ALGORITHMS FOR EFFECTIVE COMMUNICATION IN WIRELESS BODY AREA NETWORK

Thesis Submitted by

SRIYANJANA ADHIKARY

DOCTOR OF PHILOSOPHY (ENGINEERING)

Department of Information Technology
Faculty Council of Engineering & Technology
Jadavpur University
Kolkata, India

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Supervisors Details

Name: Prof. Samiran Chattapadhyay
Designation: Professor
Institution of the Supervisor:
Department of Information Technology
Jadavpur University, Salt Lake Campus
E-mail: samiranc.ju@gmail.com
Kolkata-700106
West Bengal
India

AND

Name: Prof. Sankhayan Choudhury
Designation: Professor
Institution of the Supervisor:
Department of Computer Science and Engineering,
University of Calcutta, Salt Lake Campus
E-mail: sankhayan@gmail.com
Kolkata-700098
West Bengal
India

List of Publications

Journals

1. Sriyanjana Adhikary, Samiran Chattopadhyay, Biswajit Ghosh, Sankhayan Choudhury, Shubha Brata Nath, Nilkantha Garain. “Reliable routing in Wireless Body Area Network using optimum number of relay nodes for enhancing network lifetime” in J. Ambient Intell. Smart Environ. 14(2):135-153,2022.

2. Biswajit Ghosh, Sriyanjana Adhikary, Samiran Chattopadhyay and Sankhayan Choudhury. "Achieving Energy Efficiency in a WBAN through Optimal Placement of the Relay Node" in Wireless Personal Communication 130, 1861–1884 (2023). https://doi.org/10.1007/s11277-023-10361-z

3. Sriyanjana Adhikary, Samiran Chattopadhyay and Sankhayan Choudhury. "Mitigate Inter-WBAN Interference in Body-to-Body Network to Restrain Epidemic Spread" accepted in SN COMPUT. SCI. 4, 68 (2023). https://doi.org/10.1007/s42979-022-01459-5

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1. Sriyanjana Adhikary, Biswajit Ghosh, Sankhayan Choudhury. “QoS Enhancement in WBAN with Twin Coordinators” in Advanced Computing and Systems for Security Springer, Singapore, 2021. 85-97.

2. Sriyanjana Adhikary, Samiran Chattopadhyay, and Sankhayan Choudhury. "A Novel bio-inspired algorithm for increasing throughput in wireless body area network (WBAN) by mitigating inter-wban interference" in Advanced Computing and Systems for Security Springer, Singapore, 2018. 21-37.

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PROFORMA – 1

"Statement of Originality"

I, **SRIYANJANA ADHIKARY** registered on **06/04/2018** do hereby declare that this thesis entitled"**ALGORITHMS FOR EFFECTIVE COMMUNICATION IN WIRELESS BODY AREA NETWORK**" contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is 8%.

Signature of Candidate:

Sriyanjana Adhikary.
——————————

(Sriyanjana Adhikary)
Date : 27/01/2023.

Certified by Supervisors:
(Signature with date, seal)

Samiran Chattopadhyay
PROFESSOR
Deptt. of Information Technology
JADAVPUR UNIVERSITY
Block - LB, Plot - 8, Sector - 3
Salt Lake, Kolkata - 700098, India

1. ——————————
   (Samiran Chattopadhyay)

Sankhayan Choudhury
Professor
Department of Computer Science & Engineering
University of Calcutta

2. ——————————
   (Sankhayan Choudhury)

PROFORMA – 2

“CERTIFICATE FROM THE SUPERVISOR”

This is to certify that the thesis entitled ”**ALGORITHMS FOR EFFECTIVE COMMUNICATION IN WIRELESS BODY AREA NETWORK**” submitted by Mrs. **SRIYANJANA ADHIKARY**, who got her name registered on **06/04/2018** for the award of Ph.D. (Engg.) degree of Jadavpur University is absolutely based upon her own work under the supervision of **Prof. Samiran Chattopadhyay, Department of Information Technology, Jadavpur University, Kolkata and Prof. Sankhayan Choudhury, Department of Computer Science and Engineering, University of Calcutta, Salt Lake, Kolkata** and that neither her thesis nor any part of the thesis has been submitted for any degree/diploma or any other academic award anywhere before.

Samiran Chattopadhyay
PROFESSOR
Deptt. of Information Technology
JADAVPUR UNIVERSITY
Block - LB, Plot - 8, Sector - 3
Salt Lake, Kolkata - 700098, India

1. ——————————————————
Signature of the Supervisor
and date with Office Seal

Sankhayan Choudhury
Professor
Department of Computer Science & Engineering
University of Calcutta

2. ——————————————————
Signature of the Supervisor
and date with Office Seal

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Sriyanjana Adhikary

ABSTRACT

Improvement in technology helped society to live a better life in all aspects. Enhancement of computing environmental capabilities of every new gadgets forced human beings to get attracted towards it. Healthcare system also got the essence of using better equipment. As per current healthcare scenario, chronic illness largely accounts for death rate in a developing country like India. These are largely preventable by creating early awareness among people. This created a necessity to regularly check a person's health statistics. The demand of continuous monitoring of a patient became one of the main cost factor for wired structure of healthcare system. Moreover, people became neglected towards health and only consults a doctor when became ill. This reactive nature can be changed if caring for health did not demand an extra attention and a cut off from daily routine. Wireless Body Area Network (WBAN) is a promising solution of shifting the scenario to wireless medium. This architecture ensures 24/7 self-monitoring of a person without hampering daily activities. It also provides consultation from a doctor all the time. Additionally, all the medical history of the person is also digitally present securely without any manual intervention. In the current era, a person is unaware of its own health status. To facilitate this awareness WBAN must be cost effective. As it deals with health data, reliability should be ensured to have an efficient system. Transparency, privacy, access and convenience became the key factors in this system that can revolutionize healthcare sector. The main contribution of this thesis is to present several algorithms for efficient routing, many of which are based on analytical foundation, that can effectively transfer the data in one or more WBAN systems without compromising a number of QoS parameters. The efficiency and effectiveness of these algorithms or protocols are evaluated through extensive simulation which measure several parameters such as energy consumption, transmission power, stability of a network, delay, throughput (PDR) , lifetime of a network, SAR etc. Considering the stringent QoS requirement for a WBAN it has been observed that the current state of the art, though provides numerous solutions, but none of them jointly optimize these parameters. So, there is always a trade off between between one and another. The Healthcare sector based on WBAN deals with critical health data. Classifying the data into proper categories and routing them accordingly is one of the major task in this thesis. We have also identified that SAR is an important parameter that cannot be ignored at any point while dealing with sensors which are on the human body. Many of our proposed protocols attempt to overcome these shortcomings and prove to be much better than a naive algorithm implementing the WBAN IEEE 802.15.6 based CSMA/CA technology.

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CHAPTER 1

INTRODUCTION

1.1 Background and Objectives

"To keep the body in good health is a duty...otherwise we shall not be able to keep our mind strong and clear."
–Buddha

Global trend of increasing population growth rate is 0.49% and death rate is 7.309%. In India, population having age 65 years and above (%in total) was reported to be 6.20% in 2020, according to the World Bank Collection of Development indicators [1], [2]. The burden of chronic diseases is rapidly increasing worldwide. Mostly, diseases like cardiovascular disease, obesity and diabetes leads to untimely demise. The worrying trend is that they have started to appear earlier in life. Further, these chronic diseases do not show any symptoms while in infant stage. Healthcare system in India is reactive in nature; that means, people do not maintain a regular health checkup, rather prefer to be ill, then cured. WHO had projected that by 2020 above 70% of deaths would be caused by the chronic disease in developing country like India.

Chronic ailments are largely preventable diseases if they can be sensed or detected in their early stages. According to modern wired centralised healthcare scenario, patients are only able to get medical treatment and diagnosis after being physically present at any health center or hospital. This hinders privacy and mobility of the patient. It also ensures a high out of pocket cost for travelling along with medical expenses across rural and urban India. Availability of service becomes useless if is not utilised by commons overcoming all barriers. This brings into sharp focus the WHO theme of 2018, which calls for "Universal Health Coverage-Everyone, Everywhere." This ensures that availability of service must be guaranteed with quality of continuous care. Further, they even addressed that progress cannot be limited to only rural area. Basic healthcare facilities should also be there in primary healthcare sectors which was still lacking according to [3] till 2012.

The increasing gap between demand-supply in basic healthcare system urges a smart health ecosystem which ensures technology-enabled patient engagement strategies that

Figure 1.1: Patient Centric Care

improvise prevention of disease, rather than curing them. This demands an urgent shift from disease-centric healthcare system into patient-centric one as given in Figure 1.1 [4]. A person actively participating in making a healthy society is a patient-centric approach. Here, the patient, along with family and friends get involved in decision making method to cure a disease .

1.2 Research Motivation and Approach

Advancement in technology promises an improvement in current healthcare practise by shifting the paradigm from wired (as depicted in Figure 1.2) to wireless nature of communication system (shown in Figure 1.3). As patients become active participants in these types of models, transparency, privacy, access and convenience become key elements in functional healthcare ecosystem. Every individual should be able to monitor his/her vitals 24/7, rather than critical period. This makes them aware of their health conditions. Awareness instigates to promote a healthy lifestyle among communities that is both proactive and preventive. Wireless Body Area Network (WBAN) has been one of the promising technology that has capability to cater all these features.

For patients getting treated for chronic diseases, regular check ups are very important to get details regarding condition of patient or early detection of relapse of the disease. Treatment plan is dependent on 'what-to-monitor', 'when-to-monitor' and 'how-to-adjust'. Specialised bio-sensors can be used to continuously monitor physiological parameters of patients that can prevent them from severe effect of any emergency situations as shown in Figure 1.3. In this architecture, healthcare system becomes proactive and predictive. Being proactive towards your health indicates prevention of the disease rather than curing them.

Figure 1.2: Wired Healthcare Scenario

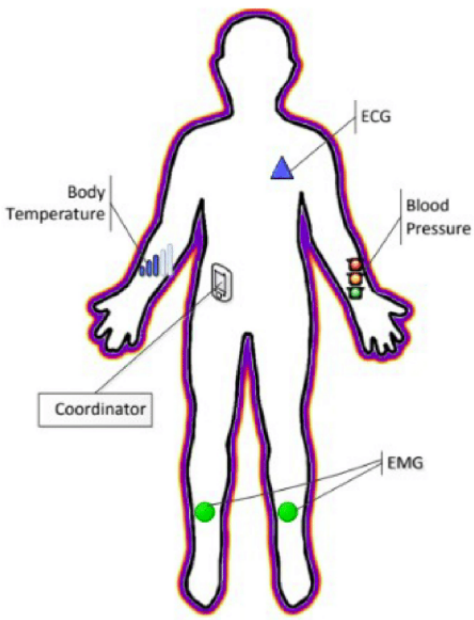

Figure 1.3: Wireless Healthcare Scenario

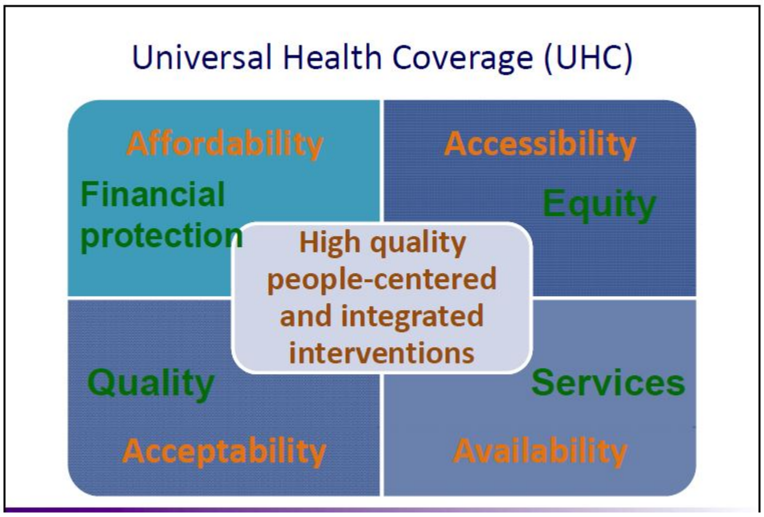

Figure 1.4: Features of Universal Health Coverage

WBAN can keep an eye on its hosts $24X7$ unobtrusively as they communicate in wireless fashion. Sensors in this architecture are miniaturised, non-repetitive and highly resource constrained. Each WBAN enabled person is equipped with multiple sensors attached in, on, or around the body. Each body vital is monitored continuously using an individual sensor. These values give an awareness to the user about his own health status. Thus, these sensors must be in a working condition for the maximum time to capture data and transfer them without eating up the battery power too much. Communicating data from the source sensors to the coordinators must be handled efficiently to have a clarity of the analysis. We must also give an equal importance to the power with which the sensors are transmitting because the heating effect of the sensors affect human tissues. The sensors, thus, must always abide by threshold values of thermal effect. As this thesis deals with impact of WBAN on healthcare sector, delayed delivery of data is strictly forbidden. So, efficient communication can only be possible if we satisfy quality of service parameters simultaneously. This is the pillar of success to shift the healthcare system paradigm from wired to ubiquitous wireless system.

WHO defines *Universal Health Coverage (UHC)* "as a system with a motive of equity in access through promotive, preventive, curative and rehabilitative" health interventions as shown in Figure 1.4. WBAN-based healthcare approaches must satisfy the following features to be acceptable.

