathways for the data. This has helped to improve the network throughput by 13.84% in comparison to EPCT algorithm and maximum of 97.67% in comparison to MCR algorithm. When the base station is shifted to the corner of the network, the network throughput has improved by 290.12% in comparison to the SEP protocol and by 15.53% from EPCT protocol. The efficiency in placement of the cluster heads based on average distance and residual energy of the network demonstrate the positives of the proposed approach.

The first node death of the network determine the network stability attained through the proposed REDCR algorithm while the duration till which 80% of the nodes remain active determine the network scalability. Estimation of the network stability and scalability is necessary to establish the technical strength of the proposed algorithm.

8.3.2.2 Study of Network Stability and Network Scalability with REDCR algorithm

The network stability is the measure of the round of data transmission when the first node death occurs in the designed network. The comparisons of the network stability of the designed network through REDCR algorithm have been done with SEP, MCR, DBMCR and EPCT algorithms. Figure 8.34 represents the results for the round of first node death (FND) to determine the network stability for sink positions at center and at the corner [394]. The observations from Figure 8.34 suggest that the FND in case of proposed REDCR algorithm considering initial energy of 0.5J and base station at center (100,100) has found to occur at the end of 1122 rounds. This has been found to be far later than all the other previously tested algorithms such as EPCT, DBMCR, MCR and SEP algorithms. When the base station is shifted to the corner of the network, the first node death is found to occur at the end of 506 rounds. The round of first node death is largely reduced compared to base station at center, however it is found to be still better than the other works in literature. The proper load balancing and optimal placements of cluster heads through cuckoo search algorithm ensure node death is delayed in case of REDCR algorithm. When the base station is at the center all the nodes placed are almost equidistant from the base station but the distances are unequal for the node when the base station is at the corner. The node placed farthest from the base station dies out first since they require more energy consumption when base station is at the corner.

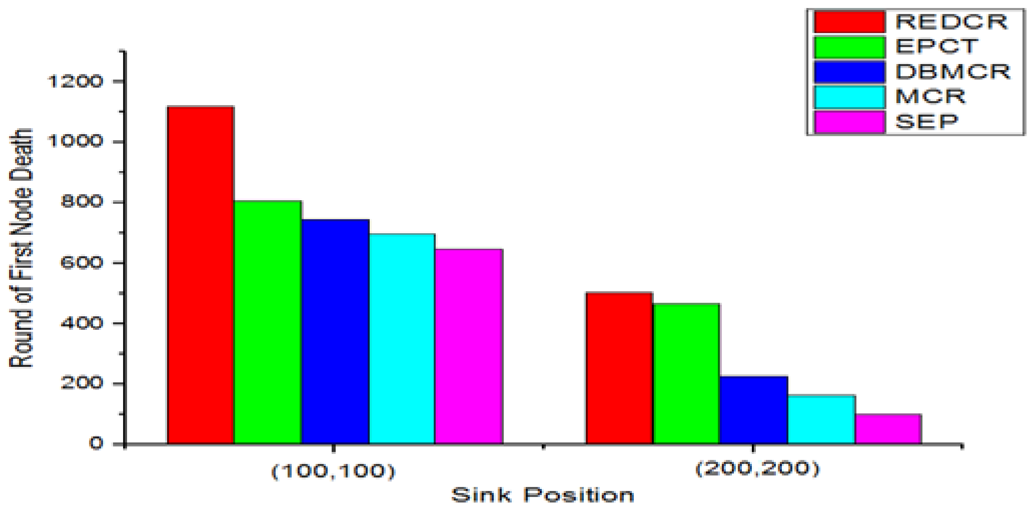


Figure 8.34 Network stability in terms of first node death at different sink positions

The network scalability of the network is estimated by calculating the number of rounds of data transmission required for 80% of the nodes to die out. Figure 8.35 depicts the round for 80% node death in case of the proposed REDCR algorithm considering initial energy of 0.5J. It has been found that 80% node death occurs at end of 2557 rounds of data transmission for sink node at center while it occurs at end of 2196 rounds of data transmission when sink node is at the corner. Comparative results EPCT, DBMCR, MCR and SEP algorithms suggest that the network scalability is highly improved since the round for 80% node death is delayed. As the number of members in a single cluster is aimed to be kept constant and data traffic is aimed to be balanced amongst the positioned cluster heads in the network, most of the nodes remain active for longer periods through the proposed REDCR algorithm. However, the number of rounds for 80% node death is found to be less for base station at the corner since the energy consumption is higher in this case as the nodes needs to forward the data over a larger distance to the farthest corner.

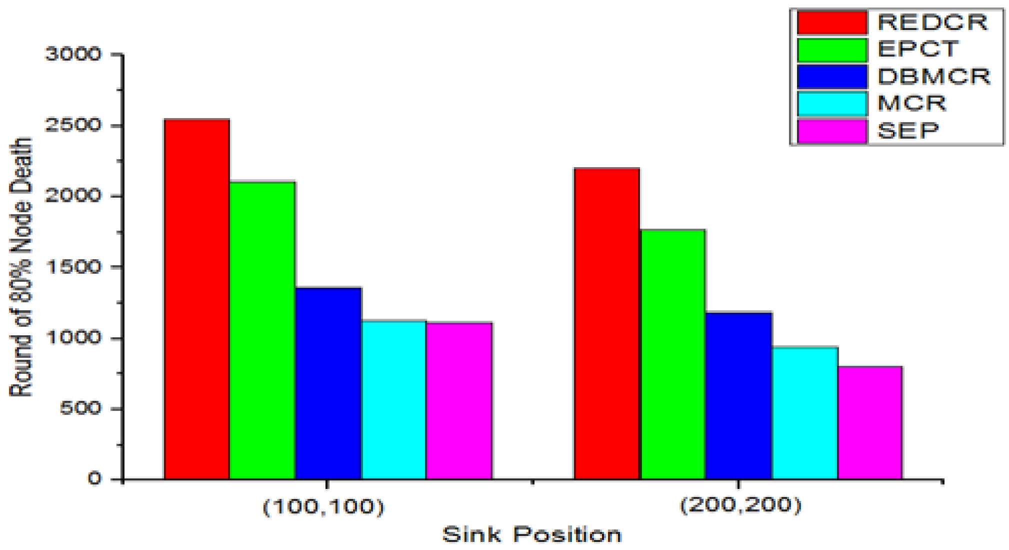


Figure 8.35 Network scalability in terms of 80% node death at different sink positions

A comparative study related to the evaluation of the round of node deaths for different number of nodes helped to establish the improvement of network lifetime achieved through the proposed REDCR algorithm.

8.3.2.3 Comparative Study related to Rounds of Node Death of the Network

Table 8.18 presents the various rounds at which the first node death (FND), half node death (HND), 80% node death and last node death (LND) occur in case of network designed through REDCR algorithm. The results related to these parameters have been compared with the results obtained for SEP, MCR, DBMCR and EPCT algorithms. It can be seen that an improvement in the number of rounds has been achieved for all the considered instants of node death evaluation. The optimized placement of the intermediate hops and conservation of the energy during data transmission aids in increasing the lifetime of the network. The total energy consumption and throughput of the network has been analyzed by putting the sinks at different positions and by varying the number of nodes to establish the superiority of the proposed protocol.

Table 8.18 Comparative analysis in terms of rounds of FND, HND, 80% node death and LND

Parameter	Sink Position	Algorithms				
		SEP	MCR	DBMCR	EPCT	REDCR
First Node Death (FND)	At Centre	647	696	745	807	1122
	At Corner	101	162	224	465	506
Half Node Death (HND)	At Centre	965	987	1160	1390	2231
	At Corner	472	592	625	1110	1654
80% Node Death	At Centre	1114	1122	1359	2105	2557
	At Corner	804	942	1187	1770	2196
Last Node Death	At Centre	1190	1210	1520	2230	2652
	At Corner	890	1130	1390	1980	2429

8.3.3 Performance Analysis for Sinks at Different Locations and Varied Number of Nodes

The analysis of the simulation results using REDCR algorithm for a wireless network implementation scenario has been presented here considering the area of implementation to be 200×200 sq. unit area in dimension. The sink nodes have been positioned at three different positions; at the center of the network (100, 100), at an intermediate point (150, 50) and at the corner of the square area (200, 200) to analyze the performance of the network related to energy consumption during data transmission. A comparative study of the proposed REDCR algorithm with previous clustering algorithms such as LEACH [219], E-OEERP [268] and PSO-ECHS [269] in terms of total energy consumption for varied sink positions and different number of node deployment in the network has been presented. The total energy consumption of the network has been evaluated based on the summation of individual energy consumption of the nodes during data transmission after a certain amount of data transmission in the network. The amount of data packets transmitted for varied number of node deployments and different sink positions have been studied to understand the ideal design of wireless network for maximum data packet delivery.

8.3.3.1 Comparative Analysis of Energy Consumption for Sinks at Different Location

The performance of the REDCR algorithm in comparison to LEACH, PSO-ECHS and E-OEERP algorithm in terms of total energy consumption has been performed for sink location at the three aforementioned co-ordinates. This has been portrayed in Figure 8.36.The results related to energy consumption for REDCR algorithm outperforms all the other algorithms in terms of lower energy consumption for all the scenarios. This is due to the fact that the proposed approach using REDCR algorithm aims to look for the optimal path for transporting the aggregated data from the cluster head to the sink. The energy consumption is seen to increase gradually when the base station position is shifted from the center to the corner for all the algorithms. However, the margin of difference in the energy consumption is found to be smaller in case of REDCR algorithm in comparison to other existing algorithms. The results suggested that the improvement related to energy consumption has been found to be maximum when the sink node is at the corner. An improvement of about 80% with respect to LEACH algorithm, 60% with PSO-ECHS and 20% with E-OEERP protocol have been obtained through REDCR algorithm for base station at the corner. This establishes the fact that the designed objective functions and proposed solution technique is ideal to design energy efficient communication architecture through wireless sensor network.

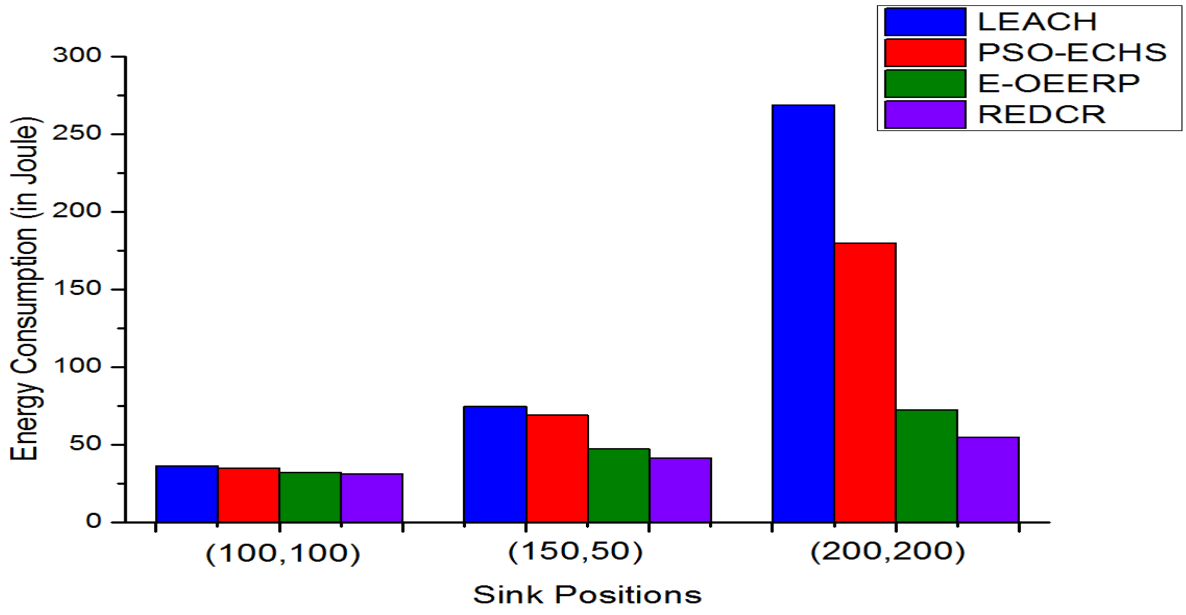


Figure 8.36 Comparison between 4 protocols for total energy consumption for different positions of sink node

The effects of the variation of the number of the nodes in terms of energy consumption have been studied as a comparison with the LEACH, PSO-ECHS and E-OEERP protocols.

8.3.3.2 Variation in Energy Consumption due to Different Number of Nodes in the Network

The energy consumptions in the network through variation in the number of nodes have been compared for the proposed REDCR algorithm with existing LEACH [219], PSO-ECHS [269] and E-OEERP [268] algorithms. Figure 8.37 illustrates the performance comparison by varying the number of nodes from 100 to 300. For experimental purpose, the sink node has been fixed at the center of the network and the initial energy for all the nodes has been considered to be 0.5J. For all the instances of different number of nodes employed in the network, the proposed REDCR algorithm has helped in lesser energy consumption in comparison to other existing algorithms. The energy consumption has seen to have a gradual increase with increase in the number of the nodes since more nodes are involved with data transmission in the network. However, the energy consumption curve shows a lower slope in comparison to the other considered algorithms. This is due to the fact that the optimal positioning of cluster heads (CHs) in the network through Cuckoo Search algorithm helped in uniform distribution of cluster heads throughout the network and allowed balanced energy consumption amongst all the nodes. The selections of the cluster heads through LEACH algorithm based on higher residual energy of the nodes have helped in energy efficient clustering throughout the monitoring field. This causes balanced energy consumption in the network and enhances network lifetime for all the cases of variation in number of node deployment in the same application area.

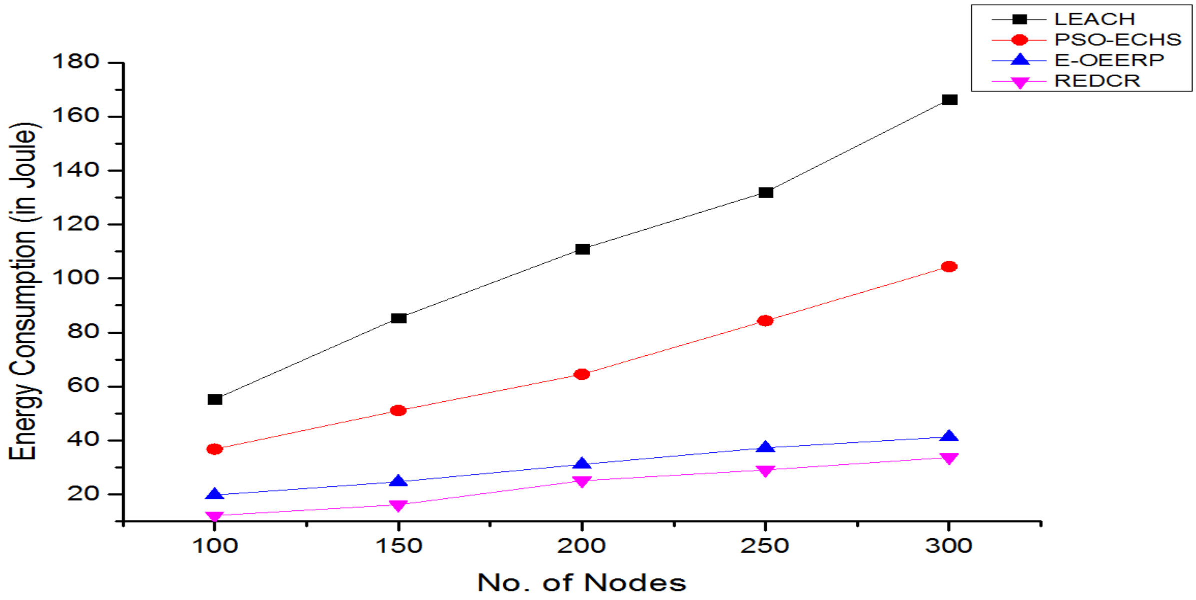


Figure 8.37 Comparison between 4 protocols for total energy consumption for variation in number of nodes

The network throughput of the designed wireless network by the proposed REDCR algorithm has been tested for different positions of the sink node and variation in the number of deployed nodes to establish the efficiency of the proposed algorithm.