- Affordable

  The cost of the proposal must be minimal. This considers all people including the poorest and most vulnerable. This assures financial protection of the system.

- Accessible

  Healthcare system should be designed in such a way that resources are available and it is accessible for every entitled person. This ensures equity of the system.

- Acceptable

Quality of service(QoS) must be maintained for the system to be acceptable. WBAN plays a vital role in maintaining QoS for health data. In this thesis QoS is defined in terms of efficient use of energy to minimize interference, SAR and delay enhancing throughput and lifetime of the network.

- Available

  Full range of good quality health service must be available to the user all the time. Users should access its data anytime anywhere without any hindrance.

Figure 1.5 and Figure 1.6 depict the relationship between QoS parameters, performance metrics with the research objectives. Once the broad research objectives are identified, they are elaborated latter in this chapter and the final outcomes are described latter. For each of these objective, a separate chapter has been dedicated. In these chapters, a proper survey has been conducted on related state of art literature and these are analyzed to identify the research gaps. Finally, new methods are compared latter in these chapters to bring out the novelty and contribution of the thesis.

1.2.1 Research Approach

In this thesis, we have addressed a few problems in healthcare scenario. Studies lead us to pin point the issues which should be addressed immediately to have a better system. WBAN is an emerging technology that has a promising approach to revolutionize medical sector. This can only be achieved if we can effectively communicate health data through this system.

In our work, we have followed a deductive research approach where we start with gripping existing theories relevant to the area of interest. Then test its implications with data. The flow of this type of method is shown in Figure 1.7.

Figure 1.8 shows a flow diagram of how this thesis has been addressed.

Initially we have recognised that medical sector should be proactive rather than reactive nature to have a better health status of every individual. WBAN has the potential to address the issues of current healthcare system if its communication is handled efficiently to effectively transfer health data. Thorough study of WBAN standard protocol (IEEE 802.15.6) has been carried out. Investigations were done on desirable properties of WBAN for designing communication protocols. We have also studied why the existing wireless protocols are inappropriate in this architecture. After reviewing current literature on the area of interest, we have clarity on the research gaps that need to be addressed. This helped us to identify open research problems and propose our research objectives. To verify and validate our proposal we have simulated our models by implementing protocol stack in a simulator called Castalia 3.2.

It is a simulator for low power embedded devices like Wireless Body Area Network, Wireless Sensor Network. This OMNeT++ based simulator provides a platform for researchers to simulate and test their protocols in realistic wireless channel and radio model.

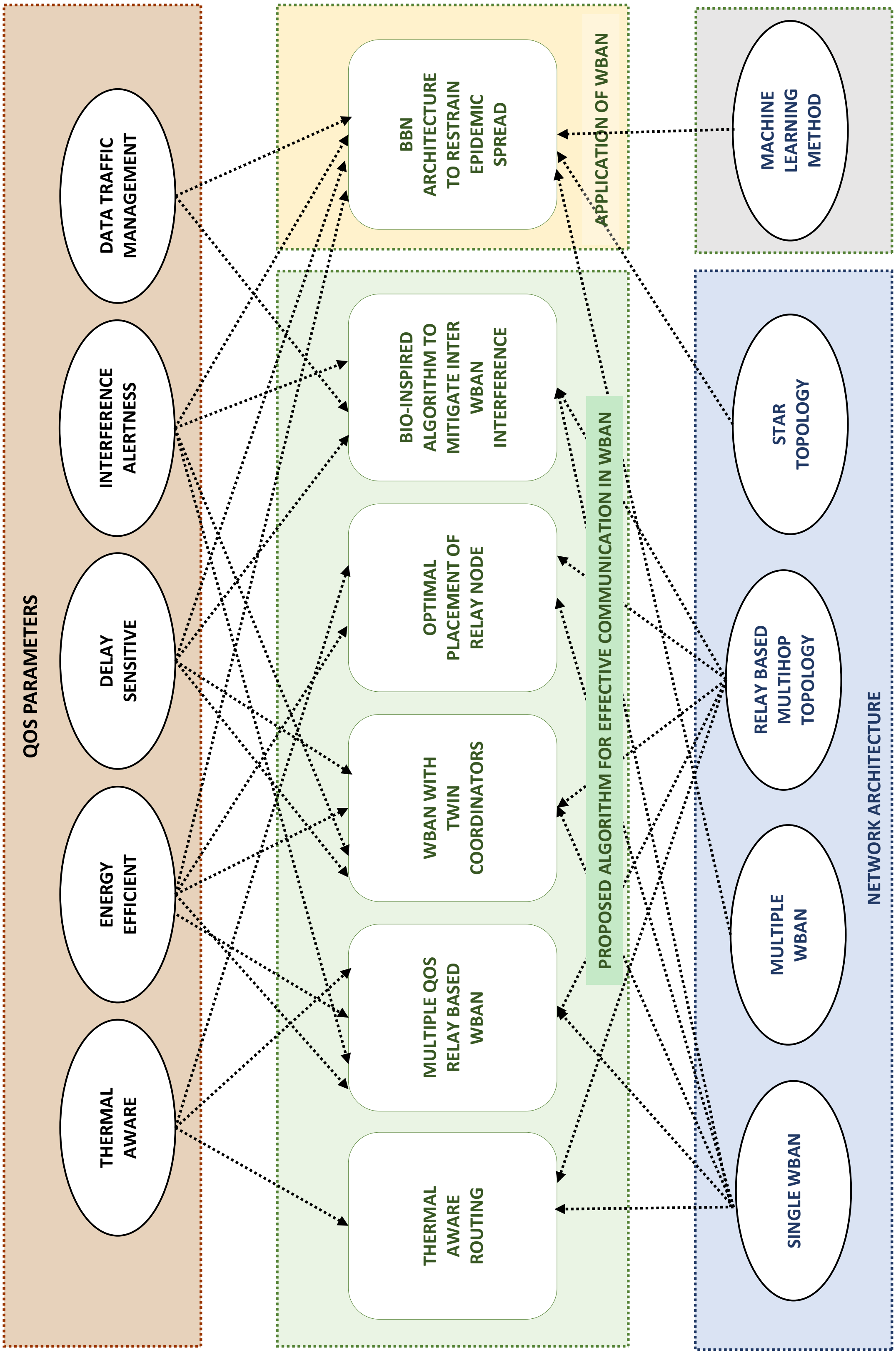

Figure 1.5: Relationship between Qos Parameters and Research Objectives

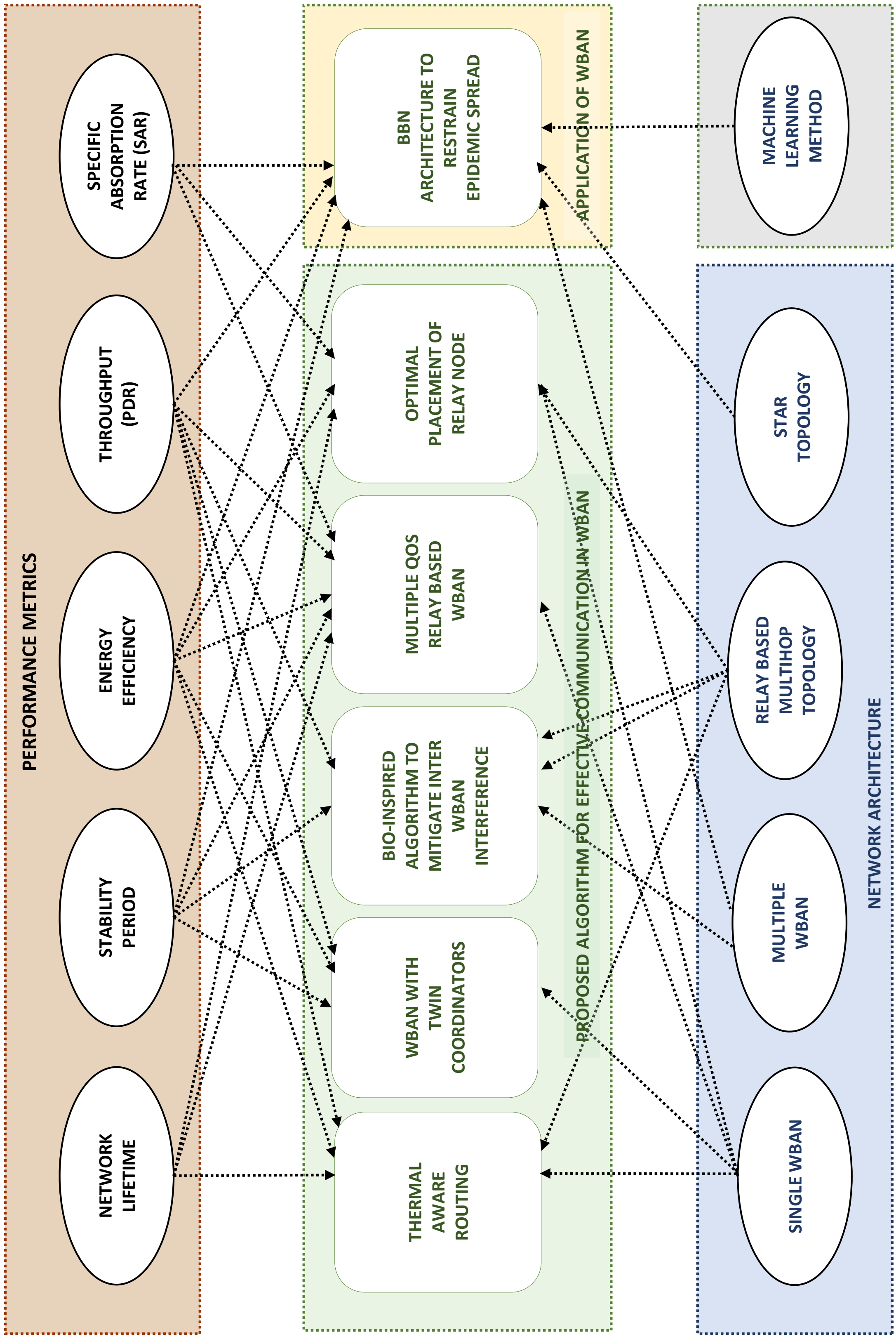

Figure 1.6: Relationship between Performance Metrics and Research Objectives

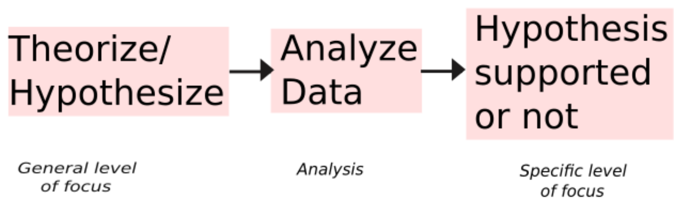

Figure 1.7: Flow of Deductive Research Approach

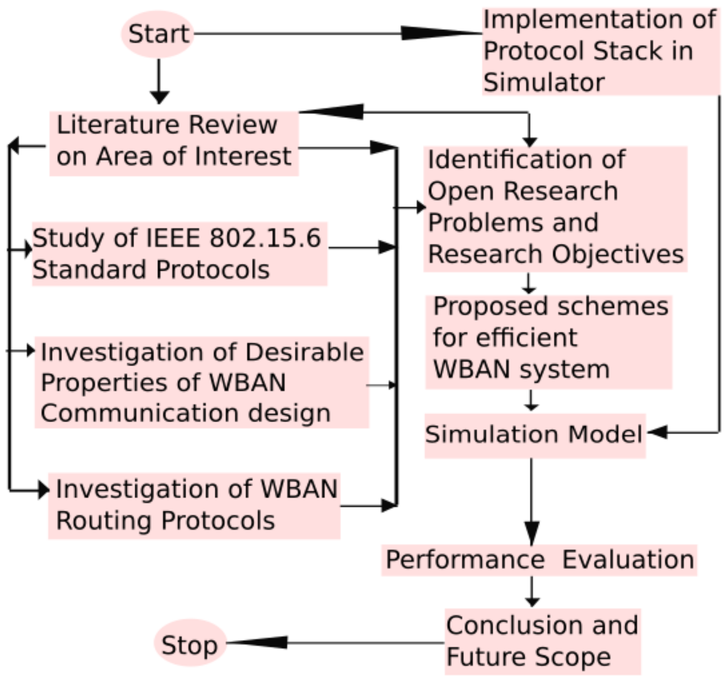

Figure 1.8: Research Approach

Because of its highly parametric nature, various platform characteristics can also be experimented for particular applications.

Performance of our proposed schemes have been evaluated using metrics like consumed energy, stability period, delay, throughput despite interference, Specific absorption rate (SAR) and lifetime of the network. This leads to analyze our system and conclude with future directions.

1.3 Thesis Outline and Main Contributions

Objective of this thesis is summarised as follows.

We aim to design QoS efficient mathematical models and relay based WBAN routing protocols. Number of relays are optimally chosen and strategically placed that pragmatically utilizes remaining energy of sensor nodes. This cooperatively minimizes interference, delay, SAR and hop count of network . Thus,throughput (in terms of PDR), network stability and lifetime is maximized. We further propose a cooperative WBAN network called Body-to-Body Network (BBN) that efficiently suggests a quarantine strategy to minimize epidemic spread.

This thesis comprises chapters which are outlined as follows.

- Chapter 1 provides a vivid introduction on the current healthcare structure. It identifies the gaps and motivates us to change the sector from wired to wireless using WBAN architecture. introduces research background and objectives of the thesis followed by motivation and a flowchart describing the accompanying approach. It also lists our relevant publications.
- Chapter 2 provides an overview of IEEE 802.15.6 protocol. It discusses about architecture, components and challenges faced while designing an efficient WBAN communication system. Background knowledge relevant to the thesis is discussed which is essential to understand state-of-art and issues related to it.
- In Chapter 3 [5], a Multi hop routing protocol for WBAN has been proposed that is efficient in terms of transmitting power, Packet delivery Rate (PDR) and network lifetime. Our approach introduces extra relay nodes. Some relays and sensor nodes act as forwarders based on a multi factor cost estimation function. Some of the factors are power of the node, velocity of the receiver, remaining energy and present position of a node from the coordinator. Simulation studies show that the proposed protocol maximizes network life time and increases packet delivery.
- Chapter 4 [6] focuses on enhancing stability period, packet delivery ratio (PDR) and the remaining energy of the network by decreasing the end-to-end delay. Here, we have incorporated an extra sink node to increase the probability closeness of the coordinator. The concept of anycasting has been modified to implement in a WBAN topology consisting of 8 sensors and 2 coordinators on the human body. The performance of the proposed protocol is compared with other state-of-the-art protocols, like anycasting in dual sink approach (ACIDS), link-aware and energy-efficient scheme for body area networks (LAEEBA) and destination-assisted routing enhancement (DARE). The results show that the modification delivered better quality of service (QoS) results in terms of stability period, packet delivery ratio and end-to-end delay, compare to DARE and LAEEBA and in few cases for ACIDS.
- The objective of Chapter 5 [7] is to reduce interference among multiple WBANs by optimizing their power to transmit. This helps in increasing throughput. The method is to assign available bandwidth fairly. We have used an analytical model to find the threshold of data. The formulation is based on Linear Programming Problem (LPP). We employed a bio-inspired solution using Particle Swarm Optimization (PSO). Simulation results show that the proposed solution converges quickly. It also outperforms 802.15.6 and other existing state of the art algorithms in terms of throughput, packet delivery ratio and retransmission of packets in high mobility scenarios.
- Chapter 6 [8] handles QoS issues like adverse effects of heating of the implanted sensors on human tissues along with energy constraints and interference issues jointly

by designing a topology which has an optimized number of relay nodes and then proposes an efficient routing algorithm. Relay nodes are incorporated to frame the backbone of the connected wireless network so that all sensor nodes are coupled with at least one relay node and none of the nodes in the network remain isolated. In the proposed method, the remaining energy of the in-vivo sensors are dissipated intelligently and homogeneously so that network lifetime is enhanced without compromising reliability. Moreover, in our method, multicasting has been used to reduce transmission of unnecessary packets. Our design also leads to minimum hop count from body sensors to the sink node. The effectiveness and feasibility of our proposed approach has been evaluated and analyzed through numerous simulations. The analysis illustrates the efficacy of the proposed solution in terms of delay, network lifetime, energy efficiency, SAR and throughput.

- In Chapter 7 we have investigated the best location to deploy a relay node on a human body. We assume that an adaptive decode and forward relay node (R) can move linearly between the source (S) and the destination (D) nodes. Moreover, the assumption is that a relay node can be deployed linearly and that the body part of a human is a flat surface and hard. We have investigated the most energy-efficient data payload size based on the optimally placed relay location. The impact of such a deployment on different system parameters, such as distance (d), payload (L), modulation scheme, specific absorption rate (SAR), and an end to end outage

- In Chapter 8 [9], early detection of epidemic is achieved by using multiple cooperating WBANs that leads to a network called Body-to-Body Network (BBN). We have also proposed quarantine strategies by minimizing contact between different staged WBANs based on their health status. An unsupervised learning algorithm is used to efficiently divide the area into non-overlapping clusters minimizing inter-WBAN interference. We have considered two test case scenarios based on how the WBANs are distributed in BBN architecture. Castalia-3.2 simulator is used to evaluate routing protocol in BBN network. Performance of our system is assessed based on network parameters like Packet Delivery Ratio (PDR). Results ensures that our method guarantees low epidemic spread of disease in enclosed area by enhancing throughput and minimising interference of our stable system.

- In Chapter 9, we conclude by summarizing the contributions and the limitations and highlighting some direction open issues for future research.

Chapter 2

Review of Related Concepts and Technologies

2.1 Introduction

This section provides a comprehensive study of Wireless Body Area Network technologies. It also provides the key features of the new technology along with their crucial limitations and assumptions. We also touch upon the issues of routing and congestion which are essential for the subsequent chapters. However, specialized survey per contribution has been detailed in individual chapters.

2.2 Overview of Wireless Body Area Network

Today's 'on-the-edge' world is fast and truly emphasizes on 'time is money'. In this busy world, human beings pay least attention to regular health checkups unless it is called for. Naturally, it takes a toll on both health as well as wealth. So, the necessity of continuous health monitoring without hindering normal routine of a person is the call of the hour. This demand is being supplied by a special wireless network called Wireless Body Area Network (WBAN). Applications on sports, remote health monitoring, self monitoring health, multimedia and many others got attracted by the unconstrained freedom of human movement while the vitals being monitored. To absorb the potential of WBAN, data needs to be communicated efficiently. By the term *efficient* in this thesis emphasized on delivering data from sender to receiver within threshold time, maintaining energy level of individual sensors. This must be maintained to ensure safety of human tissue due to negative effect of heating. Special attention should be given to make sure that interference from other signals do not disrupt data.

To understand the problems clearly, we must first have a clarity of the WBAN system. This is described in details in the following sections.

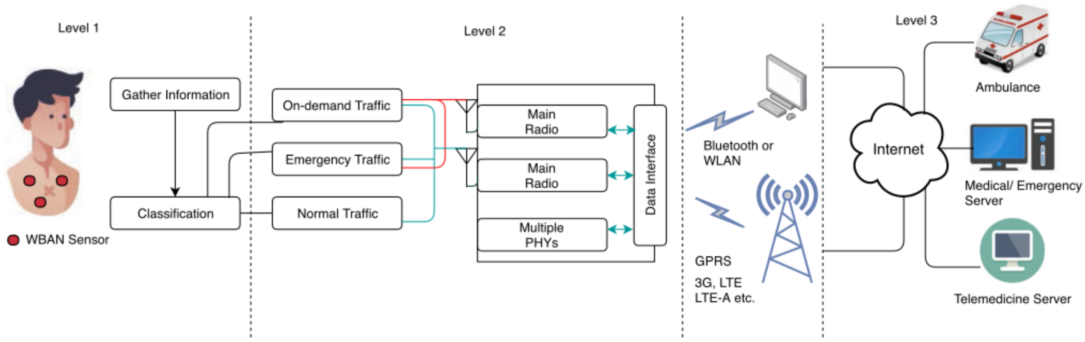

Figure 2.1: A Typical WBAN architecture

2.3 Components of Wireless Body Area Network

A typical WBAN architecture consists of the following components.

- sensors that measure biological parameters.

  Each parameter is measured using a single sensor. No backup sensor is used to collect and transmit the data. Thus, each alive and working sensor indicates continuous monitoring of that health parameter.

- a coordinator on the body that collects all the vitals

  Generally a coordinator is connected with the sensors in a star topology. Transmission of data directly to the sink requires extra power that may be hazardous in case of WBAN. Thus, multihop star topology is most used in this type of system.

- an Access Point that acts as a gateway From every coordinator, data is transmitted to the access point for further sociability. This helps data to be collected, transmitted, analyzed and accessed almost in real time.

- Remote server that transmits data to intended users. From the access points, remote doctors or any intended person can access the health data. He analyses and transmit his decision to the user in real time. Thus, a person can have an eye on his health without hindering day-to-day activities.

Figure 2.1 depicts the orientation of the components in a 3-tier format based on [10]. Communication details amongst the components are described in the following section.

2.4 Communication Architecture

WBAN sensor nodes are placed on the body or implanted inside the skin. They are generally placed in a star or multi-hop topological fashion covering the entire human body. They are connected with the coordinator using wireless communication channel. After receiving, the coordinator categorizes the sensors based on received data traffic. There are generally

3 types: on-demand, emergency and regular (see Figure 2.1). This forms Tier 1 architecture, also called Intra-WBAN communication.

The coordinator, which is also called sink, acts as a gateway. It transmits accumulated data to the access point in a wireless manner. This phase is denoted as Tier 2 or Inter-WBAN in the architecture.

Then comes Tier 3 which is termed as Beyond WBAN. In this zone, data is being transmitted from access points to the intended users where analysis and decisions are taken.

WBAN plays a revolutionary effect in the medical field. A person equipped with WBAN can continuously measure and monitor the biological vitals without affecting regular schedule. The greatest advantage is that the person no longer needs to stay in hospital bed, but can freely does her normal routine without paying any extra cost for hospital bed and miscellaneous expenses. This surely improves quality of life, ensuring diagnosis of health issue at initial stages. Fig 2.2 depicts the role of WBAN architecture in our daily life. This depicts a WBAN enabled person doing daily chores is remotely monitored and is always aware of his health status. Thus, uncertainty is decreased which guarantee a better healthy environment.

To utilize the potential of WBAN, we must take care of its pot holes. The following section describes the challenges and corresponding state of art technologies.

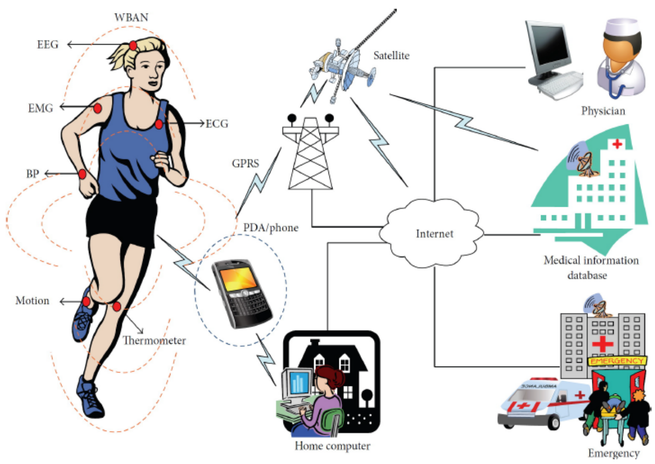

Figure 2.2: Basic Architecture of WBAN

2.5 Challenges, Trends, and Emerging Technologies

Essence of WBAN technology can only be tasted if and only if its effectiveness can be enjoyed by both individuals and healthcare providers. With every advancement in technology sweeps in its own challenges. The major goal towards progress of WBAN is to prevail the basic challenges while solving problems. The basic challenges of WBAN are described as follows.

- Restricted Energy:

WBAN sensors are operated using batteries . They are small and easily portable. Implanted batteries demand a strict power management to ensure efficient usage. The miniaturised sensors cannot sustain more than a month [11]. Efficiency of the system is highly dependent on battery power usage and thus, becomes a challenging issue.

- Damage of tissues due to overheated Nodes:

  Heating up of the sensors may become injurious and hazardous to human tissues. Thus, the system should be carefully designed to minimize the temperature rise.

- WBAN Routing:

  According to the state of art, WBAN routing can be segregated into various types like thermal aware (nodes' temperature should be within permissible limit), delay tolerant (data should get delivered timely), cluster based (number of hops maintained while data being transferred), Cross-layered (multiple layers are optimised in a WBAN to fulfil application specific criteria), Quality-of-service(application specific and user specific criteria are satisfied). ([12],[13], [14], [15] and [16]).

  - Cross Layer Routing:

    According to some researchers ([12], [17]) cross layer routing protocols are not suitable for WBAN applications. In this types of protocols, energy is not utilised homogeneously among all the nodes in the system. As a result of this, hotspots are formed. Thus, some nodes are unable to participate in the network. This situation is dangerous in WBANs, because a single node is responsible to capture and transmit a specific health parameter. Moreover, the overhead of such complex system is impractical for such resource constrained systems like WBAN.

  - Thermal aware routing:

    Detecting a hotspot is a costly affair. This is hazardous as increase in thermal temperature of a node beyond a threshold value negatively impacts human tissue. Thus, researchers ([17] [18]) prioritise thermal aware WBAN routing protocol. Nodes consume energy due to radiation. This energy increases the temperature and may cause damage to sensitive areas of the body [19]. This in turn affect body tissues surrounding the sensor nodes [20].

  - Cluster-based Routing:

    Routing algorithms should be designed keeping in mind that temperature rise of a node must not damage body tissues. These protocols incur high energy during network operations. However, cluster based approaches are the most suitable for WBAN architecture. This is because of its inherent nature of load balancing among the nodes where the cluster or forwarder relays participate to manage the heating effect of the network.

- Security:

  Security issue is as challenging as any other in wireless body area network. There can be mainly two types of attacks. When links between two nodes are compromised active attack is caused where data is captured. This data is then modified and sent back to the receiver. Here, the receiver is not conscious of it being attacked by insignificant malignant data. On the contrary, when data is being silently snooped authoritatively, the user is affected by passive attack. Here also, the user is unaware of its data getting leaked and being available to others. To handle these issues some of the techniques like biometric, mutual authentication, key management are used as mentioned in [21]. Biometric technique obtained about 82% of reliability and 78% of accuracy where as key management scheme [22] obtained 79% of reliability and 81% of accuracy. Mutual authentication scheme [23] also obtained 89% of reliability and 85% of accuracy. Compared to other techniques mutual authentication scheme achieves higher reliability. Most of the current studies deals with security issues of the wireless network link but as WBAN deals with health data, the data itself is highly vulnerable and should be secured in near future. Mutual authentication may also play a vital role in maintaining security in wireless body area network.