8.3.3.3 Network Throughput Comparison for Varied Sink Position and Number of Nodes

Figure 8.38 depicts the comparison in the network throughput by REDCR algorithm for difference in number of nodes when the number of nodes increases in the same application area.

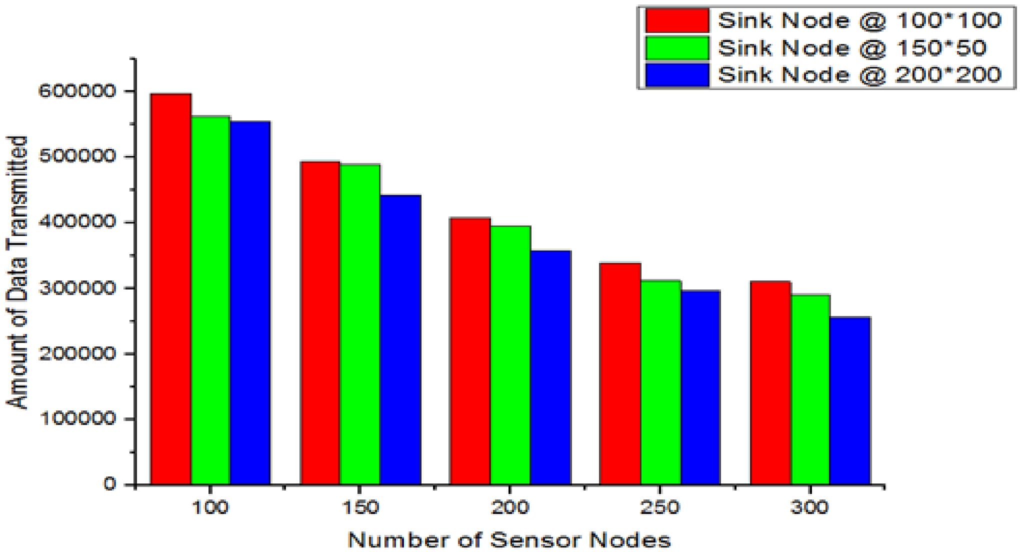


Figure 8.38 Variation in network throughput for variation in sink position and node number

The network throughput obtained from the simulations of REDCR algorithm shows a gradual decrease for increase in the number of the sensor nodes in the same application area. This is because dense crowding of the network results in increased data collision due to which some data packets are lost leading to decrease in network throughput. The network throughput is also affected by the position of the sink node in the network. It is seen to decrease continuously when the base station is shifted from the center, to the intermediate position and finally to the corner of the network. Such a pattern of decrement of throughput can be attributed to the increased complexity of calculation of the positions of the cluster heads which is introduced when the base station is shifted to the corner. The network throughput for 100 and 150 nodes in the same area of application are still comparable but it decreases largely with further increase in the number of nodes for all the positions of the base station in the network. Rotation of the role of the nodes as cluster head also introduces extra transmission delay that affects the network throughput since all the data does not reach the base station simultaneously. However, the overall improvement in terms of the other parameters allows this trade off with the transmission delay of the network.

8.3.3.4 Performance Evaluation with respect to Other Techniques involving Soft Computation Technique in Lifetime Enhancement Problem

The different clustering approaches found in literature based on LEACH-C algorithm [267] and E-OEERP [268] algorithm have aimed to improve the network lifetime of the wireless sensor networks. The novel approach involving the REDCR algorithm introduces selection of cluster heads by rotation based on available energy and optimizes the intermediate hops from the sensor nodes to the sink node. This approach helped to preserve the energy of the nodes thereby increasing the residual energy of the network which also helps to enhance the network lifetime. The comparison results based on last node death and energy consumption of the network for various sink positions has been presented in Table 8.19. The initial parametric conditions for this comparison consider initial energy of 2J and 500 nodes deployed in a network of size 200×200 m^2. The comparative results suggest that the last node death for REDCR algorithm has occurred after 11865 rounds for sink position at center and after 11250 rounds for sink at the corner. Both the results are far more improved than the other considered two algorithms. The results for network energy consumption after 5000 rounds suggest that the energy consumption is lowest for REDCR algorithm amongst the three algorithms for both the sink positions.

Table 8.19 Comparison in terms of last node death and network energy consumption

Parameter	Sink Position	Algorithms		
		LEACH-C	E-OEERP	REDCR
Last Node Death(LND) [in rounds]	At Centre	6933	8047	11865
	At Corner	5810	7731	11250
Network Energy Consumption after 5000 rounds (in Joule)	At Centre	898.9	790.6	478.7
	At Corner	956.4	828.8	502.6

The results suggest that the proposed engineering technique has provided superior results in comparison to the other algorithms in terms of all the considered parameters that determine the network performance. The time complexity of the designed algorithm also needs to be tested to have a clear idea whether the proposed algorithm can be undertaken by the engineers while planning a wireless network design.

8.3.4 Time Complexity of the Designed Algorithm

The time required for simulation of each of the steps of the proposed algorithm has been evaluated and presented in Table 8.20 to suggest the engineers a detailed idea about the time complexity of the designed approach. It has been earlier discussed that the designed REDCR algorithm consists of two parts to jointly attain the objective of joint clustering and routing in the network. The LEACH algorithm part helps to select the cluster heads of the network while optimization of the designed algorithm through Cuckoo Search algorithm helped to position the cluster heads in the network to establish the multi-hop transmission architecture of the network. To calculate the time complexity of the designed approach, it has been considered that the entire algorithm has helped in data transmission for 2000 rounds. At the same time 50 iterations are performed at each round of data transmission to optimize the fitness function to obtain the best positions of the cluster heads. The REDCR algorithm has been made to run for 15 trial attempts to find out the average run time of the algorithm.

Table 8.20 Time required for simulation of different sections of REDCR algorithm

Program Section	Time Required (in seconds)
Total REDCR Algorithm	2243.8927
Cluster Head Selection by LEACH	763.169
Rotation of Cluster Head based on Residual Energy	584.212
Determination of Intermediate Hops by CS algorithm	1482.83
Generation of Cuckoo Eggs and Update of Cost Nests	1208.456
Minimization of the Objective Function	100.253

The mean run time of the program by REDCR algorithm is observed to take an average of 2243.8927 seconds for 2000 rounds of data transmission over the 15 trial runs. The average run time for LEACH algorithm is observed to be 763.169 seconds for selection of cluster heads over the 2000 rounds out of which the time dedicated for selection of cluster heads based on residual energy of the nodes is 584.212 seconds. Initially the number of the nodes was 100 and hence there were higher number of cluster heads in the network. This increased the time of compilation of the program for election of cluster heads initially but the time taken was lesser in the later rounds as the number of cluster heads required decreased due to node deaths. The optimization of the objective function has been attempted through Cuckoo Search Algorithm and the optimization takes about 1482.83 seconds. A total time requirement for the entire REDCR algorithm has been presented because an individual step time requirement is difficult to be calculated since with decrease in number of nodes the complexity of the program reduces over the iterations.

Considerable improvements for network stability, scalability, lifetime and energy consumption have been obtained through REDCR algorithm in comparison to existing protocols. This protocol is thereby suitable to be adopted by the industries and different real time applications for placement of wireless nodes in a monitoring architecture needed to be employed for longer duration. The improvement in network stability ensures proper balancing of load distribution in the network to ensure that the network remains active for longer period of time. The conservation of energy in the nodes obtained through this algorithm ensures less frequent replacement of dead nodes thus leading to economic benefits.

The performance of the network has been analyzed in the next part of the work based on variation in the number of cluster heads to be employed in the network.

8.4 Performance Analysis based on Cluster Head Variation by hybrid CS-LEACH Algorithm

To determine the performance of the wireless network designed through the hybrid approach involving CS and LEACH algorithm, the main parameters namely network lifetime and energy consumption has been evaluated. The last round of data transmission till which the network remains active is termed as the round for Last Node Death (LND). Increase in the round for LND ensures an improvement in the entire lifetime of the designed wireless network. The energy consumption of the network is evaluated as the summation of the energy consumed at each node during data transmission, data reception and data aggregation. Lower energy consumption in the network ensures conservation of residual energy of the network that can be reutilized in further rounds of data transmission. The nodes with higher amount of energy elected themselves as the cluster heads of the network. The role of the cluster heads being rotated at every round of data transmission ensure that the data traffic load of the network is distributed in a balanced manner amongst all the deployed nodes of the network. This ensures that the communication links remains well established between a sensor and a gateway as early node death of the intermediate nodes is prevented through this approach. For the considered problem, the nodes are considered to be deployed in a square area of dimension 200×200 $m^2$and the number of nodes to be deployed in the network is varied from 300 to 700 nodes. The evaluation of the network performance has been done on the basis of the hybrid CS-LEACH approach considering different scenarios and the obtained results have been compared with other existing works available in literature. Table 8.21 represents the initial parametric settings used for network analysis [273].

Table 8.21 Simulation parameters for election of cluster heads

Parameter	Value
No. of nodes (N)	300– 700
Size of the Network	200*200 m^2
Base Station Location	Centre (100, 100) Corner (200, 200) Out of field (300,300)
E_{elec} (Data Aggregation Energy)	50nJ/bit/round
ε_{fs} (amplification co-efficient in free space)	10pJ/bit/m^2
ε_{mp} (amplification co-efficient for multi-path transmission)	0.0013pJ/bit/m^4
Initial Energy	2J
Packet Size	4000bits
No. of Cluster Heads (M_c)	5% or 10% of N

8.4.1 Performance Evaluation of Network Energy Consumption for Varied Number of Cluster Heads and Different BS Positions

In order to study the performance of the proposed approach in terms of designing the wireless network, four different sensor node deployments in the same application area has been undertaken. The four different wireless network architectures have been named as WSN-1, WSN-2, WSN-3 and WSN-4 in which the number of nodes deployed have been considered to be 300, 400, 500 and 700 respectively. In the considered network architectures, the first deployment suggested dispersed node deployment architecture while the structure WSN-4 indicates dense deployment architecture. The number of cluster heads in the network has been pre fixed to 5% or 10% of the total number of nodes involved with the certain network design. The total energy consumption for all these network architectures has been studied to evaluate the energy consumed for routing of data to the base station through the employed cluster heads in the network. The rounds of data transmission possible with the proposed engineering approach are also decided based on the simulations of the proposed approach. The network performance subjected to variation in cluster heads and for different positions of the base station has been studied to ensure the efficiency of the algorithm. The total energy consumption of the network is sure to increase with the increase in number of rounds of data transmission. It is assumed that the nodes finally stop to operate once the residual energy of the node goes below the threshold requirement for energy communication in the network. The network performance related data obtained through this CS-LEACH approach has been compared to other existing algorithms namely LEACH [219], LEACH-C [267], PSO-C [268], LDC [273] and PSO-ECHS [269] for varied number of sensor nodes and different number of cluster heads to establish the superiority in performance of the proposed technique.

8.4.1.1 Case 1: Considering Diverse Node Deployment Architecture for Base Station at 100×100 location

In order to examine the amount of energy consumption of the network for an application area of 200×200 m^2, the initial energy of the nodes was considered to be 2J and the base station was fixed at the center of the network at co-ordinate (100,100) [273]. The simulations based on the hybrid CS-LEACH approach was carried out to test the energy consumption for varying number of sensors nodes from 300 to 700. This test case considered the architectures WSN-1, WSN-2 and WSN-3 to have been tried in the application area. The architecture WSN-1 considered two scenarios with 5% and 10% of sensor nodes as CHs while only 10% of the sensor nodes were selected as CHs for the considered WSN-2 and WSN-3 architecture. The simulations were run to test the energy consumption at the end of 5000 rounds of data transmission and the obtained results were compared with the results of previously existing algorithms as mentioned above.

Figure 8.39 and 8.40 depicts the energy consumption in the network considering 15 cluster heads and 30 cluster heads respectively for WSN-1 architecture having 300 nodes. The results suggest that the energy consumption for the network design through the proposed CS-LEACH approach has achieved data transmission with lesser energy consumption in comparison to other algorithms. In the initial rounds, the energy consumption results are quite comparable for all the algorithms but the differences in the energy consumption are quite visible in the later rounds. At the end of 5000 rounds, the energy consumption for data transmission through CS-LEACH approach has been found to be 321J and 272J for 15 CHs and 30CHs respectively in the WSN-1 network architecture. At the same instant, the network design through LEACH and LEACH-C protocol has been observed to have used up all their residual energy resulting in inactive network architecture. The designed objective function stated in Eq. (5.21) takes care of the residual energy of the nodes and the distance of the cluster head from other cluster heads and its cluster members while identifying the positions of the cluster head in the network. This results in overall lesser consumption of the energy since the transmission distances are found to be optimum through this cluster head placement. The results also suggest that the network with 30CHs provided better results in comparison to the network with 15CHs proving that the appropriate choice of the number and position of the cluster heads helped to decrease the network energy consumption.

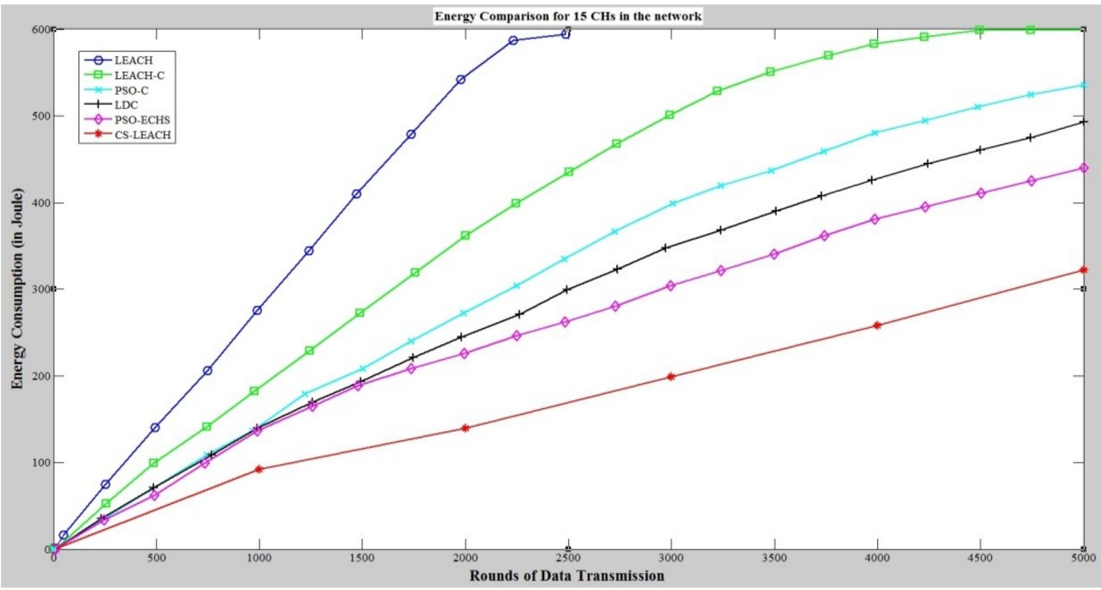


Figure 8.39 Energy consumption considering 300 nodes and 15 CHs with BS at centre

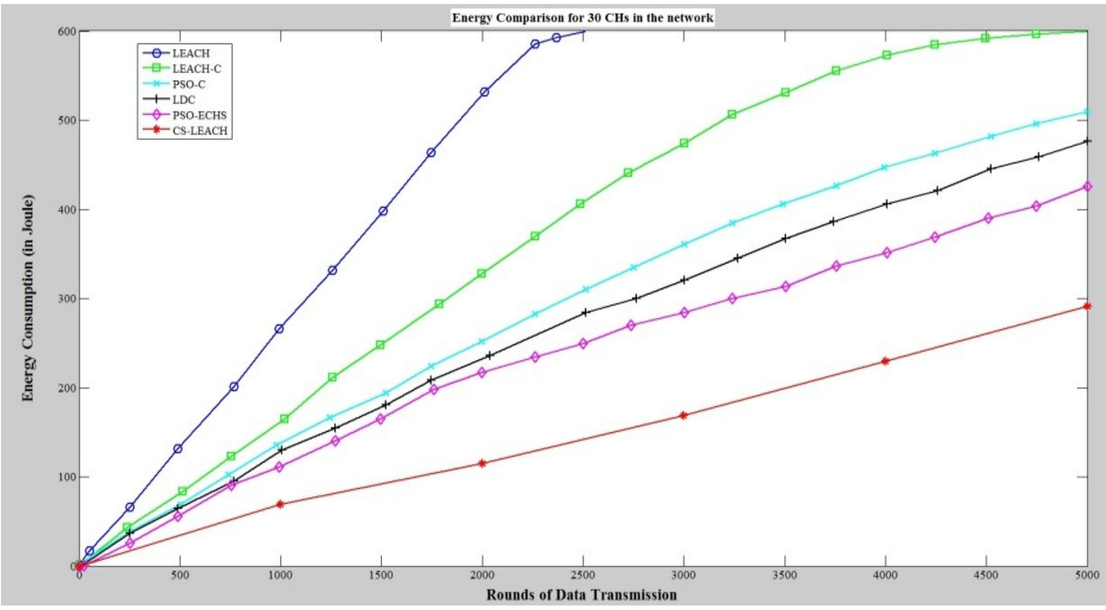


Figure 8.40 Energy consumption considering 300 nodes and 30 CHs with BS at centre

With increase in size of the number of nodes in the same application area, the performance related to the wireless networks show a decrement due to increased signal overlaps and interferences. The results related to energy consumption of two dense network deployment schemes involving 400 and 500 sensor nodes with 10% of the nodes as cluster heads has been illustrated in Figure 8.41 and Figure 8.42. The increase in total energy consumption of the network in comparison to the previously considered WSN-1 architecture is quite obvious due to increase in the number of the deployed nodes in the network. However, calculation of the average energy consumption of the nodes suggest that at individual nodes the energy consumption has been higher relative to the previously considered architecture of 300 nodes with 10% of the nodes as cluster heads. This can be attributed to the fact that for dense network architectures the energy required for data aggregation is more compared to the wireless architecture considering lesser number of node deployments.

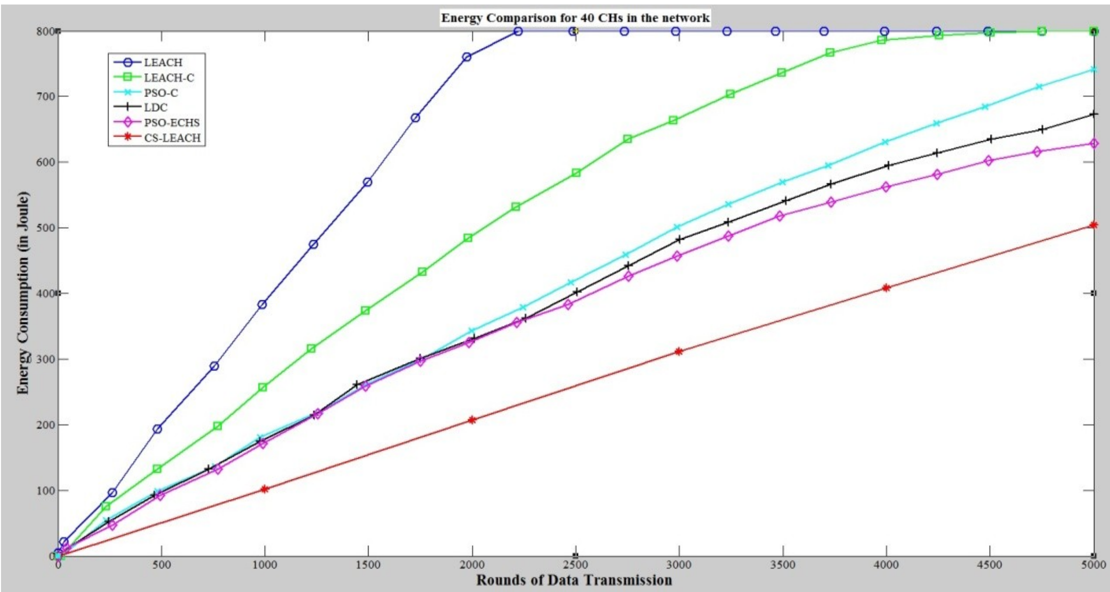


Figure 8.41 Energy consumption considering 400 nodes and 40 CHs with BS at centre

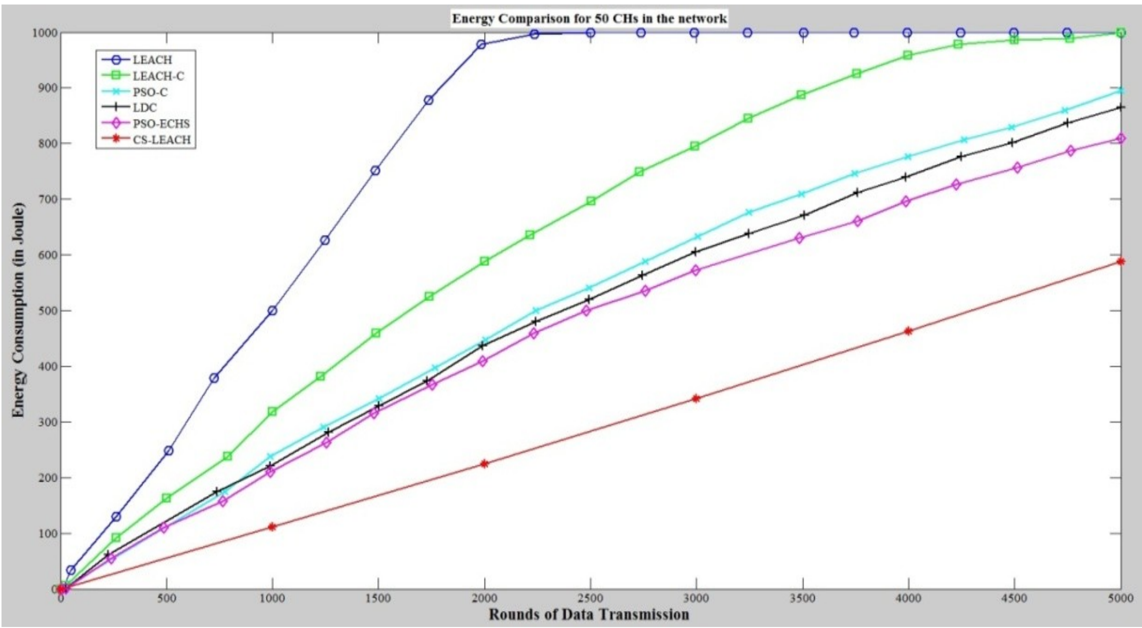


Figure 8.42 Energy consumption considering 500 nodes and 50 CHs with BS at centre

The performance of the wireless network designed through the proposed CS-LEACH approach has shown improvements in comparison to the other existing technique progressively with every round of data transmission. This is because with increase in the number of rounds of data transmission, the residual energy of the nodes have decreased and efficient cluster head selection and positioning based on the residual energy has then played an important role in enhancing the network lifetime of the network. The proposed CS-LEACH algorithm has been seen to outperform the other considered existing approaches involving PSO-ECHS, LDC, PSO-C, LEACH-C and LEACH algorithms in terms of lower energy consumption. In order to authenticate the claims regarding the superiority in performance achieved through the proposed CS-LEACH approach, the network performance of the wireless network was studied for three different positions of the base station with varied number of cluster heads.

8.4.1.2 Case 2: Taking into account the Effect of Increase in Number of Cluster Heads at Different Positions of BS

To test the total energy consumption of the network, three network architectures of WSN-1, WSN-3 and WSN-4 have been selected in this case consisting of 300, 500 and 700 nodes respectively. The number of cluster heads for all the architectures have been chosen to be equal to 5% of the total nodes. For the simulation study of the energy consumption of the network after 5000 rounds of data transmission, the position of the base station has been fixed at three different co-ordinates. Three positions of the base station have been considered: at the center of the field at (100,100) co-ordinate, at the corner of the field at (200,200) co-ordinate and out of the WSN field at (300,300) co-ordinate. Figure 8.43, 8.44 and 8.45 represents the network energy consumption for different sink locations for the considered wireless network architectures. From the results, it is confirmed that the performance of the proposed algorithm surpasses all other algorithms in terms of network energy consumption. The amount of energy consumed is seen to linearly increase when the base station has been shifted from central to the out of the field position. This can be attributed to the fact that when the base station is shifted out of the field, the data from some of the sensors needs to travel through a longer distance to reach the base station leading to larger energy consumption for reliable transmission through such large distance.