- Quality of Service (QoS)

  WBAN applications are not restricted to medical scenarios. They are broadly utilised in non-medical cases also. These applications are real life and life threatening situations demanding to follow specific criteria to guarantee the delivery of data. The end users of this system are either clients or providers. Various applications demand different QoS requirements. A WBAN enabled person would prefer a comfortable wearable device that would be easy and safe to use in term of radio frequencies. They would also accept it in daily life if and only if it is not bothering their daily activities or movement while monitoring the vital stats. They will not get bothered about the details of it. Whereas a WBAN service provider would be careful in terms of accuracy, precision, security, delay, bandwidth. throughput, communication reliability, power consumption etc. Provider would ensure the Quality of service not only to the user but all the users of three tiers of WBAN. Thus, the different forms of categorisation of the term 'Quality of Service' is given in following Figure 2.3 [24].

- Mobility

  WBAN nodes are placed on human body. Data is collected from the sensors attached on or implanted in human body. Though sensors themselves are not mobile, but, movement of a person is not restricted. So, the nodes must follow protocols that are aligned and compatible with human body movements. Environment factors also affect the mobility of the nodes.

2.6 IEEE 802.15.6 WBAN Standard

IEEE 802 established a Task Group called IEEE 802.15.6 with an agenda of standardization of WBAN [25]. This standard specified recent WBAN Physical layer (PHY) and Medium Access Control (MAC) layer.

Frequency bands available and used by different countries are summarised in Figure 2.4 [26].

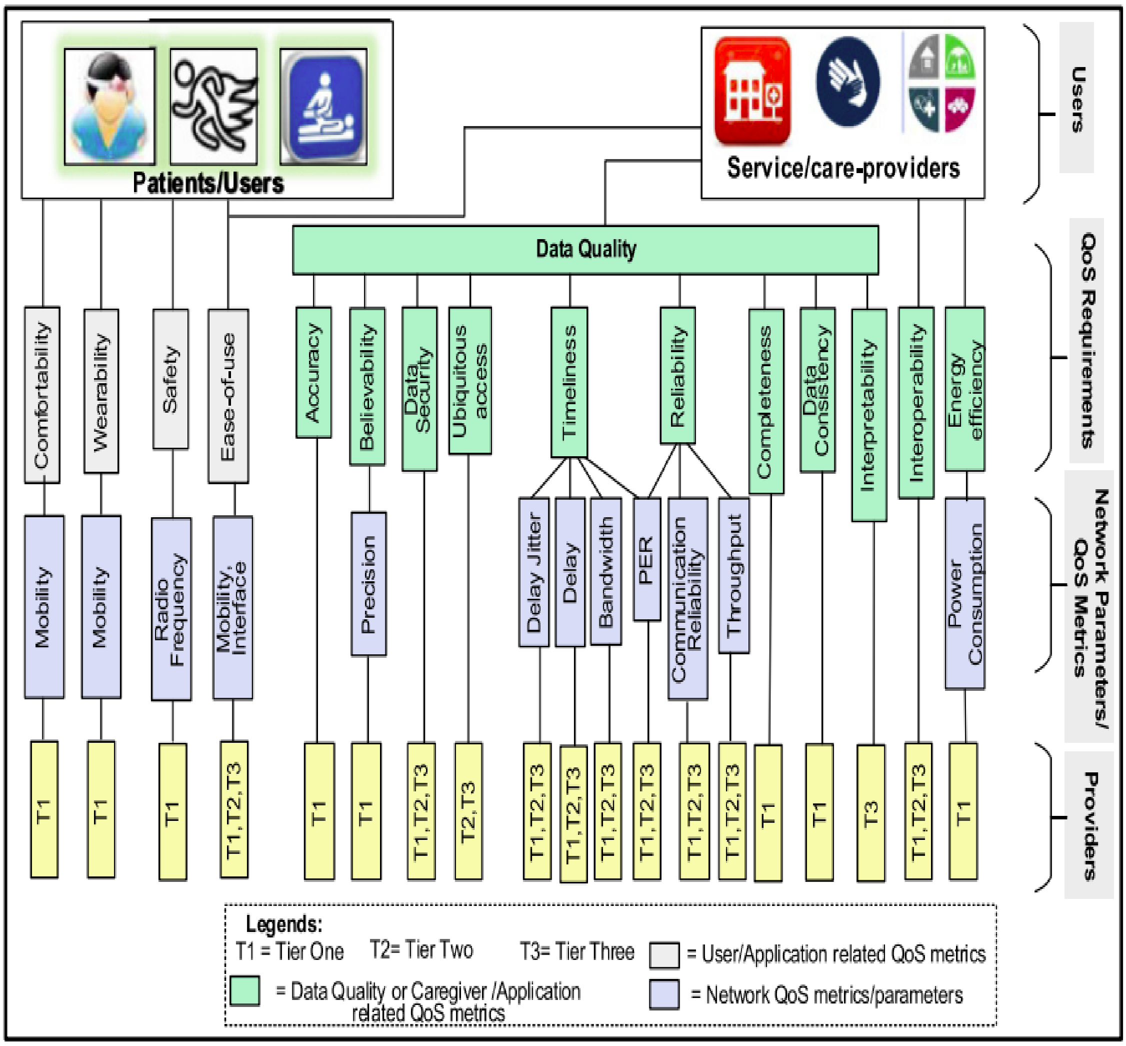

Figure 2.3: QoS taxonomy in WBAN

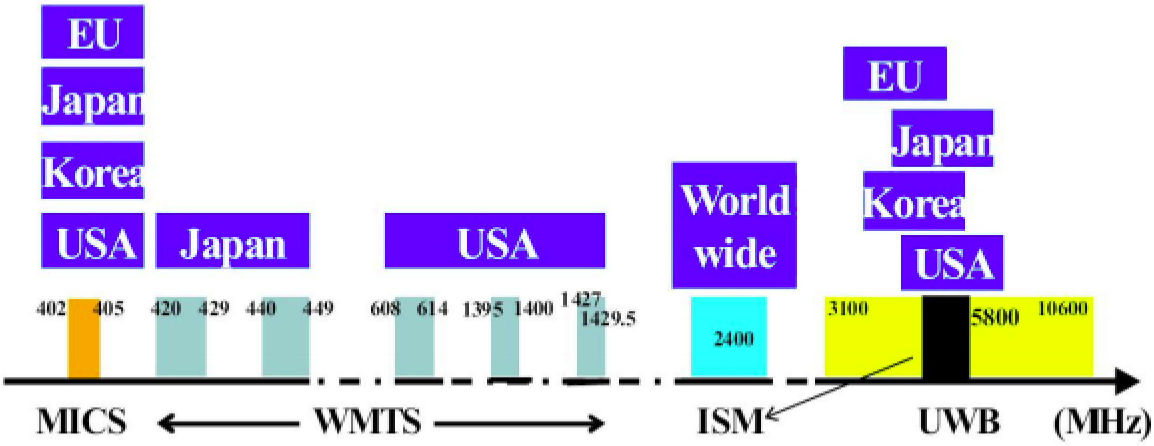

Figure 2.4: Frequency Band of WBAN

2.6.1 Physical Layer

WBAN physical layer establishes a reliable link between a sender and a receiver. The sender transmits binary data through this link. This activates and deactivates radio transceiver.

Narrowband PHY (NB) NB focuses on communication with on body wearable nodes and implanted nodes inside the body. Figure 2.4 shows different channel numbers of operation bands. Any WBAN devise must support transmission and reception in one of these frequencies available. Figure 2.5 shows PLCP header and PSDU. PLCP stands for physical layer convergence protocol and PSDU stands for physical service data uniot. Only Gaussian Minimum Shift Keying (GMSK) technique is used between 420 MHz 450 MHz.

Band (Number of channel)	Packet component	Modulation	Data rate (ksps)	Encoding Rate (k/n)	Signal data rate(kbps)
402~405 MHz (10)	PLCP Header	π/2-DBPSK	187.5	19/31	57.5
	PSDU	π/2-DBPSK	187.5	51/63	75.9
	PSDU	π/2-DBPSK	187.5	51/63	151.8
	PSDU	π/4-DQPSK	187.5	51/63	303.6
	PSDU	π/8-D8PSK	187.5	51/63	455.4
420~450 MHz (12)	PLCP Header	GMSK	187.5	19/31	57.5
	PSDU	GMSK	187.5	51/63	75.9
	PSDU	GMSK	187.5	51/63	151.8
	PSDU	GMSK	187.5	1/1	187.5
863~870 MHz (14)	PLCP Header	π/2-DBPSK	250	19/31	76.6
	PSDU	π/2-DBPSK	250	51/63	101.2
	PSDU	π/2-DBPSK	250	51/63	202.4
	PSDU	π/4-DQPSK	250	51/63	404.8
	PSDU	π/8-D8PSK	250	51/63	607.1
902~928 MHz (60)	PLCP Header	π/2-DBPSK	250	19/31	76.6
	PSDU	π/2-DBPSK	250	51/63	101.2
	PSDU	π/2-DBPSK	250	51/63	202.4
	PSDU	π/4-DQPSK	250	51/63	404.8
	PSDU	π/8-D8PSK	250	51/63	607.1
950~958 MHz (16)	PLCP Header	π/2-DBPSK	250	19/31	76.6
	PSDU	π/2-DBPSK	250	51/63	101.2
	PSDU	π/2-DBPSK	250	51/63	202.4
	PSDU	π/4-DQPSK	250	51/63	404.8
	PSDU	π/8-D8PSK	250	51/63	607.1
2360~2400 MHz (39) 2400~2483.5 MHz (79)	PLCP Header	π/2-DBPSK	600	19/31	91.9
	PSDU	π/2-DBPSK	600	51/63	121.4
	PSDU	π/2-DBPSK	600	51/63	242.9
	PSDU	π/2-DBPSK	600	51/63	485.7
	PSDU	π/4-DQPSK	600	51/63	971.4

Figure 2.5: Modulation parameter for Physical Layer

Figure 2.6 shows the format for the PPDU [27]. PLCP preamble, the PLCP header, and the PSDU are the three main components which are listed in the order of transmission.

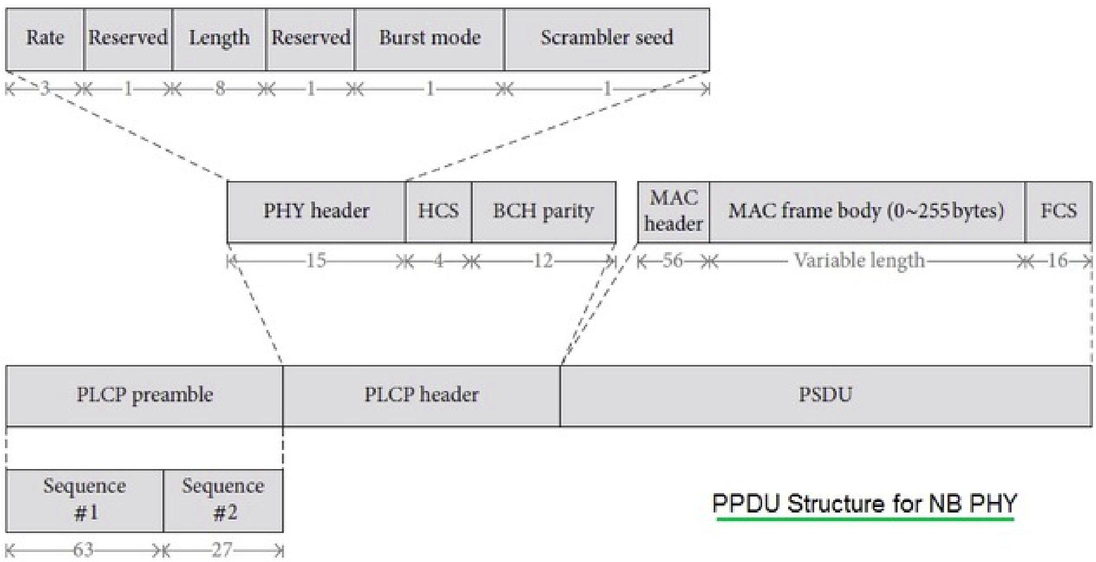

Figure 2.6: Structure of NB PPDU

Ultra Wideband PHY (UWB)

The preamble synchronization header (SHR), physical layer header (PHR) and physical layer service data unit (PSDU) are clubbed to form UWB PPDU as illustrated in Figure 2.7 [27]. Roubustness of a WBAN with high complexity low power consumption can be tuned using suitable design of UWB PHY.