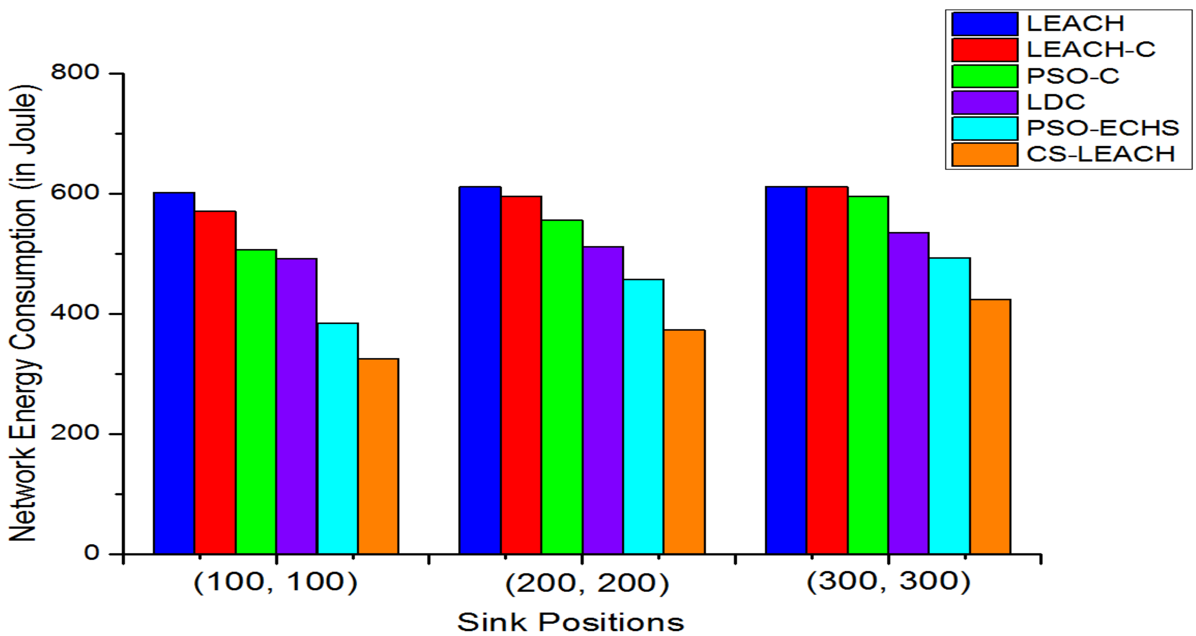


Figure 8.43 Network energy consumption for 300 nodes at different BS positions

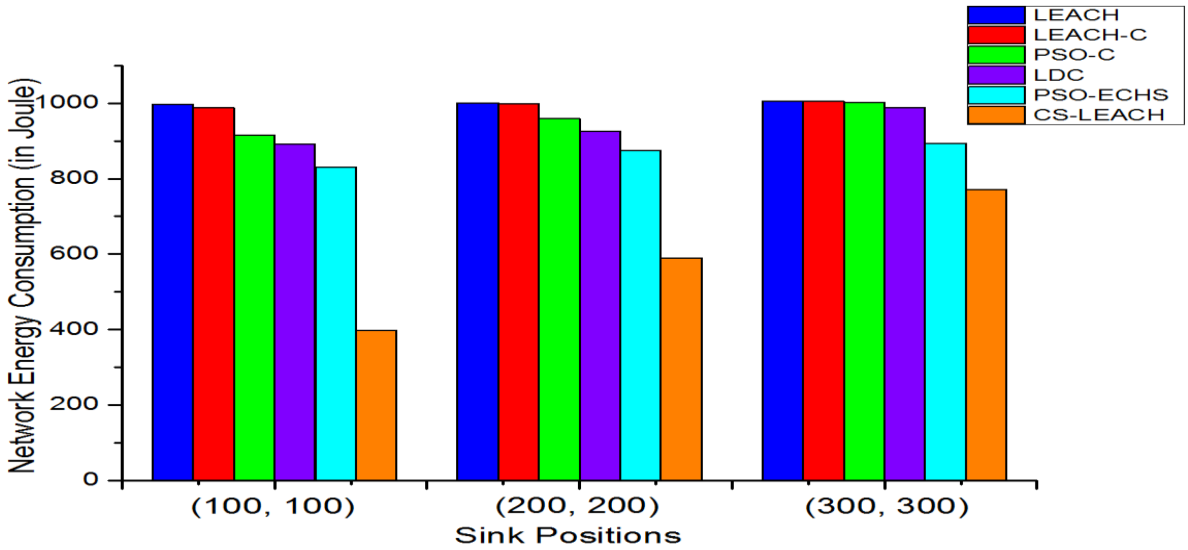


Figure 8.44 Network energy consumption for 500 nodes at different BS positions

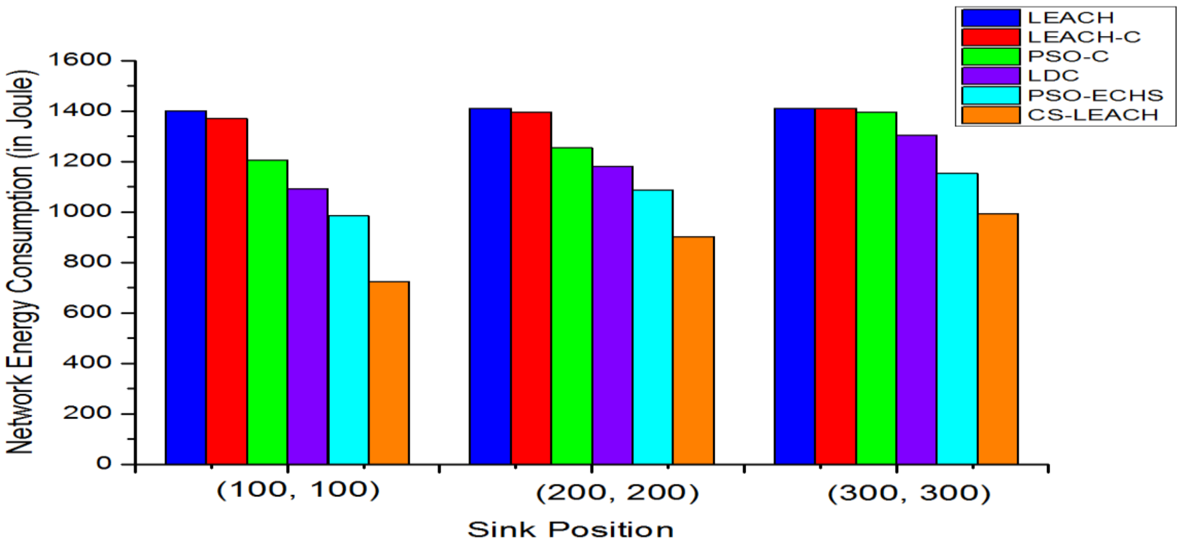


Figure 8.45 Network energy consumption for 700 nodes at different BS positions

Comparing the results obtained from energy consumption from Figure 8.43, 8.44 and 8.45, it can be stated that the energy consumption has been found to be the highest for WSN-4 architecture compared to WSN-1 and WSN-3 architecture. Considering dense network architecture as in WSN-4 architecture, the number of signal overlaps is more compared to the other architectures leading to increased energy consumption. The results for the WSN-4 architecture suggest that the energy of the network designed through LEACH and LEACH-C algorithm has been completely used up at the end of 5000 rounds. The improvement in network energy consumption by CS-LEACH algorithm has been observed to be 16% in comparison to PSO-ECHS algorithm which is highest amongst the considered algorithms. This improvement can be attributed to the fact that while solving the fitness function for choosing the cluster head position, CS-LEACH algorithm considers the sink distance from the CHs. The decrease in energy consumption of the network contributed to the fact that more amount of energy is left over for the network to perform data transmission over longer periods which results in increment of the network lifetime.

8.4.2 Enhancement of Network Lifetime through Proposed Algorithm for Varied Number of Cluster Heads and BS at three different positions

In order to ensure that the lifetime of the designed wireless networks have improved through utilization of the proposed CS-LEACH algorithm, the algorithms have been made to run until the last node in the network dies out. Estimation of the round of Last Node Death (LND) helped to compare the results of network lifetime obtained through the proposed CS-LEACH algorithm with other algorithms available in literature namely LEACH, LEACH-C, PSO-C, LDC and PSO-ECHS algorithms. Three aforementioned architectures namely WSN-1, WSN-2 and WSN-3 have been considered for the comparison purpose where the numbers of the deployed sensor nodes have been varied from 300 to 500 and the number of CHs varied from 15 to 50. The results of network lifetime have been tested for three different positions of the sink node as mentioned in Section 8.4.2.1 to establish the dominance of the proposed approach over existing techniques.

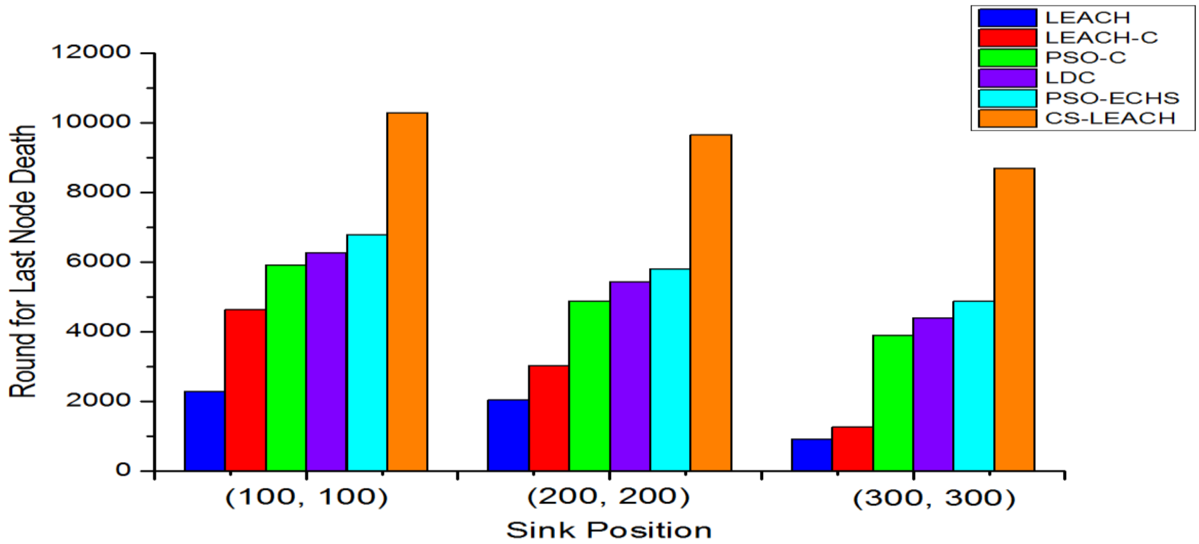


Figure 8.46 Network lifetime for 300 nodes and 15 CHs at different BS positions

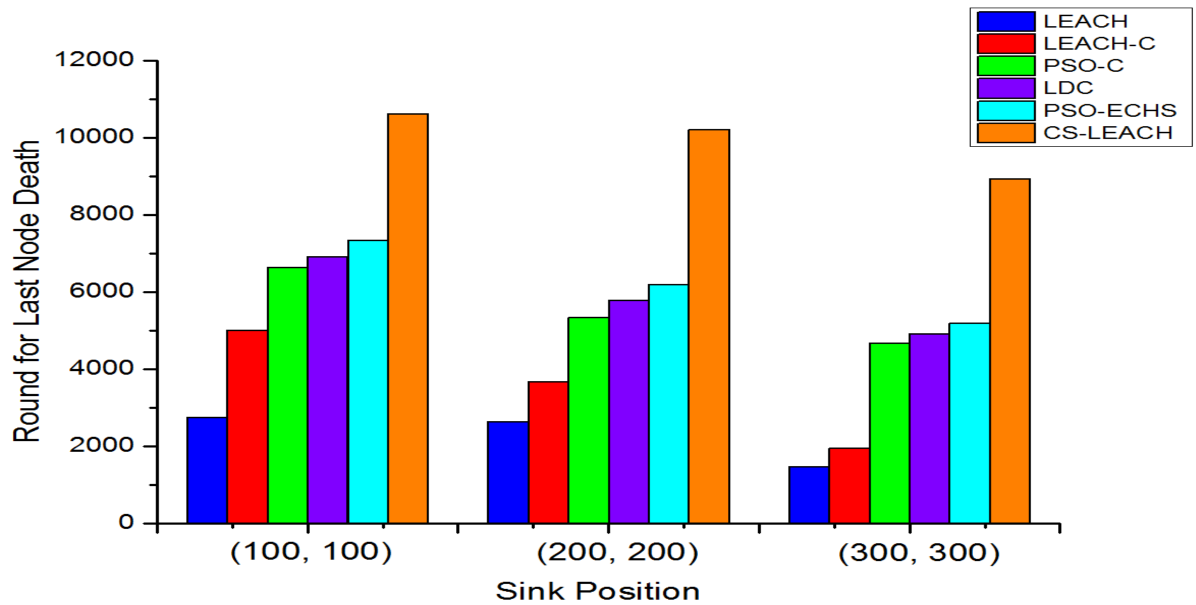


Figure 8.47 Network lifetime for 300 nodes and 30 CHs at different BS positions

The network lifetimes for the WSN-1 architecture considering 15 CHs and 30CHs for different base station positions have been depicted in Figure 8.46 and Figure 8.47 respectively. The observations for both the scenarios suggest that an overall decrement in the network lifetime can be examined for all the considered techniques when the base station is moved from the center of the field to the corner of the field. The network lifetime was found to be least when the base station was placed out of the application area. This can be attributed to the fact that the energy consumed is higher for the nodes to transmit the data over larger distances to the base station placed out of the field and the need for better data aggregation adds up the energy requirement. The results also suggest that the lifetime of the network is also directly related to the implementation of higher number of cluster heads in the network. For same number of nodes in the network area, implementation of 30CHs has provided better results related to network lifetime in comparison to 15CHs in the network. It has been also taken care that the deployment of the cluster heads is not more than the optimal level since it would not allow further improvement and again these nodes would perform the same function as the normal nodes. However, the practice of optimal placement of the chosen cluster heads has provided a minimum improvement of 50% in comparison to PSO-ECHS protocol for round of LND when base station is placed at the center of the field. The average improvements have been seen to be about 67% when base station is at the corner and about 80% when base station is out of the field for both the considered scenarios. This validates the superiority in performance of the proposed algorithm in terms of cluster head selection and positioning.

Figure 8.48 and Figure 8.49 depicts two other scenarios considering the WSN-2 and WSN-3 network architecture and the results obtained from LEACH, LEACH-C, PSO-C, LDC, PSO-ECHS and CS-LEACH algorithms.

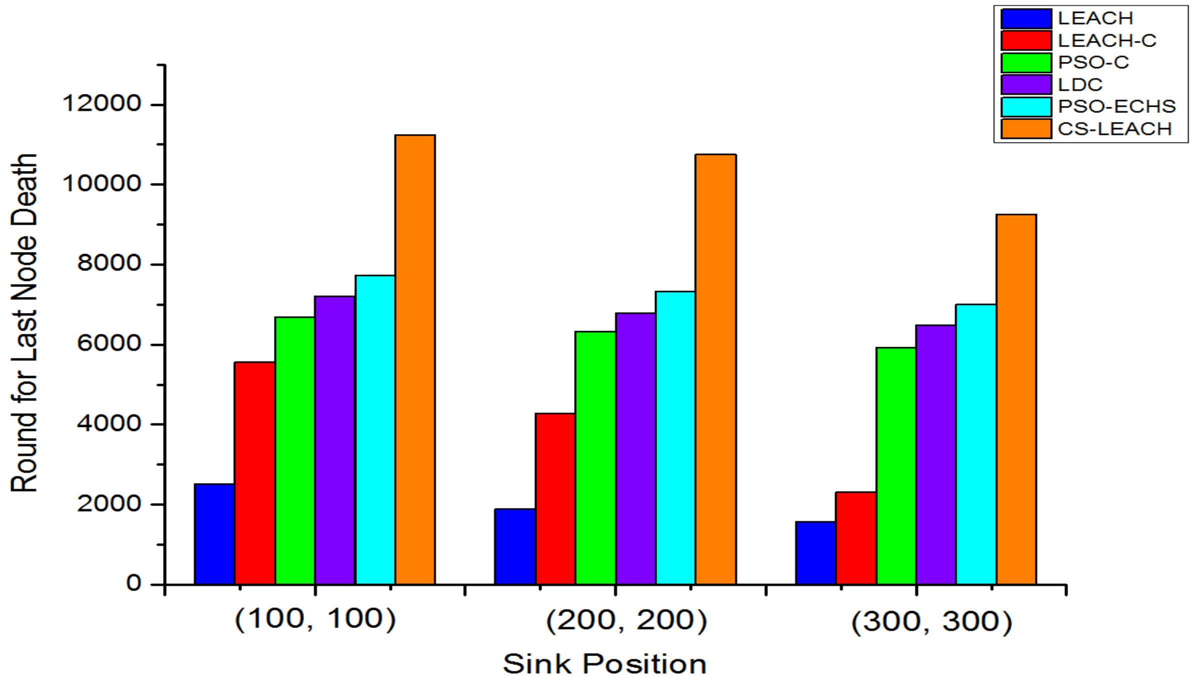


Figure 8.48 Network lifetime for 400 nodes and 40 CHs at different BS positions

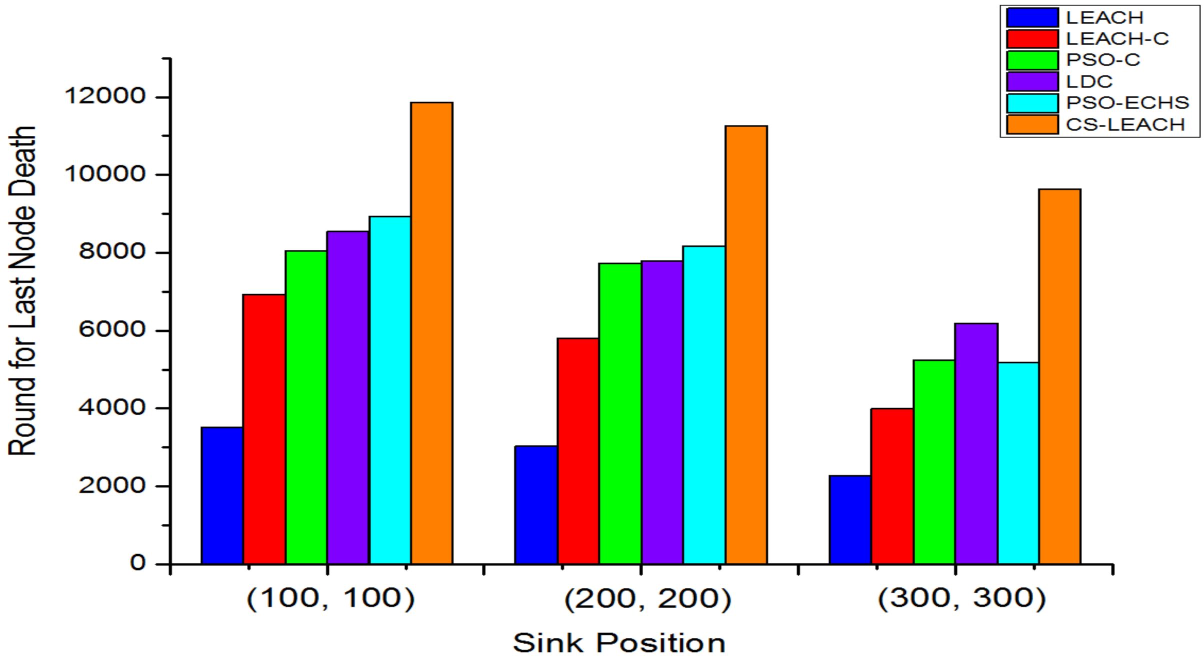


Figure 8.49 Network lifetime for 500 nodes and 50 CHs at different BS positions

The results suggest that proposed CS-LEACH algorithm has provided better results in terms of round of Last Node Death (LND) compared to other algorithms for all the positions of the base station. The improvement is remarkable in comparison to LEACH and LEACH-C algorithms. The improvement in comparison to PSO-ECHS algorithm has been observed to be about 40% in WSN-2 architecture and about 30% in case of WSN-3 architecture for all the three positions of the base station. The network lifetime for the considered WSN architectures have shown marked improvements in comparison to the WSN-1 architecture since the number of nodes and simultaneously the number of cluster heads have also increased enhancing the clustering process of the network. The network lifetime declines for base station at corner or out of the field in comparison to base station at center for all the algorithms. However, this decrement is less for the proposed hybrid CS-LEACH approach in comparison to the other considered algorithms. This suggests that the designed objective function for selection of cluster heads based on the residual energy of the nodes and distance between the CHs and the sink node has provided fruitful results for the proposed technique.

The designated cluster head in the network needs to perform more functions than a normal sensor node as it executes all the duties of data collection, data aggregation and data transmission in the network. Thereby, the energy consumption is highest in case of CHs than at the normal sensor nodes creating a high chance that a single node fixed as cluster node throughout the duration of operation resulting in early dying out of that node due to quick energy depletion. Sudden death of a cluster head in the network would have affected the network performance since the communication links would break down affecting the network lifetime. This was the primary reason why the random rotation of CHs based on residual energy of the nodes was undertaken at every round of data transmission. As the proposed approach attained the objectives of lesser energy consumption and network lifetime enhancement, the number of data packets successfully transmitted to the control station was also increased. The superiority in comparison to existing techniques and the efficiency of the proposed algorithm in all the test cases helped to establish this algorithm as one of the best suited technique for wireless network design for large applications.

A statistical study of the results obtained through the proposed CS-LEACH algorithm and the comparisons with other algorithms related to last round of node death helped to validate the claims about the supremacy of the proposed technique.

8.4.3 Statistical Comparison of Last Round of Node Death with other Algorithms

In order to verify the uniformity in the results obtained through CS-LEACH algorithm, the program was made to run for 15 independent trial runs to obtain the results for the round of last node death and energy consumption in the network. The initial parameters for simulation for all the 15 trial runs have been considered to be same as the parameters calculated in Table 8.21 and the base station has been considered to be placed at a fixed co-ordinate (100, 100) for all the trial runs. Initially 300 nodes have been considered to be deployed in the network, out of which a maximum of 5% of the nodes are permissible to remain as the cluster heads. The statistical study of the obtained results has been done through histogram plot and Q-Q plots while the comparative study with other algorithms has been done using box plot.

The histogram plot for the round of last node death considering a maximum of 15 permissible cluster heads in the network has been depicted in Figure 8.50. The results suggest that for most of the trial runs, the round of last node death has been found to lie between 10000 to 10500 rounds. The mean value for the 15 trial runs has been obtained to be 10285 which suggested that the obtained results from CS-LEACH algorithm follow the rule of central tendency for statistical distributions.

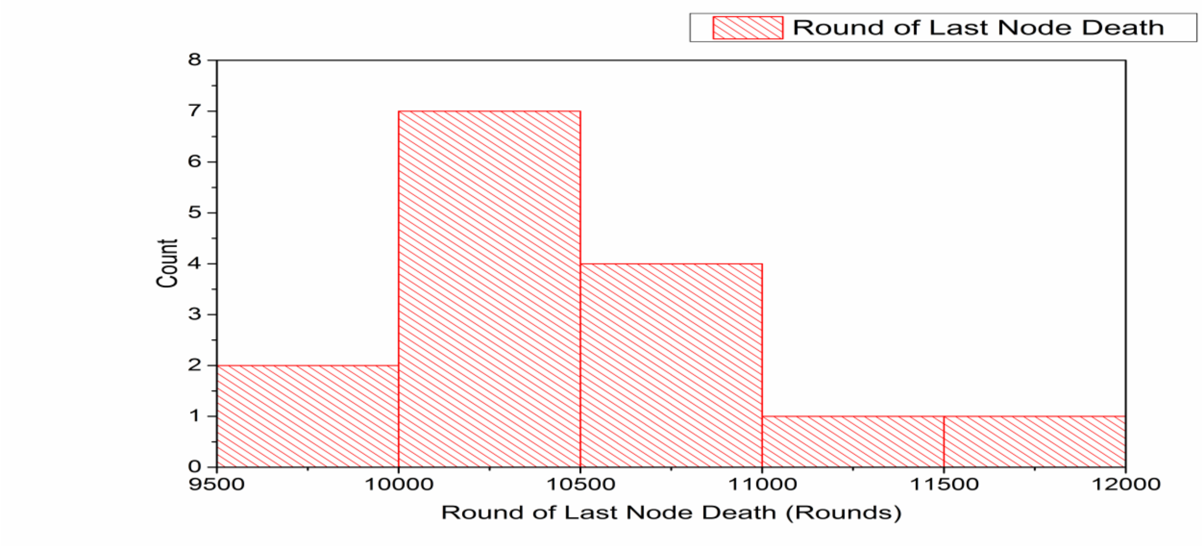


Figure 8.50 Histogram plot for round of last node death for 15 trial runs for 15 cluster heads

The statistical study about the energy consumption of the network has been done using Q-Q plot which is demonstrated in Figure 8.51. From the Q-Q plot, it can be found that the values related to energy consumption in the network obtained from the 15 trial runs lies more or less close to the 45^0 line drawn through the origin. This suggests that the distribution of the obtained through 15 trial runs follows a normal distribution. The mean value of the energy consumption over 15 trial runs has been obtained to be 722.04667 with a standard deviation of 14.29. The cluster of the data near the center of the line suggests that the distribution has followed the rule of central tendency as most of the values have been obtained close to the mean with a very low standard deviation.

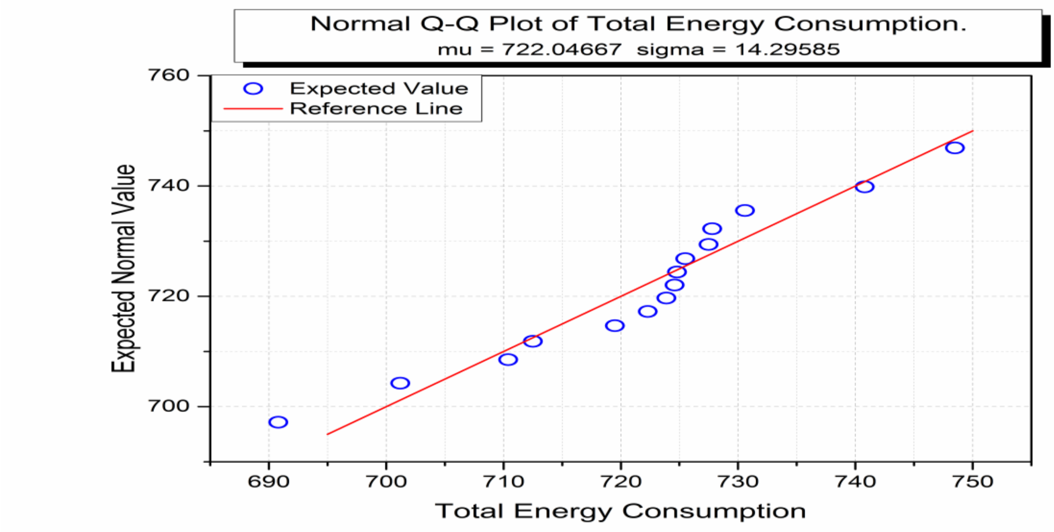


Figure 8.51 Q-Q plot for total energy consumption over 15 trial runs for 15 cluster heads in the network

The test of the superiority in the performance of the proposed technique in comparison to existing algorithms available in literature namely LEACH, LEACH-C, PSO-C, LDC and PSO-ECHS in terms of round of last node death has been obtained by box plot analysis. Figure 8.52 depicts the box plot to study the betterment of the results obtained through the proposed technique over the other techniques.

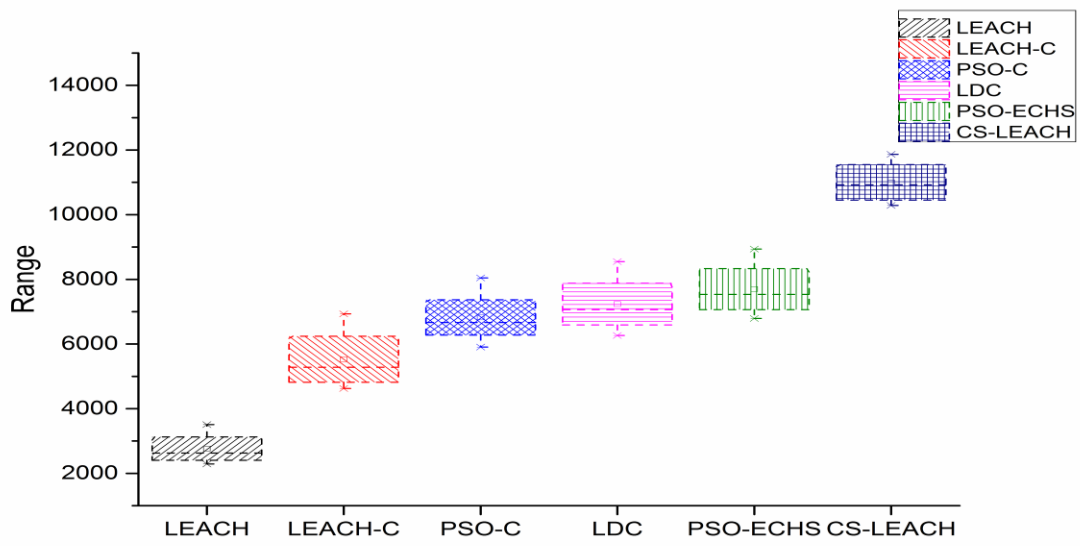


Figure 8.52 Box plot in terms of comparison of round of last node death

For the following statistical analysis, four different network architectures with four different cases based on variation in the number of node deployments have been studied. The range of value for the round of last node death for these considered conditions has been obtained. The highest and lowest values form the upper and lower boundary of the boxes formed related to each algorithm. As the range between the highest and the lowest value varies for the algorithms, the boxes are of different dimensions during the analysis. But it can be seen that the range of the values obtained through the proposed CS-LEACH approach has provided better values compared to other algorithms for any number of cluster heads considered in the network. This statistical comparative analysis of the proposed technique helped to prove the effectiveness of the proposed technique to enhance the lifetime of the designed wireless network.

The different approaches that have been proposed in this work till now helped to enhance the reliability of the network through C-CSA technique and improved the network lifetime by help of REDCR algorithm. The cost effectiveness achieved through lesser replacement of dead nodes due to lifetime enhancement makes it suitable to be used in different applications. Such an application of wireless network application to balance the home energy usage in order to earn cost benefits was tried in the next part of the work. The results related to appliance shifting based on the ToD tariff structure by help of bi directional signal flow between the deployed sensors and Emu was achieved through WSN framework. The load reduction during peak periods helped to establish the suitability of the wireless network to form a controlling architecture in home energy management infrastructure.

8.5 Economic Benefits achieved through Home Energy Management Scheme

The results obtained for the designed Home Energy Management Scheme based on Cuckoo Search Algorithm depicted that the appliance schedule generated by this approach had resulted in reduction of energy cost during the operation of the appliances in one bungalow of the considered area. The results of appliance shifting obtained through this energy management scheme suggested that the load during the peak tariff periods had been efficiently reduced through this energy management scheme. The appliance schedule generated has also satisfied the input constraints of customer satisfaction along with earning economic benefits. This same energy management scheme was planned to be implemented in the 50 bungalows of the chosen area having almost the same load profile. The proposal of introduction of prosumers in the network has also been entertained who are involved in power generation from the rooftop solar panels. The houses being considered in the same geographical area suggests that they achieve same type of solar insolation. This helped to create a small rooftop solar park in the area which sells off its generation to the traditional grid to generate more economic benefits for the low demand prosumers.

8.5.1 Appliance Shifting to ensure Demand Side Management

The designed energy management scheme helped shifting of the load from the peak periods to the mid peak periods and the appliances running in mid peak period to off peak periods. While designing the schedule for the appliances, the customer’s need regarding the number of times an appliance is operated during the day and the comfort hours of operation for the customers were taken care. In order to design the schedule, a maximum waiting period of 4 time periods equivalent of 2 hours is considered as a limiting constraint for all the appliances.