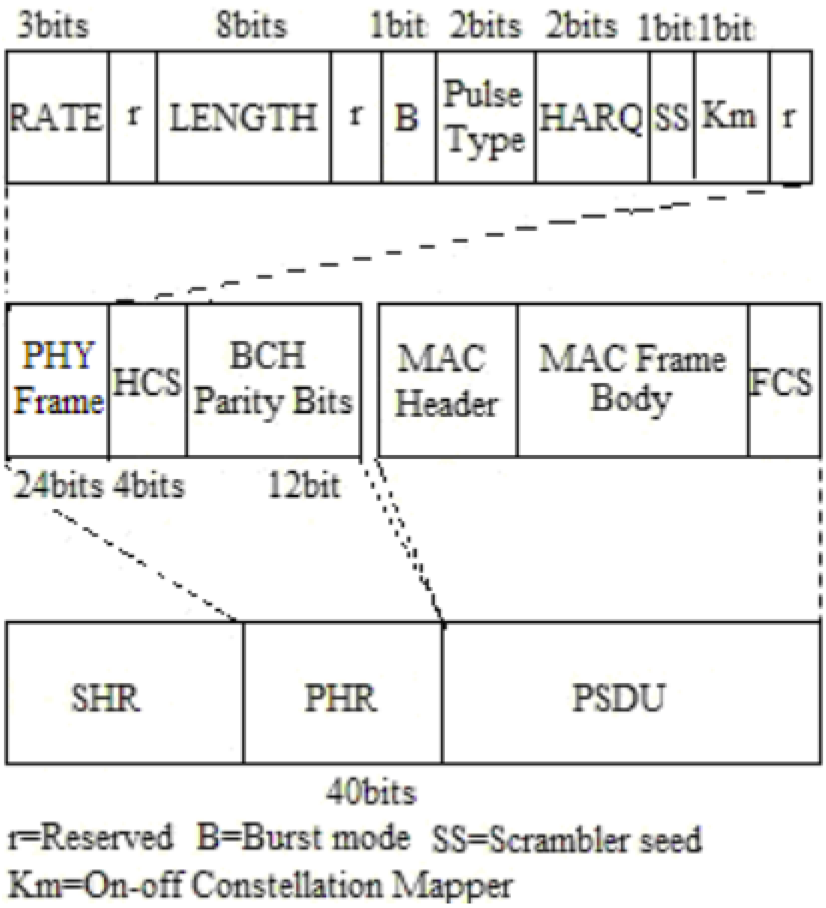

Figure 2.7: Structure of UWB PPDU

Human Body Communication PHY (HBC)

The human body is used as a communication medium between devices on and around the body using HBC communication. Standard defines that the band of operation is centered at 21MHz, data rates distributed in 164.1 kbps, 328.1 kbps, 656.3kbps, and 1312.5kbps respectively. The HBC packet frame format is shown in Figure 2.8 [27].

2.6.2 MAC Layer

IEEE 802.15.6 standard for WBAN systems. Each WBAN comprises a sink or a coordinator along with some sensors called nodes ranging from 0 to a fixed mMaxBANSize. This architecture comprises nodes that connect with the coordinator either with star or multihop star topology. In case of multihop transmission, relay nodes are incorporated to transmit data from a sender to the coordinator. This relay can be a health sensor node or it can also be a fixed node that just acts as an intermediate forwarder. According to the standard, the channel is divided into Beacon period of super frames of equal length for transmission of data frames. Each super frame contains allocation slots of equal duration that varies from 0 to 255. The coordinator is responsible to transmit the beacons to define the boundaries of the super frame and also to allocate slots for non beacon mode where the boundaries of

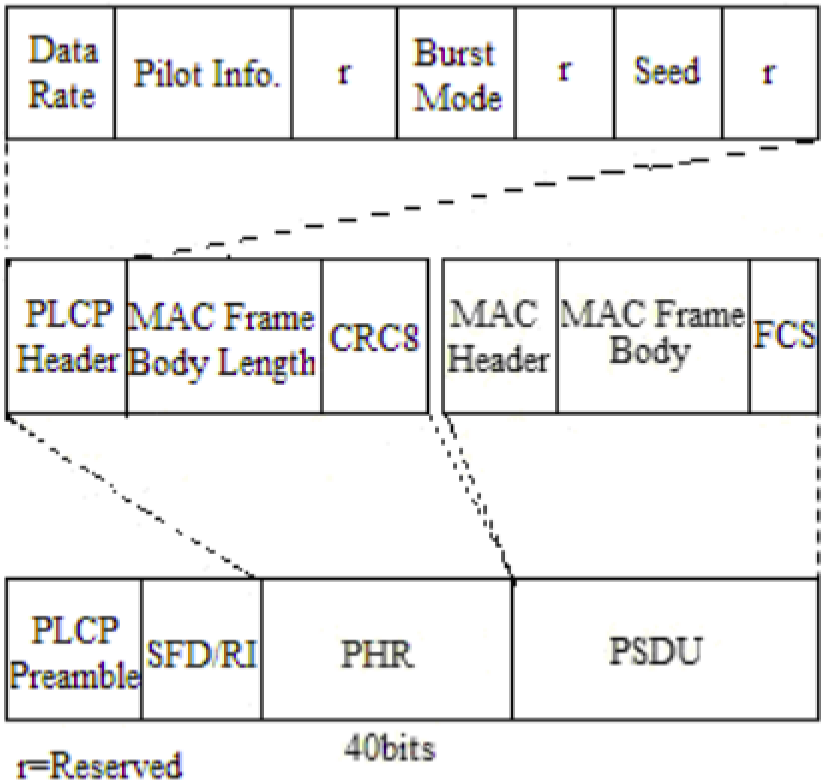

Figure 2.8: Structure of HBC PPDU

the super frames are defined by polling frames. The coordinator shifts or rotates the offset of the Beacon period, shifting the schedule allocation slots.

Efficient slot allocation by the coordinator is a very difficult task as network resources are constrained. To solve the slot allocation problem in WBAN, two different design decisions were taken for MAC protocols. They are: super frame structure (SS) and multiple access (MA) scheme also called Scheduling Access Scheme. In MAC superframe structure, there are various formats of data frames and several schemes for MA. Typical access methods like TDMA, FDMA, Aloha, Slotted Aloha and CSMA/CA are available. The following sections present the Mac frame format 2.9, and different communication modes 2.10 and access mechanisms that are defined in the standard.

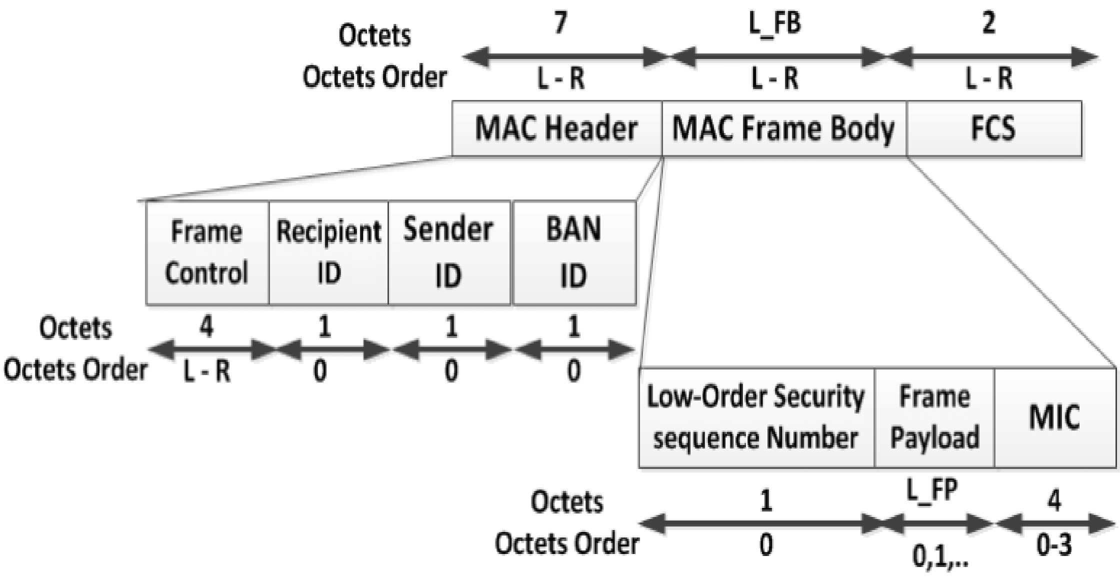

Figure 2.9: IEEE 802.15.6 MAC 802.15.6 Frame Format

As stated in [28], an efficient MAC protocol for WBAN must oblige the following QoS parameters.

- Energy Efficient WBAN sensor nodes are battery operated. There is no backup sensor for a particular physiological data. Hence, energy of the nodes must be utilised in the best possible way to enhance the lifetime of the network.
- Scalability: WBAN enabled patients may add or remove sensors in the network based on the parameters they are monitoring. This process needs to be performed easily without affecting the ongoing WBAN network.
- Interference Mitigation: Due to high mobility and various other ambient wireless communication, channel conditions of WBAN network deteriorates significantly. An effective MAC protocol must take care of interfering signals to deliver an efficient network.
- Throughput: This parameter is application dependant. But, in this thesis, as we are dealing with healthcare scenario for WBAN, data loss may result in a lamentable scenario. MAC should be designed to achieve high throughput.
- Latency and Reliability: Health data received after stipulated time window is as bad as data not received. Further, data generated by sensors must concur with the data received. WBAN should be also capable of delivering highly reliable and less delayed data to cater emergency cases.

Authors in [29] have classified MAC protocol design into two levels. The first level is based on MAC schemes that have seven genres. Each of this can further be classified into sub genres based on how a slot is allocated.

First level categorization of WBAN MAC Protocols

- TDMA based MAC
- TDMA with Frame Slotted Aloha or FDMA MAC
- CSMA/CA with TDMA based MAC
- CSMA/CA with Aloha MAC
- Slotted Aloha MAC
- Hybrid Approaches based MAC

TDMA based MAC protocols are divided into two types. In predefined time slot, each sensor waits for its particularly allotted slot. This approach fails in emergency data transmission due to low reliability with high latency. In case of predefined allocation based on prediction, the coordinator allocates slots based on types of data. Data generally falls into either low grade (like temperature, respiratory), medium grade (like ECG, blood pressure) and high grade (like EMG, capsule endoscope). Though this scheme can handle single sensor emergency case, but for real life scenario, when multiple sensors try to send critical emergency data, it fails.

In CSMA/CA with TDMA based slot allocation MAC protocols, sensors consume high energy during contention period. Clock synchronization experiences a high delay in data transmission which can be fatal during an emergency. Synchronization overhead pays a hefty loss in the overall performance.

U-MAC [30] and AC-MAC [31] use CSMA/CA with Aloha based slot allocation MAC protocols. Reliability of data in terms of delay and collision gets affected. Thus, it is not acceptable for critical data. In AC-MAC [31] several channels carries health data in a distributed manner. But as emergency data gets prioritised, general monitored sensors takes a back seat during channel contention. This restriction increases the reliability of receiving critical data by lowering energy consumption.

HR-MAC [32], A-MAC [33] use Slotted Aloha based slot allocation MAC protocols. HR-MAC [32] consumes low energy to allocate slots to sensors. This protocol fails when two sensors have similar critical data at the same time. A-MAC [33] does not specify patient's data. So, high energy is consumed during contention period to access the slot. The problem of allocating slot still persists in this. Thus, permission-based slot allocation is an optimal solution.

In TDMA with Frame Slotted Aloha based MAC protocols, sensors have long waiting period to access its predefined time slots. These sensors are instructed to hibernate in sleep mode and periodically wakes up to check the network. In case of critical situations, it is preferable to generate an alert command towards the coordinator. While this process solves the conflict of allocation of slot between two vitals.

TDMA with FDMA based MAC protocols show that nodes transmitting non critical data use transmission method, whereas nodes that transmit delay sensitive emergency data

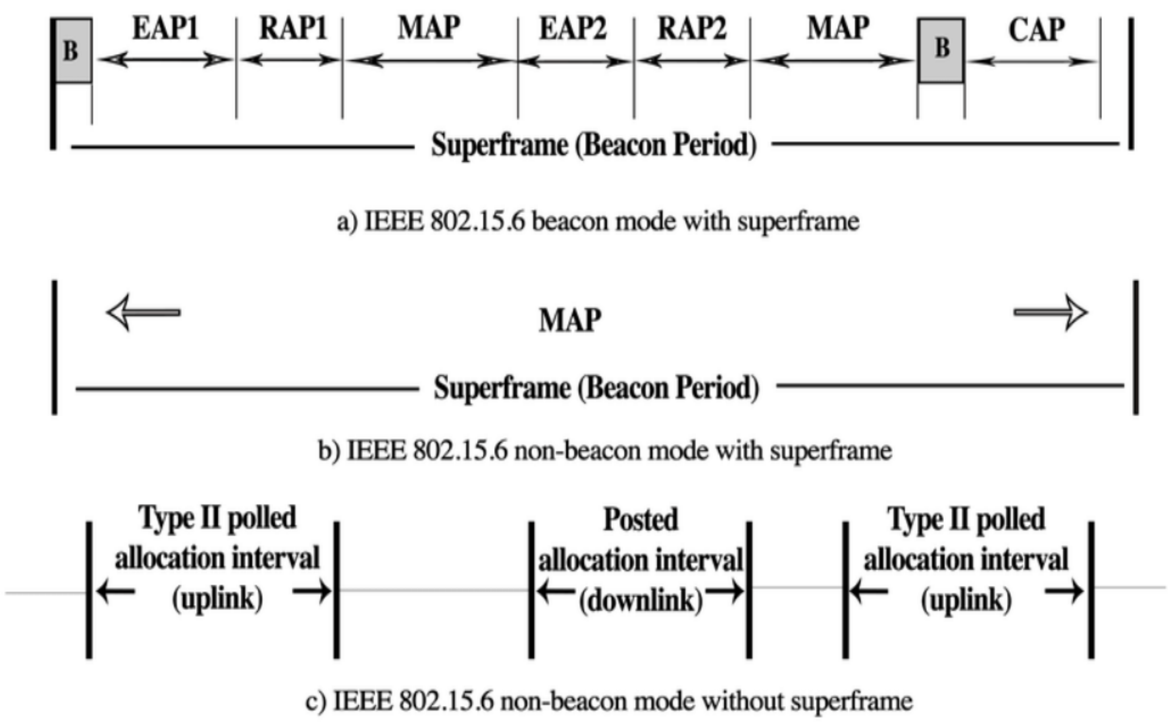

Figure 2.10: Different MAC Communication Structures

generate alert command to notify the coordinator. This achieves low energy usage and high reliability as transmission method is dependent on type of data the patients want to transfer during that slot. Moreover, alert based system provides minimum energy usage. But, it fails to solve the problem of slot allocation for two equally prioritised nodes generating alert.