Table 8.22 Status of appliances before and after DSM

Time of Run	Appliance 1		Appliance 2		Appliance 3		Appliance 4	
	Before DSM	**After DSM**	**Before DSM**	**After DSM**	**Before DSM**	**After DSM**	**Before DSM**	**After DSM**
1	OFF	OFF	*	*	*	*	*	*
2	**ON**	**ON**	*	*	*	*	*	*
3	OFF	OFF	*	*	*	*	*	*
4	OFF	OFF	*	*	*	*	*	*
5	OFF	OFF	*	*	*	*	*	*
6	OFF	OFF	*	*	*	*	*	*
7	OFF	OFF	*	*	*	*	*	*
8	OFF	OFF	*	*	*	*	*	*
9	**ON**	**ON**	*	*	*	*	*	*
10	OFF	OFF	*	*	*	*	*	*
11	OFF	OFF	*	*	*	*	*	*
12	**ON**	**ON**	*	*	*	*	*	*
13	OFF	OFF	OFF	**ON**	*	*	*	*
14	OFF	OFF	OFF	**ON**	*	*	*	*
15	OFF	OFF	**ON**	**ON**	*	*	*	*
16	OFF	OFF	**ON**	**ON**	*	*	*	*
17	OFF	OFF	**ON**	OFF	**ON**	**ON**	*	*
18	**ON**	**ON**	**ON**	OFF	**ON**	**ON**	*	*
19	OFF	OFF	OFF	OFF	OFF	**ON**	**ON**	**ON**
20	OFF	OFF	OFF	OFF	OFF	**ON**	**ON**	**ON**
21	OFF	OFF	OFF	**ON**	**ON**	OFF	**ON**	**ON**
22	OFF	OFF	OFF	**ON**	**ON**	OFF	OFF	OFF
23	OFF	OFF	**ON**	**ON**	OFF	OFF	OFF	OFF
24	OFF	OFF	**ON**	**ON**	OFF	OFF	**ON**	OFF
25	OFF	OFF	**ON**	OFF	OFF	OFF	**ON**	**ON**
26	OFF	OFF	**ON**	OFF	**ON**	**ON**	**ON**	**ON**
27	OFF	OFF	OFF	OFF	**ON**	**ON**	OFF	**ON**
28	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
29	**ON**	OFF	OFF	OFF	OFF	OFF	**ON**	OFF
30	OFF	OFF	OFF	OFF	**ON**	OFF	**ON**	OFF
31	OFF	OFF	**ON**	**ON**	**ON**	OFF	**ON**	OFF
32	OFF	OFF	**ON**	**ON**	OFF	OFF	OFF	OFF
33	OFF	**ON**	**ON**	**ON**	OFF	OFF	OFF	**ON**
34	OFF	OFF	**ON**	**ON**	OFF	**ON**	**ON**	**ON**
35	OFF	OFF	*	*	OFF	**ON**	**ON**	**ON**
36	**ON**	**ON**	*	*	**ON**	OFF	**ON**	OFF
37	*	*	*	*	**ON**	OFF	OFF	OFF
38	*	*	*	*	OFF	OFF	OFF	**ON**
39	*	*	*	*	OFF	**ON**	OFF	**ON**
40	*	*	*	*	OFF	**ON**	OFF	**ON**
41	*	*	*	*	OFF	OFF	*	*
42	*	*	*	*	OFF	OFF	*	*
43	*	*	*	*	OFF	OFF	*	*
44	*	*	*	*	OFF	OFF	*	*
45	*	*	*	*	**ON**	OFF	*	*
46	*	*	*	*	**ON**	**ON**	*	*
47	*	*	*	*	OFF	**ON**	*	*
48	*	*	*	*	OFF	OFF	*	*

*represents **NOT** in the selected time period of operation

Table 8.22 represents the time periods during which the appliances remain switched oon before the appliance schedule is generated and the suggested time periods from Energy management Unit (EMU) after DSM. The appliance 1 in the observation table refers to the microwave oven, appliance 2 is the induction oven, appliance 3 depicts the air conditioner while the computer is represented by appliance 4. Based on the number of times the appliance is required to be switched on and the specified time zones of operation in Table 7.5, the appliance shifting results have helped to satisfy the customer's needs. The control signals from the EMU to co-ordinate the appliance operation are transmitted by the help of the implemented WSN communication architecture that ensure minimal appliances run during the peak period. It is seen from the appliance operation schedule in Table 8.22 that the customer's require all the appliances to run simultaneously during the peak periods from time periods 23 to 32. This peak period suggested the evening hours from 5Pm to 10Pm when most of the family members of any household remain at home and thereby utilization of the modern appliances increases during this period. In order to reduce the energy consumption during the peak period, the operation of the appliances have been tried to be shifted to the next mid peak period as much as possible. For example, appliance 3 which initially started operating in the 30th time period within the peak pricing slot was shifted to the 34th and 35th time period of the next mid peak period. The same result has been seen for an instance of appliance 4 when its operation got shifted from the 29th time period to the 33rd time period. However, at some instances, for example appliance 3 in the 26th time period and appliance 4 in the 24th time period is needed to be switched on immediately during the peak period itself since the waiting period of the appliance suggested by the EMU crossed the limitation of maximum delay of 4 cycles to get shifted to the mid peak period. On the other hand, considering appliance 2 which has an operation duration of 4 cycles needed to be switched on during the 31st time interval within the peak period since the appliance was allowed to operate only upto the 34th time interval. Similar instances of appliance shifting has been seen for appliance 3 whose operation has been shifted from the second mid peak period to the off peak period as only appliance 3 is working during the off peak period. The last operation of the appliance 4 has been found to be switched on during the 36th time period since the time zone of operation of this appliance is limited to the 38th time period. The time intervals which do not lie within the comfort hours of operation of the appliances has been denoted by the symbol '*'. The effect of controlled appliance shifting by help of wireless sensor network becomes more prominent when the load distribution over the entire day and energy consumption during the peak period is studied.

8.5.2 Load Reduction

The study of the load reduction attained through the energy management scheme especially in the peak periods contributes mainly to the economic benefits attained throughout the course of the day.

8.5.2.1 Peak Load Reduction

The pie charts demonstrated in Figure 8.53 suggests the load consumption of the households during the different tariff periods before and after the demand side management scheme has been applied. The areas under the curve help to identify the decrement of load consumption during peak periods and increment in consumption when the tariff is low.

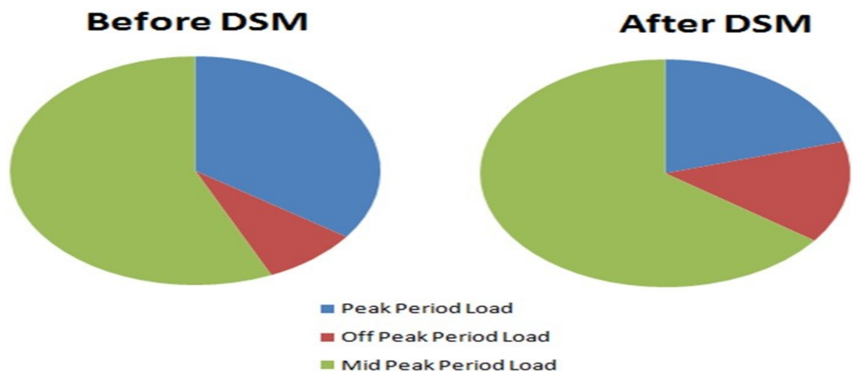


Figure 8.53 Distribution of load over the various periods before and after DSM

The results obtained from the pie charts depicting energy consumption during the different zones over the day before and after DSM suggest that the load during the peak period is considerably reduced through the considered energy management scheme. The load consumption designated in this section includes both the shiftable and the non-shiftable loads such as light, fan, etc which consumes about 4-5kW over the course of the day. The load consumption during the peak tariff period was initially 34.8% of the total energy consumption over the course of the day. After the DSM has been applied, the energy consumption considerably reduces and equates for only 20.4% of the total energy consumption. This amount of load from the peak periods is shifted to the mid peak and the off peak periods showing an energy consumption during these periods. The load consumption during the off peak period increases from 8.45% to 14.6% after the DSM has been applied and the increase in load consumption during the mid peak period is also considerably visible. These results proved that the proposed scheme has efficiently controlled and coordinated the operation of the appliances to attain economic benefits through demand side management. The study of the variation of the load consumption over the course of the entire day would help to give a better idea about the load shifting in the home environment.

8.5.2.2 Difference in Energy Consumption over the day

The variations obtained in the load consumption pattern before and after DSM have been depicted in Figure 8.54. The 24 hour of operation from 6AM on one day to 6PM on the next day is divided into 48 equal time periods and the load consumptions for each time period has been studied. The peak period has been considered for the time periods 23-32. The load consumption during this period is seen to be largely reduced through the energy management scheme. The constraint input that the load consumption in a certain time interval should not exceed 2KWh has been well maintained through the designed energy management scheme. However, there is a sudden increase in load consumption in the 33rd time period and 39th time period. This is because, the loads which were active during the peak period has been shifted to the first interval of the mid peak period satisfying the limitation of the waiting period resulting in sudden increase of the load. Similarly the loads shifted from the mid peak to the off peak period increased the energy consumption during the 1st time period of the off peak period which is the 39th time interval.

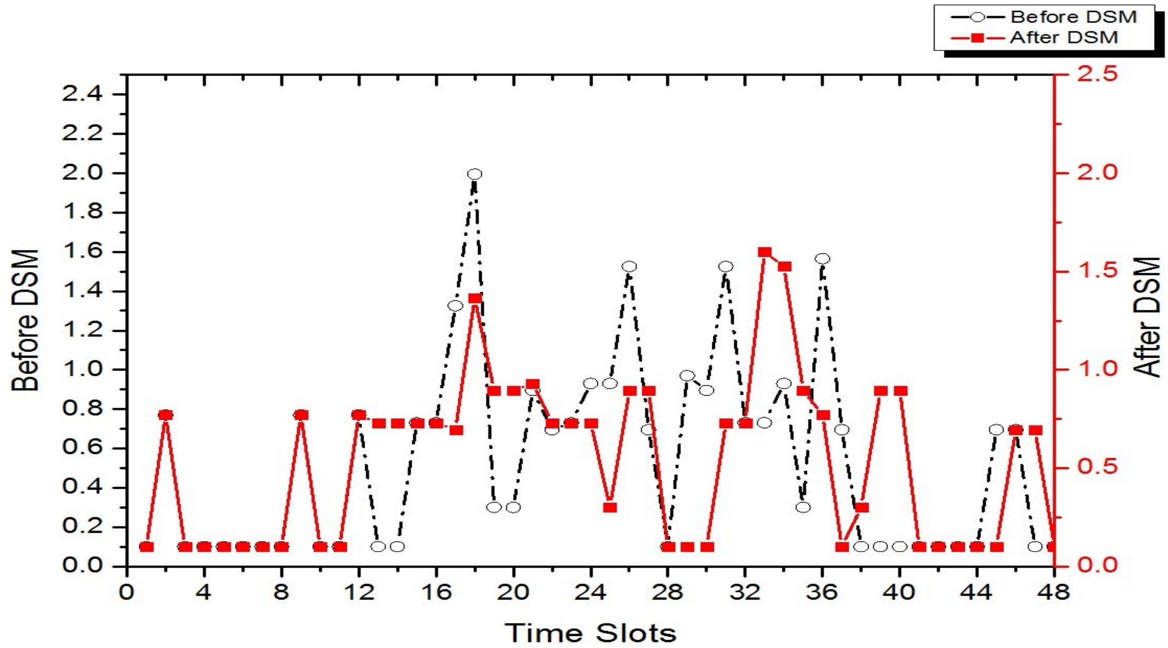


Figure 8.54 Comparison of load distribution over the entire day

Over the course of the entire day, it is seen that demand side management has been duly achieved since there is overall load reduction during the peak periods and increase in load consumption during the off peak periods. This energy management scheme has shown prominent effects on the economic aspect of residential energy management.

8.5.3 Monetary Benefits through Load Shifting based DSM

The energy management scheme designed through Cuckoo Search Algorithm has been made tom run over 50 iterations to find out the minimum cost that can be achieved from the implemented energy management scheme. The final results related to the shifted run hours of operation for the individual appliances are determined based on the minimum energy cost obtained through the Cuckoo Search algorithm.

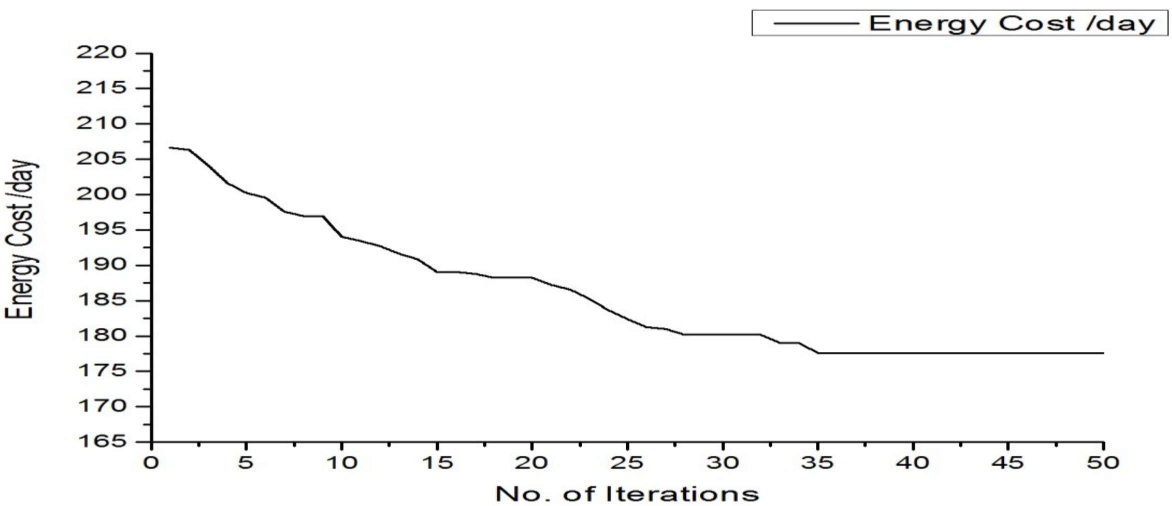
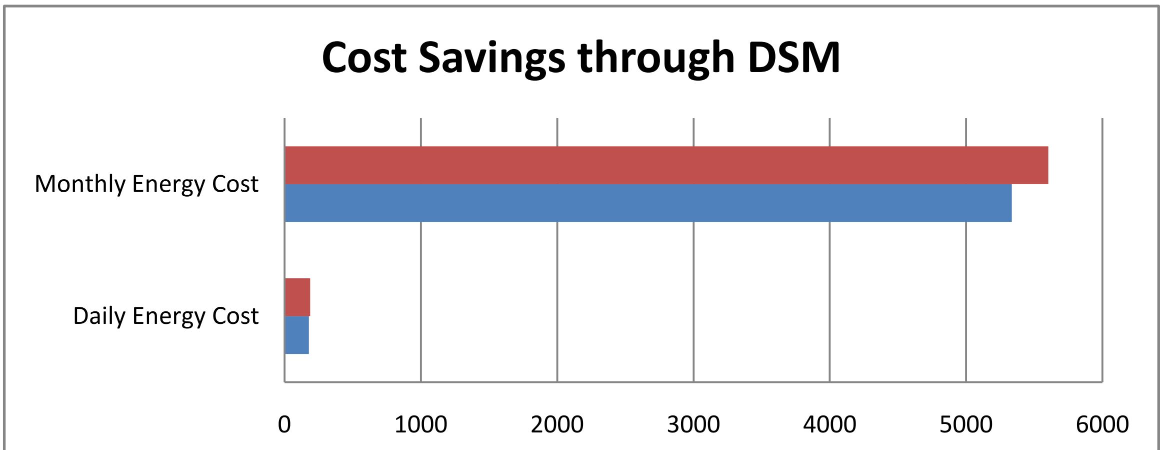


Figure 8.55 Convergence analysis of energy cost/day with number of iterations

Figure 8.55 plots the convergence curve for the energy cost per day against the number of iterations. The optimized result obtained at the end of 34th iteration evaluates the minimum cost for energy consumption over a day as Rs 177.87. A comparison of the energy costs before and after DSM based on daily basis and monthly basis would help to analyse the cost efficiency attained through this energy management schemes. The cost savings obtained through controlled load shifting by the proposed energy management scheme has been evaluated on daily and monthly basis and is depicted in Figure 8.56. The results suggest that the cost savings obtained over the course of a day is found to be Rs 8.865 equivalent to $0.129 based on the average dollar rate. The savings over the course of a month has been obtained to be about Rs 266 or $3.88. The annual economic benefits through the designed energy management scheme for a particular household has been obtained to be Rs 3235.85 or $47.24 which is quite a large amount considering a single house. Taking into account all the considered 50 houses in the society are subjected to similar types of load shifting and economic benefits over the year, the total annual profits achieved by the central co-operative power distribution unit is calculated to be Rs 161791.725 or $2361.93.The efficient switching of the appliances accomplished through the control and monitoring architecture framed by the wireless network has helped in earning such huge economic benefits in the different households. This proves efficient design of communication architecture attained through proper placement of wireless nodes proves to be an apt tool for real time monitoring and control when cost-efficient demand side management for residential environments are planned.



	Daily Energy Cost	Monthly Energy Cost
Before DSM	186.7362	5602.086
After DSM	177.8709	5336.127

Figure 8.56 Cost savings obtained through load shifting by the proposed energy management scheme

In order to achieve additional economic benefits, installation of rooftop solar panels in all the households has been planned that generates power based on the available solar insolation. The generated power from all the households is accumulated in the central co-operative power distribution unit which feeds back the generated energy to the traditional grid. The power distribution companies buy back the power generated from these resources and adjust the amount with the customer electricity bill. The installed solar panels are also continuously monitored by the wireless networks to evaluate the power generation from these panels and assess the performance of the system over the course of several years. Efficient monitoring of these systems ensures large amount of power generation from these sources which helps to add to the profits obtained from the demand side management scheme and generates a low payback period for the solar installations.

8.5.4 Economic Benefits obtained through Rooftop Solar Installation

The modern houses have a rooftop area of about $350ft^2$ to $400ft^2$ which is ample to install the rooftop solar panels. The thumb rule states that $10m^2$ or about $125ft^2$ of rooftop area can support solar panels of 1kW power capacity [385]. This suggests that the following rooftops can support installation of rooftop solar panels upto a maximum capacity of 3kW in each household. Considering 50 bungalows are present in the considered residential area, the minimum capacity of the solar installations has been considered to be 50kW and it can support a maximum capacity of 150kW in the network. Similar types of solar panels are intended to be installed in the network and considering the availability of the sunlight is uniform throughout the area, the capacity utilization factor for the installed solar panels has been considered to be constant. Here, the houses have been considered to be present in the eastern parts of India where the availability of sunlight is relatively higher. The Capacity Utilization Factor (CUF) for these parts of India has been typically considered to be 19% [385]. The generated energy from the rooftop solar panels is sold back at Rs 6.45/kWh which is the weighted average of the tariffs considered throughout the day. The installation cost of solar panels in India is considered as Rs 55 per Watt for installations ranging from 10kW to 100kW by Ministry of Non Renewable Energy, Government of India [386].

The economic analysis related to the profits earned and the payback period for the solar installation of sizes 50kW to 150kW is represented in Table 8.23. The annual profit obtained through selling of the generated solar power to the grid is added with the economic benefits earned from the energy management scheme applied to the entire area of 50 bungalows. The payback period for the different sizes of solar panels is evaluated by dividing the initial investment costs by the total annual profits generated at the end of the year.

Table 8.23 Cost and payback period analysis with rooftop solar installation

Parameters	**Rooftop Solar Installation Size**				
	50kW	**75kW**	**100kW**	**125kW**	**150kW**
Energy generated/year (in kWh)	83220	124830	166440	208050	249660
Income from selling power to grid (in $)	7836.04	11754.06	15672.09	19590.1095	23508.1514
Total yearly benefit from DSM and rooftop solar (in $)	10197.963	14115.983	18034.013	21952.0325	25870.0744
Installation cost of solar panel (in $)	40145.99	60218.98	80291.9708	100364.964	120437.956
Payback period (in yrs)	3.93	4.26	4.45	4.57	4.65

*The calculations have been made considering the current rate of 1$ = Rs 68.5

Installation of 1kW solar panels at the rooftops of each household yields the lowest payback period along with considerable profits from the solar panels. The total rooftop solar installation of 50kW has generated annual profits of $10197.963 through the solar installation energy management system and has yielded a payback period of 3.93 years. With increase in the size of solar installations, it has been seen that the profits earned for the prosumers has increased. But installation of higher sizes of solar panels also increases the initial investment costs of the solar panel and the payback period for the installations. The results depicted in Table 8.23 provides a complete details about the profits and the payback periods related to the different sizes of solar installation in the considered locality with 50 bungalows.. A solar PV module comes with a warranty of 25years from supply. However, there is a chance of degradation in the performance of the solar panels after 6years which might affect the output from the solar panels. Considering the rooftop will have enough empty space to install 2kW panel, a balance between the initial investment costs and the profits to be earned in the future has been considered. The design based on generation of 100kW solar power will ensure that the installation costs and the payback is not high while generating considerable amount of profits thereafter.

The decreasing solar prices would help to lower the payback period and larger solar installations can be thought of to support the traditional grid in times of excess demand. This proposed model for the prosumers involving energy management scheme and power generation at households from solar panels can be undertaken by different companies for business purposes to earn excess revenues. The competence of the wireless sensor network as the monitoring and the control tool for home energy management schemes has helped to predict future smart grid network designs for wide area implementations in university campuses for load levelling throughout the area.

8.6 Future Smart Grid Network Design for University Campus

The cost benefits and the peak load reduction obtained through the designed energy management scheme for home environment scenario can attract engineers to implement smart grid networks for a university campus. The wireless sensor network can be integrated with this smart grid architecture to form the communication architecture in the network. A future smart grid architecture planned for the university campus has been depicted in Figure 8.57. The planned architecture considers conventional supply as the main source of electricity supply while additional PV panels and wind turbines have also been proposed to be implemented at the rooftop of the university campus [404]. Different sensors and actuators are planned to be employed at various sections of the university campus to monitor the load consumption at those sections. The wireless nodes act as tags to collect data from the sensors to make up the smart meters of the planned network [404]. The monitored data is transmitted in digital form to the control station by help of the intermediate routers placed at optimal positions decided by soft computation algorithm. The data stored in the central control station helps to recreate the entire application area and the performance of the different sensors at the different locations has been analyzed. The control signals generated from the control station are transmitted back to the sensors to manage the operation of the sensors in the network. Therefore, the designed WSN architecture helps to develop a bi-directional communication framework between the sensors and the control station. The performance of the renewable sources installed in the rooftop is also monitored and the control signals instruct them to support the loads during times of peak demand. Monitoring of the data from the different sensors in the control station also enables engineers to detect if any abnormality is observed and control measures can be undertaken accordingly.

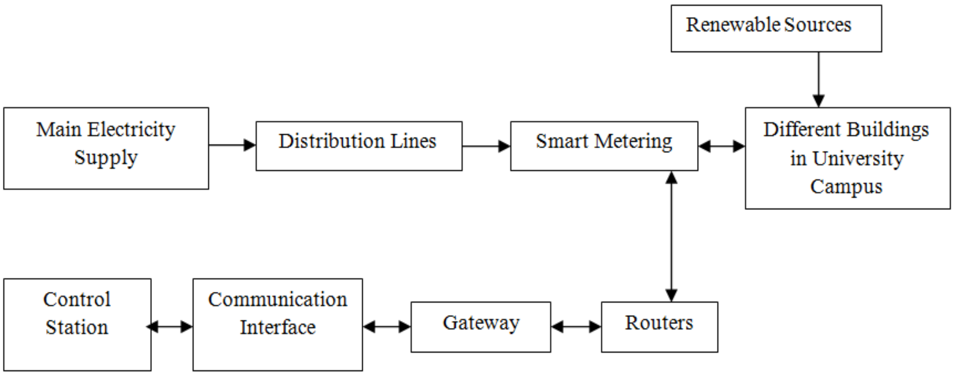


Figure 8.57 Proposed smart grid network design for JUSL campus

The proposed smart grid network architecture has been planned to be implemented in the Jadavpur University 2nd campus, Kolkata, India. Figure 8.58 provides the satellite view of the distances between the tags placed and the control station of the planned network.

Figure 8.58 Satellite view of node arrangement in Jadavpur University Saltlake Campus [21]

The positions of the wireless devices acting as tag in the network to collect data from the employed sensors have been shown in the figure from a satellite view by help of Google Maps [405]. The distances between the control station and tags suggest that a direct communication pathway cannot be established between the tags and the control station since the distances exceed the maximum range of transmission of the nodes. Thereby, these tags need intermediate routers to form the communication architecture. Some of the tags are placed at such far away distances that the tags need two or more routers. A few of the tags, for example the tag placed in the hostel, needs two or more intermediate routers to pass its information to the co-ordinator which stores data in the control station. The comprehensive implementation plan suggested through the intermediate positioning of the routers provides a detailed idea about the communication architecture developed through wireless network for efficient and continuous monitoring of load distribution in different areas of the campus.

8.6.1 Placement of Nodes in the University Campus

A better representation about the arrangement plan of the tags and the routers in the entire campus has been represented in Figure 8.59 [404].

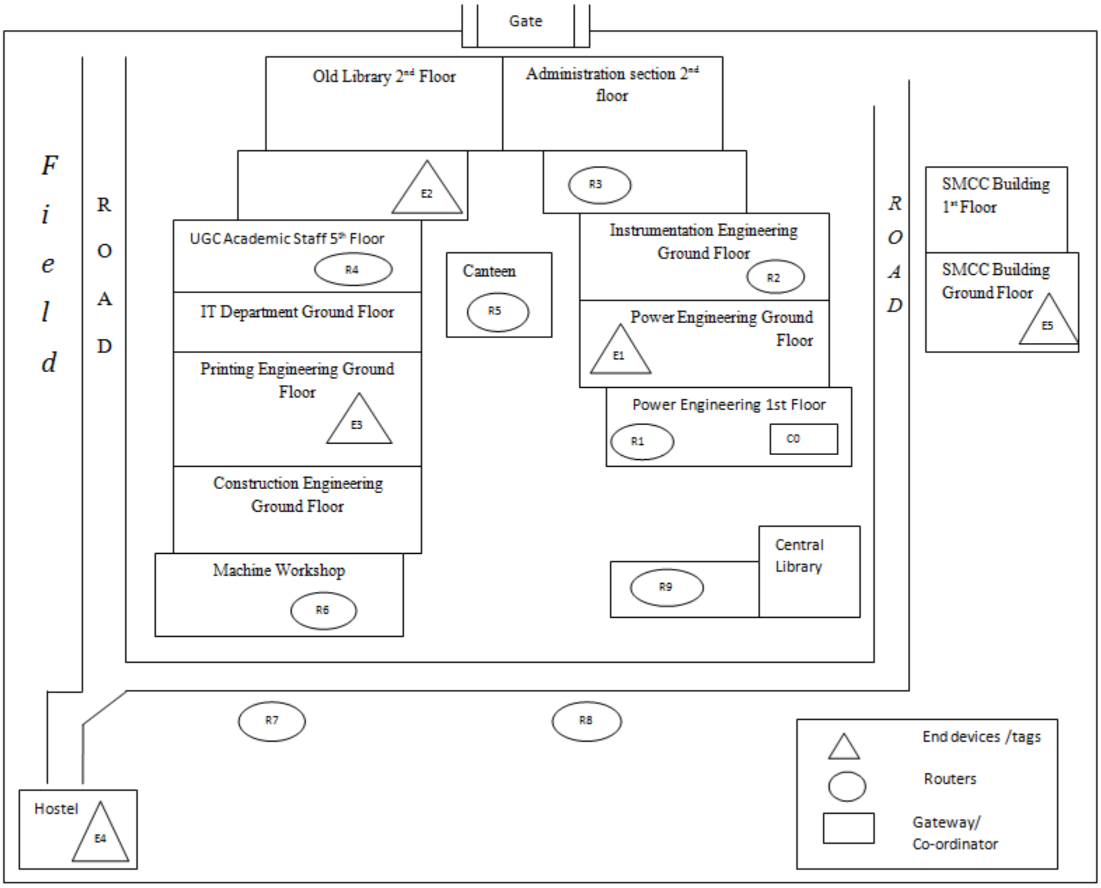


Figure 8.59 The detailed network architecture

Five end devices/ tags represented as *E1* to *E5* have been positioned at five parts of the campus to collect the data related to the load consumption of that particular section of the campus. It is seen that the tag *E1* has been planned to be placed in the ground floor of Power Engineering Department, tag *E2* in the administrative building, tag *E3* in the ground floor of Printing Department, *E4* in the hostel and the tag *E5* will be placed somewhere in the School of Mobile Computing and Communication (SMCC) building. The routers represented by *R1* to *R9* will be distributed throughout the campus by determining the best positions based on soft computation techniques to form reliable network architecture. The co-ordinator or the gateway node represented by *C0* aggregates the data in the network and stores it in the control station positioned in the 1st floor of Power Engineering department. The control station GUI software helps to recreate the entire application area and displays the data collected from the different areas simultaneously in the software suite. The arrangement of the nodes has been preferred through mesh network topology to ensure high quality network performance related to data communication in the network.

8.6.2 The Network Communication Topology

The works performed in the earlier segments have suggested that better quality of data communication is achieved through mesh topology making it most suitable for smart grid networks. The arrangement of the nodes and the communication pathways established between the different nodes has been shown in Figure 8.60 [404]. The data and the signal flow between the employed sensor nodes have been found to be bidirectional in nature for all the deployed nodes in the network. The positions of the intermediate routers have been established based on the maximum transmission range of the nodes, thereby requiring optimal number of routers to build up the entire communication framework. The tags are functional to transmit their data to the control station by involving at least one intermediate router in order to design a proper schedule for data collection in the control station. This precaution helps to prevent the data overhead in the control station that might result in data loss in the network. The tags are directly associated with the sensors and actuators present in the network to collect the information and transmits the data to store it in the control station. Any alarming condition, such as over usage of energy at any particular section or failure of the sensors to collect the data, can be easily identified from the software suite in the control station and accordingly alarm signals in form of light or sound are sent out to the malfunctioning area in the reverse path from the control station to the respective tag. The tag feeds the signal to the actuator to close an appliance or the operation of the particular section in the aim to restore normal conditions. Clustering principle has been employed during data transmission to ensure one node amongst the mesh acts as the cluster head to aggregate data from multiple nodes in the network. This approach helped to reduce the data overhead and data collision in the network which may result in the loss of data.