As none of the above mentioned mac protocols satisfy the QoS level, researchers opted for hybrid mode while allocating slots to achieve better results. As mentioned in [34], mostly TDMA and CSMA/CA are used as hybrid mode. Both of them optimally allocate slots for general monitoring of patients. However, during critical data transmission, contention and preset slots cause higher collision, re-transmission of lost packets. This results in energy wastage along with poor data reliability.

Current state-of-the-art suggest that researchers are paying attention to adaptive mac routing protocols to have an efficient WBAN. In this section some of the prominent works are highlighted along with their note-worthy features. The strengths and flaws of the mentioned protocols are also discussed.

2.7 WBAN Routing Protocols

Routing protocols play a vital role to make WBAN systems energy efficient. It is responsible for deciding the path through which data will be transferred from a source to a destination. The factors on which the scattered nodes are chosen in a path must be logical and should depreciate energy of individual nodes pragmatically. The design principles of routing protocol is a pivot point in system performance. This signifies the importance of the study of WBAN routing protocols. The analytical study gives us the ability to critically design an efficient WBAN routing protocol.

In the literature, WBAN routing protocols are classified in the following categories.

2.7.1 Classification of Routing Protocols

Routing protocol defines a set of rules to transfer data from a source to a destination in the best possible way maintaining the criteria for a particular application. This ensures efficient and reliable communication between nodes of the network. Unlike other wireless networks, WBAN deals with health parameters. As these sensors are attached on humans, for ease of movement and biological issues, only one sensor is allotted to capture and transmit a particular type of data. So, functionality of a sensor for a maximum amount of time efficiently is a challenging task. Based on the vast state of art, WBAN routing protocols are classified on the following basis. This study helps us to provide a clarity on pros and cons of each variety of routing protocols that guides us to design a better effective and efficient routing protocol.

QoS Based Routing

Different applications demand various QoS. Wellness of a person cannot tolerate delay or inconsistent data. So, WBAN protocols must be designed as QoS aware. A solution that provides energy efficiency and QoS awareness simultaneously is still in active research [16]. QoS aware routing protocols have different modules to cater to multiple metrics. Maintaining equilibrium along with satisfactory outcomes among the modules must go hand-in-hand with energy efficiency. Medical application based WBAN must comply with QoS metrics like throughput (PDR), reliability, delay, energy consumption, Specific Absorption Rate (SAR) etc. Some of the current QoS based WBAN routing protocols are discussed as follows.

Reinforcement learning based routing protocol RL-QRP was proposed in [35]. It supports biomedical sensor network with enhanced quality of service. This protocol uses two Matrix to evaluate its policy. The body sensor nodes use a distributed Q learning algorithm with location information to find out the optimal routing of the data from the sender to the receiver. This protocol does not maintain network state information. The roots are approximated and explored based on experience. Initially, results are not up to the mark but with time this protocol gives better results. But, this protocol does not emphasize on the energy metric during optimal route finding policy.

Authors in [36] proposed a localised multi objective routing for biomedical networks. In this protocol the end to end delay and packet reception ratio are improvised by classifying the input data into four categories. Data is segregated based on the type of traffic based on their reliability, delay sensitivity and criticality. There are neighbour managers maintaining the neighbourhood table and packet classification for handling data based on the four different modules of traffic. In this protocol a blind duplication of the packet is done towards sinks. As a result, the network is crowded with overhead packets degrading the overall performance of the network. This also makes the protocol an unscalable one.

Authors in [37] described DMQoS protocol which is data centric and multi objective. The proposed method is a distributed flexible mechanism to optimise the quality of service along with energy in a multi hop body sensor network. They have used modular design architecture that uses several traffic classes. This paper estimates the parameters based on simulation experimentation. So this method should be validated and verified building an analytical model that would be able to dynamically select the optimal values which is realistic to different situations with respect to medical applications of wireless body area network.

Authors in [38] proposed QoS aware peering routing on a framework like an EPR [39] routing algorithm for delay sensitive data. In this approach, author has classified data into two categories. Throughput sensitive data are called ordinary packets and emergency data are delay sensitive ones. QPRD protocol is divided into seven modules- data packets from other nodes are received by the MAC receiver module. Packet classifier module categorises the packet as hello packet or a data packet. The routing service module classifies the packets into its genre (ordinary or delay sensitive) after receiving them from the upper layers. It also finds the best fit path for packets belonging to several classifications. The queueing modules receive data packets in their corresponding queues. The received packets are stored in the queue in first come first serve method by the MAC transmitter module store that follows CSMA/CA approach. In this approach, the network size has to be very small whereas the network topology changes frequently.

Thermal Aware Routing

A thermal aware routing protocol for WBAN is discussed in [40]. Here, each node selects a minimum hop route to sink. Children nodes select an optimal route whenever the temperature of the parent node crosses the predefined threshold. Thus, the parent node often becomes inactive which is not desirable in WBAN. [41] proposes a low-delay, multi-hop, spanning tree structured WBAN routing algorithm called CICADA that applies Time Division Multiple Access (TDMA) protocol to schedule transmission to nodes. The nodes within the vicinity of the source node act as forwarder nodes or parent nodes, whose functionality is to gather data from their children and forward them to sink. Parent nodes tend to deplete their energy faster due to extraneous traffic load of the children nodes as in [40]. [42] discusses a routing protocol which supports topological changes by store-and-forward mechanism. This increases the probability of reliable delivery of data to the sink node. In this mechanism, every intermediate node stores data packets which consumes more energy and causes longer delay. [43] proposes a solution for energy efficient routing by deploying some nodes which do not act as sensors.Though this protocol increases the network lifetime, deployment of extra nodes becomes costly.

A clustering based protocol called a Self-Organizing Protocol for Body Area Networks (ANYBODY) is proposed in [44] which restricts the sensor nodes to transmit data directly to the sink. Moreover an efficient network is maintained by changing the selection criteria of cluster heads in this protocol. The overhead of cluster formation is high in the context of WBAN. [45] proposes a protocol by integrating store and forward scheme with Transmit Power Adaption (TPA). As nodes are aware of their neighbours, links are stable and minimum energy is needed for transmitting data. A similar method is proposed in [19] which also uses Transmission Power Control (TPC) scheme. Dropped packets are re-transmitted in response to Automatic Repeat Request (ARR). ARRs are generated when the link quality becomes poor. The throughput of the network increases in these cases at the expense of energy consumption by re-transmitting the lost packet. [46] and [47] use creeping waves to relay data packets to minimize energy consumption of nodes. Here, reflections from surrounding environment interfere with the transmission of health data; thus, reliability becomes an issue. In [48], the author proposed a delay tolerant protocol. Since body sensors are highly resource constrained, the store and forward mechanism used in [48] consumes unnecessary additional energy. A review of WBAN protocols may be fond in [49].

Cross Layer Routing

Transfer of information among the adjacent or non-adjacent layers of the protocol stack is termed as cross layering. This concept of information sharing has been applied in various WBAN routing protocols between network and MAC layers to enhance the performance of the system as a whole. Some relevant state of art protocols are discussed hereafter. Authors in [50] proposed a communication protocol called Biocomm for medical applications. Authors have proposed an efficient cross layer design to prevent formation of hotspots. This results in improved energy consumption reducing congestion in the network. It has been compared with Shortest hop routing, hotspot preventive routing. A later variation, Biocon-D was proposed that performed better in comparison to HPR. It reduces average packet delivery time, but fails to prioritize QoS based packet prioritisation in such in-vivo networks.

CICADA or Cascading Information retrieval by Controlling Access with Distributed slot Assignment is proposed in [51]. This protocol guarantees collision free transmission of data towards the sink by generating a distributed network tree structure. This protocol maintains low energy consumption as they put nodes in sleep mode when unused. They also provide minimal delay and remain neutral to mobility.

TImezone coordinated sleep scheduling (TICOSS) citeruzzelli2007energy improvises IEEE 802.15.4 by slicing the network into time zones resulting in better lifetime.

Authors in [52] proposed wireless autonomous spanning tree protocol (WASP) that uses a cross layer approach to set up a spanning tree that controls traffic in the network. To reduce power consumption, network delay and packet loss rate, this prototype is effective. Authors have compared this with CSMA fixed routing .protocol,

Cluster based Routing

Energy constrained nodes of a WBAN system demand efficient energy usage to enhance network lifetime. This leads to cluster based routing that minimizes power consumption and maximizes network lifetime.

Authors in [53] proposed a Cluster Based Body Area Protocol (CBBAP) to enhance the system performance by 25%. Coordinator is placed at a distance, whereas a gateway is placed at the centre of sensing nodes. Low Energy Adaptive Clustering Hierarchy (LEACH) is adapted by CBBAP using Cluster Head (CH). CBBAP outperforms LEACH protocol in terms of practical applications.

Authors in [54] proposed a cluster based routing approach that regulates the transfer of data directly from nodes to the coordinator. This protocol also ensures efficiency by altering the criteria for cluster head selection.

Authors in [55] proposes a multiple criteria based cooperative routing protocol called Energy-efficient Harvested Aware clustering and cooperative Routing Protocol for WBAN (E-HARP). A new cluster head is selected in every round to pragmatically utilize the load of the nodes of the network. Cooperation helps in minimizing redundant data in the network. In comparison with EH-RCB [56], ELR-W [56],Co-LAEEBA [57], and EECBSR [58] E-HARP improves network stability, lifetime of the network, delay and throughput.

2.8 Coexistence and Interference in WBANs

Overview

WBAN operates in 2.4 GHz using wireless technologies. The close proximity of other technologies operating in the same band degrades the performance of WBAN. Reliable transfer of data from a source to a destination without getting tampered demands mitigation of such interference. Based on the type of wireless technologies within the radar, WBAN interference is classified into the following types as shown in Figure 2.12. Taxonomy of interference is shown in Figure 2.11.

- intra interference: Transmission from different sensors present on a single WBAN cause overlapping of data.

- inter interference:

  When other WBANs and 2.4 GHz wireless devices are close then inter WBAN takes place. When two or more WBAN sensors in close proximity affect data transmission of each other, it is called mutual inter WBAN interference. The impact of wireless technologies on a WBAN operating in the same band is called cross inter WBAN interference. Various parameters like protocols, power settings, packet sizes, modulation schemes etc are different for the wireless operating nodes. Thus, completely mitigating cross layer interference in real life situations is almost impossible.

Three types of mitigation schemes are used to nullify the effects of interference.