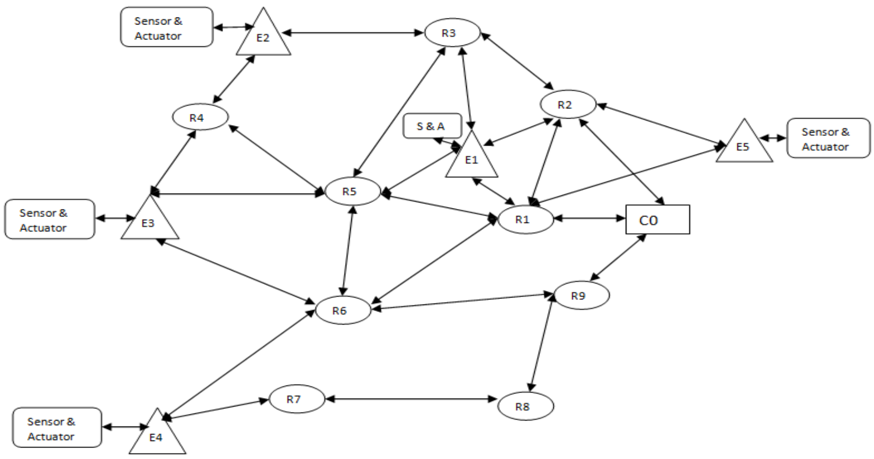


Figure 8.60 The bidirectional communication framework

Table 8.24 depicts the available pathways from each tag to the control station [404]. All the tags have been provided with a multi path communication facility to ensure that the data communication does not stop if one of the nodes in the proposed pathway fails. The pathway for data communication is determine by the OSPF protocol which enables data transmission to take place through the available shortest path. In case, there is failure in one of the available pathways or is found to be engaged in data transmission, the other available pathways are utilized by the tags to transmit the tag to the base station. Low number of routers would result in design of poor communication links that may stop to operate during node failure. On the other hand, large increase in routers number may result in higher signal crossover and interference. This necessitates choosing of an optimum number of nodes as the routers which would help in designing a multi hop multi path architecture ensuring a reliable loss less data transport in future smart grid networks.

Table 8.24 Multipath arrangement for data transmission in the proposed network

End Devices / Tags	Available Pathways
E1	R1→C0
	R2→C0
E2	R3→R2→C0
	R3→R5→R1→C0
	R4→R5→R1→C0
E3	R5→R1→C0
	R6→R1→C0
	R6→R9→C0
E4	R6→R1→C0
	R6→R9→C0
	R7→R8→C0
E5	R1→C0
	R2→C0

The results and the analysis related to the reliability enhancement and lifetime improvement of the designed wireless networks has shown considerable improvements related to other works in literature. The node deployment strategy in the considered problem has helped to minimize the signal attenuation largely. Detection of the interference in the network has helped to identify the sources of the data error in the network and accordingly the node placement has been planned. The minimization of the packet error ratio through C-CSA has helped to create a reliable wireless network and the performance related to packet error ratio has improved in comparison to the existing clustering and routing algorithms. The statistical analysis of the C-CSA with other previous works has also established the superiority in performance of the proposed soft computation approach. The router placement efficiency tested through C-CSA has proved that the network coverage has been attained to be maximal while the signal overlaps is minimized. The cost benefit analysis for node placement in wide area monitoring networks showed that for wider areas and larger number of nodes, the mesh network topology for wireless network design proved beneficial. The joint clustering and routing protocol designed in this work named Residual energy based Distributed Clustering and Routing (REDCR) protocol helped to attain lifetime increment based on residual energy conservation. This proposed protocol utilized hybrid utilization of CS and LEACH algorithm. The novel approach of selecting cluster heads based on residual energy of the nodes helped to balance the load amongst the nodes in the network. Performance analysis based on variation in number of cluster heads and different base positions showed superiority in performance of the designed protocol compared to other existing works. The results and the analysis for the different problems considered related to the wireless networks based on enhancement of network reliability and lifetime have provided future researchers new ideas about the implementation design of the wireless network. The suitability of the application in home environment monitoring has been utilized in the last part of the work as the communication architecture in home energy management scheme. The data monitored from the different appliances are stored in the control station. Based on the tariff structure over the course of the day, the energy management unit (EMU) schedules the operation of the appliances and the control signals are sent to the appliances by help of the wireless network. Rooftop solar panels for low demand prosumers has been suggested that helps to earn more cost benefits for the customers. The cost benefits earned from the energy management scheme and selling of the power generated from the solar rooftops has helped to reduce the payback period for solar installations. The Cuckoo Search based home energy management scheme for household appliances has helped to draw attention towards wireless network as the best monitoring tool for the home energy monitoring. Based on the reliable results obtained through utilization of the wireless network, a wider implementation to monitor the load from a university campus has been planned with multipath communication architecture. The next chapter helps to conclude the whole work that has been planned based on the results obtained. The summarization of the attempted objectives of this work has been presented in details. The novelties that have been anticipated at the introduction section have been confirmed through the obtained results in the conclusion part. These results have helped to provide insights to the possible future areas of research that are still unexplored.

Chapter 9

Conclusion and Future Scope

The efficiency related to the implementation of the wireless networks was analysed in this work for indoor network applications. This work mainly focussed on ensuring reliability enhancement and lifetime improvement of the wireless sensor network for indoor network applications. Novel optimization approaches was undertaken to efficiently place the nodes in the designed network and ensure minimization of the signal attenuation in the network. Combination of meta-heuristic techniques had also been attempted in this work to jointly select the cluster heads and position the cluster heads in the designed wireless network. The mathematical formulations related to signal attenuation minimization and cluster head selection has novelty in each of the approaches. The performance improvement related to the designed wireless networks involved more number of node deployments in mesh network topology. Thereby, the cost benefit analysis has been performed in order to ensure the effectiveness of the proposed approaches. The performance of the optimized wireless networks in the indoor network environment has prompted it to be used in home energy management systems as the bidirectional communication architecture in the last part of the work. The results related to the different approaches undertaken was found to be quite superlative proving the competence of this entire work.

9.1 Conclusion

The engineering optimization technique utilized in this worked helps in providing a new direction when applying wireless sensor network to indoor location such as residential complexes, hospitals or university campuses. A modified version of cuckoo search algorithm in form of Cascaded Cuckoo Search Algorithm (C-CSA) helped to simultaneously optimize two parameters through nested loop operation with the aim of reliable and quick convergence. The number of routers and their corresponding positions were optimized by solving the novel mathematical equation formulated to minimize the effects of signal attenuation by help of C-CSA. Ideal scenario demands that the signal attenuation of a wireless network is zero, however the presence of thick walls and other electromagnetic waves do contribute to the signal attenuation when data is being communicated over the wireless links. The proposed approach helped to reduce the chances of data loss since signal attenuation and network interference was highly minimized through proper placement of routers. The statistical reports based on histogram and Q-Q plots proved that the algorithm results for different parameters obtained central tendency for over 50 trial runs. The normality tests like Shapiro-Wilk and Kolmogorov-Smirnov test were employed in this work to find the possible deviations from normality. The non-normality test namely Friedman-ANOVA test and Mann-Whitney test helped to determine dominance of C-CSA algorithm over LEACH-C, HEED, HEFSPM and CHSCDP algorithms. The energy consumption spent while data is being transmitted or received and the packet delivery ratios for the different number of nodes deployment were the parameters tested to prove that C- CSA outperformed previously proposed algorithms. Further, the hardware implementation helped to validate the efficiency of router positioning in indoor area networks. A newly designed parameter termed as "Router Placement Efficiency" helped to study the extent of network coverage attained through the router placement strategy by optimal usage of nodes. This work helped to put forward low cost, low energy WSN architecture suitable for hybrid power systems and smart grid applications.

Analysis of network performance and cost of network set up based on two design schemes viable for wireless network application in wide area data monitoring has also been performed in this work. Application of wireless networks in broad areas such as university campus, residential conclaves or power utilization arena is subjected to signal attenuation due to presence of several walls and other metallic structures. Different scenarios involving variation in the network application area and variation in number of sensor in a particular area was studied based on two design schemes involving star topology and mesh topology respectively. Placement of optimum number of nodes in the intermediate positions helped in reduction of transmission energy from the sensor nodes to the base station for all kinds of network sizes and thereby improved the network run time. The wireless network design based on placement of intermediate routers was found to provide more economical benefits with increase in network area size when operated over long duration. However, when lesser number of nodes was employed in a network area of size 100×100 m^2, data transmission through star topology was found out to be cost beneficial although performance improved through mesh topology. Considering large network areas of size 500×500 m^2, star topology failed miserably since most of the nodes could not connect directly with the base station. In such scenarios, placement of intermediate routers was found to be the only way out. Now it is for the engineers to decide the best network design they want to implement for monitoring data based on the number of nodes, cost benefits and network performance.

In the next part of the work, Residual Energy based Distributed Clustering and Routing (REDCR) protocol is proposed to control the energy usage during wireless transmissions and enhance the network lifetime. Two well known algorithms namely Cuckoo Search Algorithm and Low Energy Adaptive Clustering Hierarchy algorithm were combined to design this algorithm. The newly designed algorithm aimed to jointly solve the problem of cluster heads positioning and energy conservation while data routing in the network. For this work, a novel mathematical formulation was proposed for cluster head selection during every round of data transfer through LEACH algorithm dependent on the residual energy of the nodes. The rotation of cluster heads was ideally helpful when considering large wireless networks. In the next part, the designed fitness function was minimized using Cuckoo Search algorithm. The number of nodes in a cluster, intra and inter cluster distance, the required hops between cluster head to sink and network coverage were the primary factors that determined the fitness function. The performance of REDCR was tested by varying the network scenarios taking into account different node energy and base station positions. The comparative results with other existing protocols such as SEP, MCR, DBMCR and EPCT proved that REDCR protocol significantly reduced network energy dissipation. There was an improvement around 60%, 33%, 15%, 30% and 25% in terms of network lifetime, residual energy of the nodes, network throughput, network stability and scalability when compared to EPCT protocol. The improvements were larger in case of other algorithms. The improvement results proved the superiority in performance of the REDCR algorithm. This work also presented a comparison of the network based on the variation in number of cluster heads in the network involving Cuckoo Search Algorithm and LEACH algorithm. The simulation results along with the comparison with other existing algorithms namely PSO-ECHS, LDC, PSO-C, LEACH-C and LEACH algorithm shows the superiority in the performance of the algorithm compared to the other algorithms. This algorithm has been tested extensively for different scenarios considering different positions of the sink node and different number of cluster heads in the network. The proposed algorithm performed better than the existing algorithms when considering the total energy consumption and the network lifetime. It was seen that the energy consumption of the network was minimal when sink node was placed at the centre of the application area compared to the sink node at the corner or outside of application area. The percentage improvement in network lifetime compared to the most recent PSO-ECHS algorithm was seen to be more for the architecture with 300 nodes and 30 cluster heads compared to the architectures consisting of 400 or 500 nodes representing dense deployment of the nodes. The number of cluster heads was varied in the WSN-1 architecture in two scenarios and it was seen that choice of optimal number of cluster heads and their efficient positioning helps to reduce the energy consumption in the network considerably. Thus this approach of cluster head selection has proved to be an efficient one.

Wireless sensor network controlled autonomous demand side management scheme has been proposed in the last phase of the work to optimally schedule the working of the appliances in a renewable integrated residential energy system. An area consisting of 50 bungalows of similar power consumptions has been considered and the appliance run off time shifting program has been applied to all the households. The main aim of the designed approach was to reduce the peak hour load demand and thereby reduce the electrical energy cost. Wireless sensor network helps in bidirectional communication of the monitored data from the appliances of each of the bungalows considered in the area to the Energy Management unit and the flow of control signals in the reverse path. The customer's needs and comforts related to the time period of operation of the devices and a limited waiting period has been taken as the input constraints while scheduling the appliances is the novelty of this work. Application of Cuckoo Search Algorithm to jointly schedule the appliance operation and minimize the energy cost based on Time of Day (ToD) tariff scheme is another unique feature of this work. Considering the current rate of \$1= Rs 68.5, the optimization results suggest that a cost saving of \$0.129 has been achieved per day through this optimization approach which accumulates to a saving of \$47.24 annually. Renewable integration in form of rooftop solar installation has been suggested and the sizing of the solar panels has been performed. The energy generated by the rooftop solar is accumulated in the co-operative power distribution unit which sells back the generated power to the traditional grid. A rooftop solar installation of maximum capacity of 100kW has been considered to be installed that has a payback period of about 4.45 years. This scheme of integration of the renewable in form of solar with the demand side management along with the rooftop solar installation proved to provide cost savings of around $18034.013 annually proving the proposed approach of residential energy management a cost effective one.

9.2 Future Scope of Work

The proposed algorithm in form of C-CSA can find future applications in engineering optimization problems which are based on optimization of two inter related parameters which needs to be taken care simultaneously to find the best possible result. C-CSA can also find implications in other fields such as environmental pollution monitoring applications, structural health monitoring problems and so on. Reserved power sources, improved resolution and node transmission ranges of the kits would involve lesser number of kits and simplify the network architecture in future. The proposed REDCR algorithm has considered efficient positioning of the cluster heads to determine the multi-hop routing path but no routing algorithm has been implemented to validate the routing in real life scenario. The integrated approach to jointly attempt clustering and routing in WSN would become a necessity soon for real time applications. In future, incorporation of factors like communication channel quality, noise in transmission channels and transmission delay have been planned in the proposed problem to test the performance of REDCR protocol. Future works can focus on hardware implementation of the nodes by the proposed approach and test the data routing through any existing routing algorithm. The proposed protocols can be tested in three dimensional uneven areas to know the efficiency of the algorithms. Other meta-heuristic algorithms can also be implemented to this problem to study the improvement in performance, if any. The proposed algorithm can be put to use to heterogeneous networks consisting of static and dynamic nodes. The author of this work, with the help of his research group, has thought of implementing the proposed idea and the novel techniques in real life scenario problems with the help of industries.

Future research works in the demand side management can focus on generation of power from several other hybrid systems in the customer end. The current tariff structures of electricity and dependence of the grid power on conventional sources has been considered for the current problem. But the dependence of the energy production on renewable and decreasing cost of the renewable sources may lead to increased economic benefits in the near future which may lead to different business propositions. Storage devices can be integrated to the hybrid systems and bidding strategies can be employed to utilize this stored energy at times of excess demand. Several other meta-heuristic techniques can be implemented to these problems and comparative studies can be made to obtain better results related to peak load reduction and minimal energy cost. The network performance and the data delivery need to be improved especially when these are implemented in future smart grids. Future works can focus on integration of the ZigBee technology with other wireless technologies such as Wi-Fi or GSM available for implementation in different applications. Integration of GSM technology with the ZigBee technology would enable the customer to control the different appliances and devices even from long distances. The ZigBee based wireless network would help to provide the local control while the necessary information and the alarming situations can be informed to the user easily through the GSM technology even if the user is millions of kilometres away. The user can accordingly take decision about how to control the devices when it is not possible to be physically present. Transmission delay is unwanted in case of real time applications such as in health monitoring, as well as power plants where delay in data delivery may have fatal results. A major upcoming problem is the background noise in the transmission channels which causes interference with the Radio Frequency signal communications resulting in fading of the signals due to which some data is lost. Future research works must focus on development of different protocols to balance between energy consumption of the network and reduced transmission delay to ensure maximum throughput of the system. Integrating mini solar panels or other renewable sources with the wireless kit with a mini storage unit to reduce the cost of operation and ensure continuous reliable communication architecture can be thought of in the near future. Energy back-up systems in the wireless kits can also be thought of to ensure continuous power supply to the node to prevent node failures. Several algorithms pertaining to encrypted data delivery with less computational complexities can be developed in order to prevent data loss in the network. Further technological developments in the transport layer of networking can be conceived to ensure minimum congestion at each transmission links and to avoid data collision in the network. Modified secure, reliable and energy efficient approaches of designing network architectures would make WSN the most acceptable tool for data monitoring and measurement in every field of application in near future.

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