- Analytical method

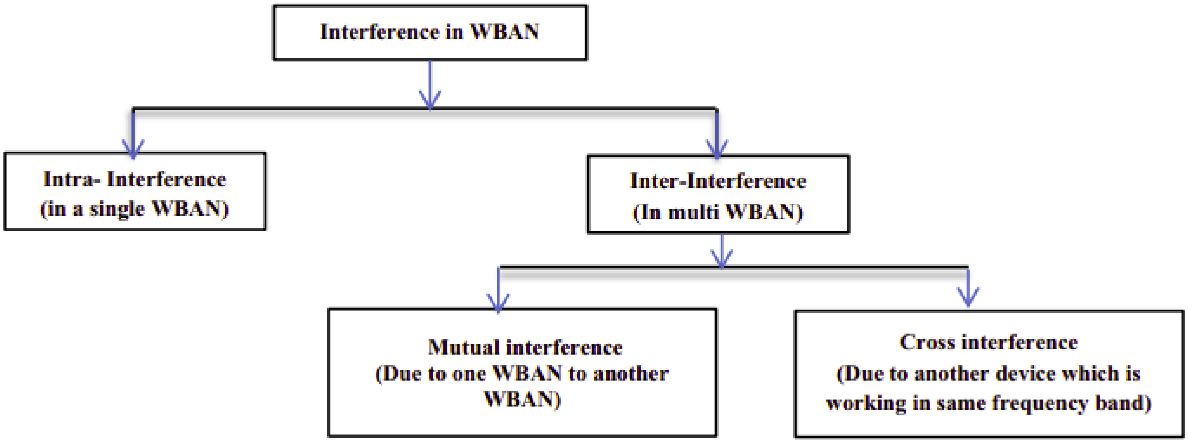

Figure 2.11: Interference Taxonomy in WBAN

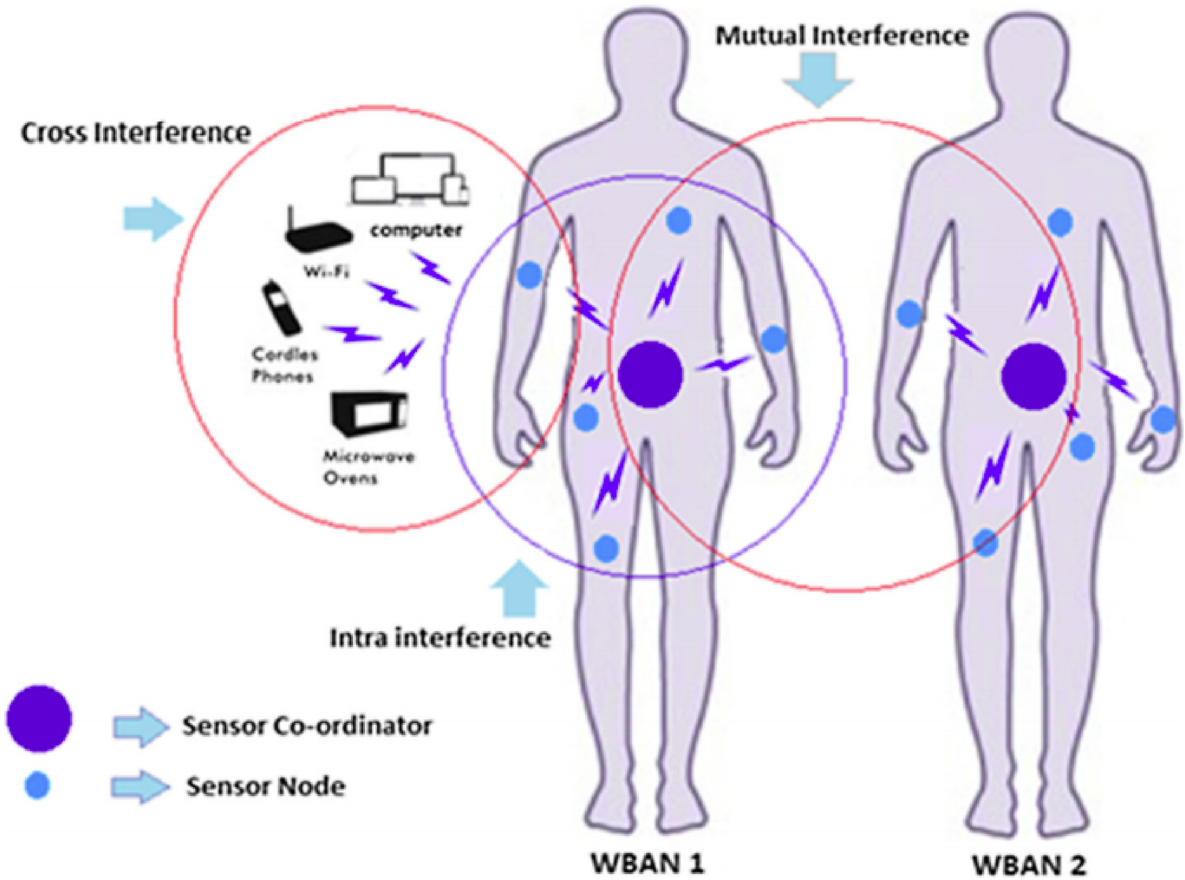

Figure 2.12: Different Interference in WBAN

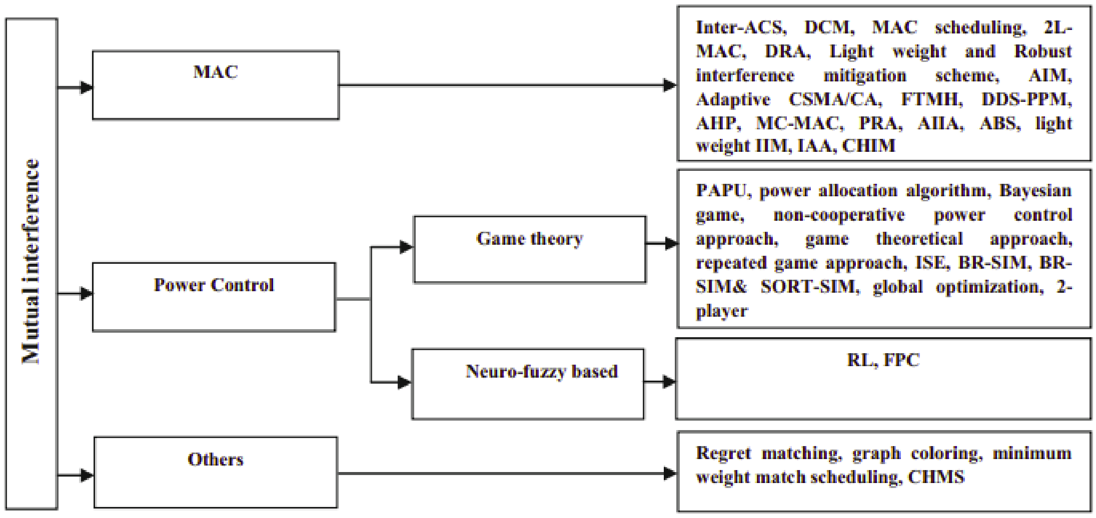

Figure 2.13: Mutual interference mitigation schemes

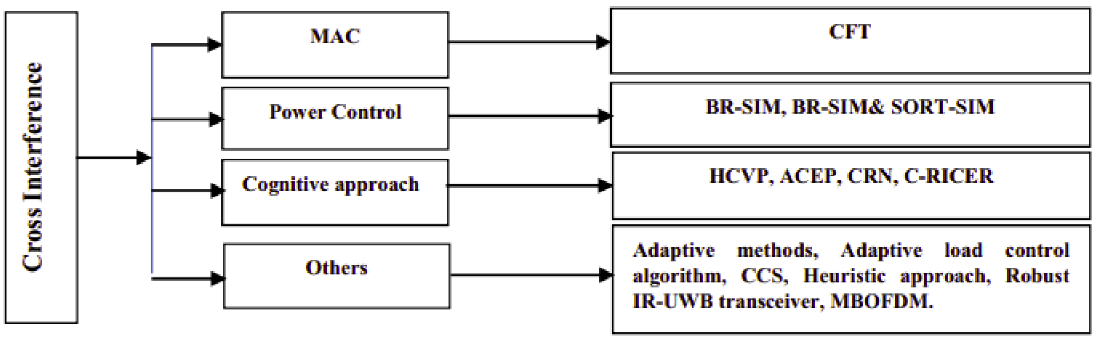

Figure 2.14: Cross interference mitigation schemes

- Simulation method
- Experimental method

Interference Mitigation Schemes

Based on the type of overlapping, different interference mitigation schemes (mutual and cross) are available in the literature. They are discussed below.

The mutual interference mitigation scheme is further categorised as shown in Figure 2.13.

Cross interference mitigation scheme is categorised as shown in Figure 2.14.

Different approaches towards interference mitigation are discussed below.

Power Control Approach

Power consumption is one critical parameter that determines the efficiency of the system. Various mitigation schemes based on neuro-fuzzy, learning algorithms, game theory etc have been proposed. The PAPU [59] algorithm provides a trade of between network utilisation and efficiency by coordinating with the transmission power to reduce interference. It has a very low convergence time but is not very useful. Author in [60] proposed a fast converging mitigation method Fuzzy Power Controller (FPC). When compared with others it provides better performance with respect to power control and convergence irrespective of the number of interfering nodes. [61] is a lightweight Reinforcement Learning (RL) algorithm. It is robust to interference. SINR is used to evaluate the method. The proposed power allocation algorithm in [62] guarantees QoS requirement using optimal power. A trade off between energy consumption and throughput is used in the Bayesian game approach [63] that provides a quick convergence time. A balance among utility and power makes a non-power control game reliable [64]. Complete network interference that is both mutual and cross are considered in BR-SIM [65] and SORT-SIM [66]. They provide good channel allocation and perform better than PAPU [59] in terms of SINR in a moderately dense WBAN network.

MAC Approach

In MAC approach, throughput is increased along with efficient power consumption resulting in enhanced reliability of the system. Continuous Frame Transmission (CFT) [67] method increases battery life of medical devices by reducing re-transmission in overlapping environments. Medium inter frame space(MIFS) is used to identify interference. Here, status of a channel is determined before frame transmission begins, or it waits for MIFS interval to avoid collision. As a packet is only sent when the channel is free, the probability of collision decreases. Hence, more energy is consumed in this method. Authors in ([68], [69], [70], [71], [72]) and [73] concentrated on enhancing QoS to have a better reliability of operation. A special parameter is used to decide the performance of the system as mentioned in [74] and [73]. We have also seen in [75] that dynamic coexistence management scheme manages the coexistence of WBANs in a distributed manner. Decreasing the delay, the transmission rate improves by 25%. Reliability increases at the cost of power consumption. A system that does not adopt this DCM method has a data loss of 40% which can even cause the system to shutdown. MAC scheduling presented in [76] prove that the protocol avoids critical packet loss. Adaptive CSMA method is implemented using dynamically changing frame length with respect to the interference level as shown in [70]. A better throughput is achieved irrespective of the number of overlapping WBANs with a minimal power consumption satisfying QoS. In comparison to other protocols, MAC protocols [70] have about 14% better performance. Authors in [77] uses fairness as a performance metric that increases energy efficiency with no complexity. The DDS–PPM method can eliminate inter user interference and narrow-band interference. Authors in [78] proposed a protocol called Analytical Hierarchy Process (AHP) that‘reduces latency and improves reliability by mitigating interference. An energy efficient protocol called MC–MAC [79] enhances throughput of the system by minimizing delay. Allocation packets in [71] are based on super frame interleaving. The schedule in scheme [80] reduces interference with a greater reliability in the ISM band.

Cognitive Radio Approach

In cognitive approach interference mitigation is based on experimental measurements the parameters focus your are throughput are consumption and mobility. the CR algorithm that is implemented in HCVP [81] minimizes interference. It considers heterogeneous network and provides a good spectrum sharing. It is based on Programmable SoC processor. Authors in [82] proposed Adaptive cognitive enhanced platform (ACEP). This protocol uses low power Programmable associate chip and reduces packet drop rate. This enhances the channel utilisation. The schemes is assessed by Interference mitigation factor (IMF). In [83], CRNs are deployed in hospitals and in novel framework to manage interference is proposed. It uses adaptive modulation data rate and duty cycle to preserve the link quality. This allows multiple nodes to operate simultaneously in presence of other wireless operating systems. In [84] authors designed novel receivers specifically for WBANs. This reduces wake up for false signals. The author has also proved that radio WUR has a good sensitivity and can be operated at various frequency. It consumes 10-100 less power consumption compared to WUR. Author in [85] proposed Cognitive Receiver Initiated Cycled Receiver (C-RISER) that operates under high ISM band in the presence of dense WBAN network. In case of WBAN the coordinator is the only receiver. So that effectiveness of the protocol is well suited for WBAN users.

Chapter 3

Energy efficient WBAN Routing Algorithm

3.1 Introduction

There are many routing protocols for wireless sensor networks (WSN) but they are not appropriate for WBAN due to their restricted abilities and usage [86], [87], [88] [89] [90].

- Unlike WSN, the monitored environment of WBAN is deployed with fewer or limited number of non-repetitive sensor nodes whose sizes are much smaller than WSN nodes.
- WSN nodes are usually static but mobility is a challenging issue in WBAN [91] that directly affects reliable data delivery which is an important measuring parameter for health data.
- Some WBAN nodes are implanted in human body. Hence, their effect on human tissues must also be considered. This aspect is not a major concern for WSN routing.

WBAN routing protocols are divided into intra body communication and inter body communication [92]. Intra body communication deals with sending of sensed data from a body sensor node to the coordinator. The second one describes how coordinators relay the sensed data to the Access Gateway. This chapter focuses only on the first case which can be handled in two ways: single hop and multiple hops.

In single hop, the sensed data can be delivered directly from source to the coordinator which is the destination. In multi hop delivery, the source sensor node forwards the sensed data to other intermediate sensor nodes to finally deliver data to the coordinator.

Though different WBAN routing schemes have already been proposed, they are not efficient enough to manage and relay critical health data reliably and efficiently. Thus, communicating health data in a WBAN from a source to a destination reliably, maintaining thermal threshold of human tissue, experiencing sustainable delay, enhancing throughput and network lifetime is still a major challenge. In case of opportunistic protocol, whenever the coordinator goes beyond the transmission range of the node, the relay nodes collect health data from its children nodes. Suppose that a body sensor is placed around the wrist of the human body which needs to send its collected data to the coordinator positioned around the waist of the body. Whenever the person moves his hands, the wireless connection between the sensor on the wrist and the coordinator on the waist gets disconnected. Precious power of the body sensor nodes and relay nodes are Unnecessarily consumed due to link failure causing higher packet drop.

This chapter proposes an efficient routing protocol for WBAN that minimizes energy consumption and increases the throughput of reliable critical health data delivery. Inspite of the sensors being fixed on the body it moves as the human body moves as a whole or at different postures [91]. The performance of the proposed protocol has been evaluated by two parameters: energy consumption and packet delivery.

Two major characteristics of the proposed algorithm are as follows.

- In the proposed scheme energy utilization is uniform among the nodes of the network; thus, each node has more stability and they remain alive.
- Higher throughput of the network is achieved as each node consumes minimum energy in a homogeneous fashion resulting larger stability period and prevention of hotspot.

Section 2 briefly discusses several routing algorithms and M-Attempt in particular, a thermal aware WBAN routing protocol. Section 3 describes details of the proposed method. Performance evaluation of the proposed protocol is discussed in Section 4. Finally, we conclude in Section 5.

3.2 Related Works

Some thermal aware routing protocols for WBAN [40], [41], [40], [42], [43] have already been discussed in the earlier chapter. Some clustering-based protocols called A Self-Organization Protocol for Body Area Networks (ANYBODY) [44], and the other protocols [45], [19], [46], [47], [48] have also been discussed in the earlier chapter.

3.2.1 Overview of M-Attempt

M-ATTEMPT [92] is a thermal aware routing protocol for heterogeneous WBANs. Critical data or on-demand data is sent as real traffic by direct communication. For delivery of normal sensed data, multi hop communication is used. Heat generated by the implanted sensor nodes may cause tissue damage. So, these nodes are to be identified. M-Attempt identifies these “Hot-spot” links and avoids routing through them. Mobility of body parts lead to disconnection of links already established.

M-ATTEMPT handles both mobility support and energy-management. During deployment, nodes with high data rate are placed on less mobile body parts. During initialization, all nodes broadcast Hello messages. This Hello message contains neighbours information and distance of sink nodes in form of hop-counts. In the next phase, routes are established. M-Attempt assumes that each node has information of all other nodes and sink's position. Thus, energy efficient routes with less number of hops can be established easily. For handling emergency, first critical data are successfully sent to sink and only then other processes are executed. During such scenarios, the implanted nodes can communicate directly with the base station.

Additionally, all sensor nodes are capable of communicating directly with the sink node when demand arrives from sink. Whenever temperature becomes higher than a threshold, a node disconnects itself from its neighbour for a while. The original route can be established only after temperature becomes normal. If the temperature of a node reaches threshold after it receives a data packet, it returns the packet to the sender. The sender identifies this link as Hot-spot. Once a route is established, the sink node prepares a Time Division Multiple Access (TDMA) schedule for communication.

3.3 Proposed System Model

The proposed protocol introduces a type of nodes in the network called 'relay nodes' that are responsible only for forwarding data towards the coordinator. Thus, energy dissipation of body sensor nodes for transmitting health data is reduced. Further, this protocol prevents formation of hotspot using energy of the nodes in a uniform manner. When the coordinator is within the range of some node, data is directly transmitted. Discovery of neighbours is done first in our approach. Then, appropriate forwarder based on a cost function is chosen to send data from sender to receiver.

3.3.1 Neighbour Discovery Procedure

The aim of the neighbour discovery is to establish the neighbour table of sensor nodes and the fixed nodes. Sensor nodes and fixed nodes build their neighbour tables to store information of the neighbours after it scans the strength of the receiving signals in its transmission range. Initially the interested sensor node sends a hello message to scan the strength of the receiving response from other nodes by running a timer. Figure 3.1 shows the format of the response from other sensor nodes which provides information about parameters like node id, current location, velocity vector and remaining energy. However, responses from fixed non-sensing node comprise only node id and residual energy. Location is represented by x and y coordinate values. Multiple responses corresponding to the same node id for a single request is ignored. Requesting sensor node stores the value of its neighbours in its information table. Every node in the network is assumed to be aware of the location of the coordinator.

After this procedure, each node is literate about their corresponding reachable nodes

Node ID	Current Loaction	Velocity Vector	Remaining Energy

Figure 3.1: Response Table

in the network. The body sensor nodes do not send beacon packets periodically. Only when the nodes are ready to send data, they just exchange a message with a set of its immediate next neighbour to check if the destination sequence number in its neighbour's table is greater or equal. If it is so, then it also changes its table accordingly presuming that the neighbours table information is updated and sends the data via the updated route. In other words, body sensors are intelligent enough to know that it has to send data to coordinator at nth time. Then, it may do the beaconing at (n-1)th time only. Thus, excess bandwidth is not consumed due to unnecessary periodic beaconing. A sensor node does not send beacons to all its one hop neighbours; it sends them only to those nodes in its one hop that has a velocity vector within a certain threshold with respect to the combined position of the source node and the coordinator. This feature further enhances energy efficiency of the algorithm.

Forwarding Procedure

The final destination of data packets within WBAN network is the coordinator. As mentioned when the source and coordinator are close, it transmits data to the coordinator directly. Otherwise, it sends data to one of the neighbour sensor node or the fixed non-sensing relay nodes. The mechanism of neighbour selection impacts the performance metrics of the whole network in the following ways.

- Energy consumption by varying with traffic load affecting network lifetime, stability period and residual energy of the network.
- Latency or delay by varying with traffic load effecting throughput and delay tolerance of the network.

Firstly, distance from a neighbour node and the coordinator is considered. Less distance can reduce the number of hops for critical health data delivery and will also consume less power and thus its adverse thermal effect on human tissues will be nominal. As a result, the average packet delay is also reduced. Secondly, the relative velocity is also considered. If a neighbour sensor node is moving with a threshold velocity towards the coordinator, then it is capable of getting selected to forward the data to the coordinator. Thirdly, the residual energy is also taken into account to enhance the stability period and the network lifetime. Either the sensor node or the fixed non-sensing relay node having larger residual energy will be preferred for getting selected as a forwarder. Moreover, movement pattern and coordinate of the neighbour nodes are known. So, instead of searching all its neighbours, it will only find a forwarder from a set of its neighbours who are aligned towards the coordinator.

Parameter	Value
No. of Nodes	8
Transmit Power	-15dBm
Simulation Time Limit	51sec
Start-up delay	1sec

Table 3.1: Simulation Parameters

Significance of fixed relay nodes is worth mentioning. Suppose, there are a few nodes (e.g., Heartbeat sensors) which are mostly near the coordinator. In this case, these nodes are affected while prioritizing between the task of sensing and forwarding its own data and relaying other nodes' data. Thus, remaining energy of these nodes are depleted sooner hampering the longevity of the network. To solve this problem, we have assumed that other than the body sensor nodes, there are some fixed non-sensing nodes that are just capable of relaying the data towards the intended destination or other intermediate body sensor nodes. Thus, the nodes (e.g., heartbeat sensors) do not get paralyzed due to the burden of relaying. Based on all these parameters, the source node calculates a cost function of other nodes within its proximity and selects a node with the least value as the most appropriate forwarder. The cost function of ith node is computed by Equation 3.1.

$$C(i) = \frac{d(i) - v(i)}{R.E(i)} \tag{3.1}$$

where $d(i)$ indicates the distance between the i^{th} node and coordinator, $v(i)$ indicates the speed of the node i towards the coordinator, $R.E(i)$ indicates the residual energy of the i-th node. Residual Energy is computed by the difference between the energy of a node at a given instant and the energy of a node at the initial deployment. Lesser the distance between the transmitter and receiver nodes, lesser the power is required to forward the data. Thus, energy dissipation will be low and as a result the temperature rise in the network will be under control.

3.4 Performance Evaluation

The simulation parameters are tabulated in Table 3.1. 8 nodes are deployed on the body in the simulation environment. Their positions are tabulated in Table 3.2. The performance of the proposed protocol is assessed by the following metrics.

- Network Lifetime: It is determined by the time until the last node dies.
- Stability Period: It is the time till its first node die.
- Throughput: The total number of packets successfully received by the coordinator.
- Residual Energy: It is the amount of left over energy of the nodes.

Node	Position
Node 0	Belly
Node 1	Head
Node 2	Between Left side of Chest and Neck
Node 3	Chest
Node 4	L-Wrist
Node 5	R-Wrist
Node 6	L-Ankle
Node 7	R-Ankle

Table 3.2: Position of Nodes

We have simulated the proposed algorithm in Castalia 3.2 simulator. We have compared the results with two existing WBAN algorithm, M-ATTEMPT, and CICADA (Cascading Information retrieval by Controlling Access with Distributed slot Assignment) and one WSN algorithm LEACH. We have chosen M-ATTEMPT as a thermal-aware WBAN routing algorithm. CICADA is chosen as another popular WBAN routing algorithm LEACH is a classic WSN routing algorithm. We chose it to show general inappropriateness of WSN algorithms in WBAN routing. As M-ATTEMPT algorithm is temperature aware, we have taken a specific case of M-ATTEMPT algorithm and simulated it. The M-ATTEMPT algorithm looks for hot-spot and bypasses the data from the hotspot and forwards the data via a different path. The dynamic nature is not shown here. Rather, we have taken a particular route in which there is no hot-spot node present. The data rate is measured in packets/sec. We have taken different data rates as inputs to see different outcomes in terms of data packets received at the coordinator node as output. The low data rate is taken for normal data delivery and the high data rate is taken for critical data delivery.

Figure 3.2 plots number of data packets received at the coordinator node for different data rates. The proposed algorithm shows the best result among the other algorithms. For high data rate, number of received packets is more in our case which is desired for high throughput.

The graph in Figure 3.3 shows that the remaining energy is higher in the proposed algorithm. The remaining energy is measured in Joules. WSN algorithm i.e. LEACH is low performing among the other algorithms. The initial energy is chosen as 18720 Joules. We have taken a high data rate to highlight energy dissipation.

The details of received packet (at the coordinator) show the effect of interference. This received packet count will not match with the graph in Figure 4 as that graph shows the output from the application module. The graph in Figure 3.4 shows the number of packets received at the coordinator without interference and in presence of interference. When we are using the proposed routing algorithm, the number of received packets is comparatively much higher. It is to be noted that this graph provides details of the number of packets received at the coordinator node, i.e., node 0 for a particular data rate i.e. 120 packets/sec. Such cases where data rate is high may happen during critical conditions. We have also

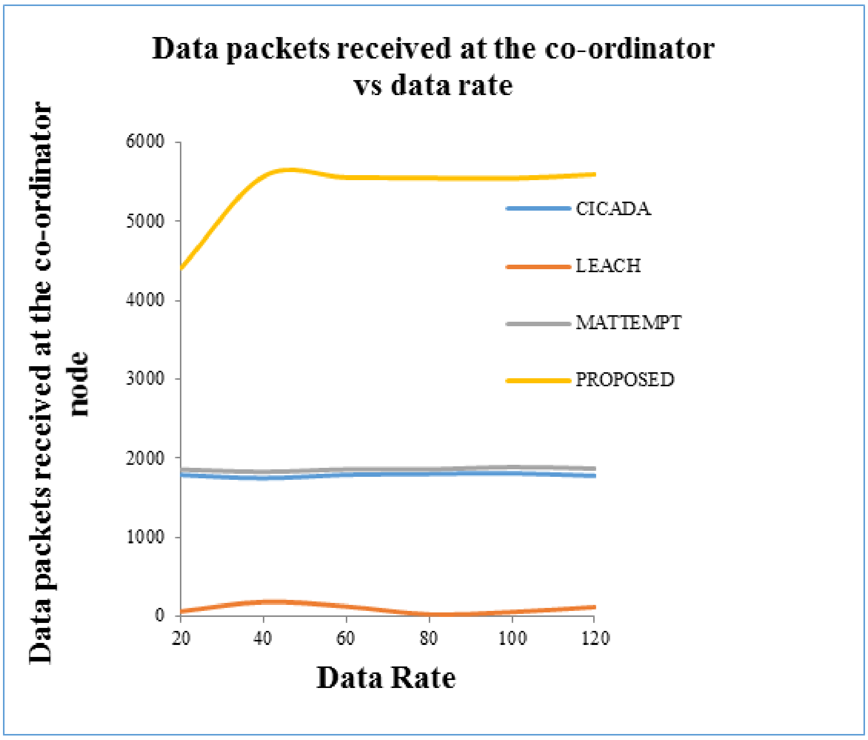

Figure 3.2: Packet received at coordinator varying data rate

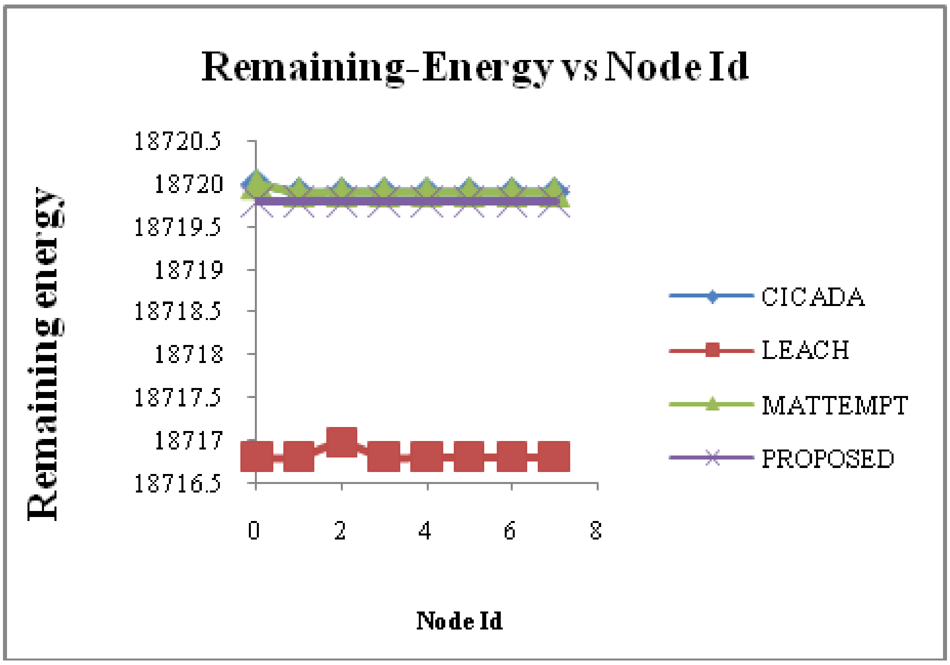

Figure 3.3: Remaining Energy wrt increasing Node

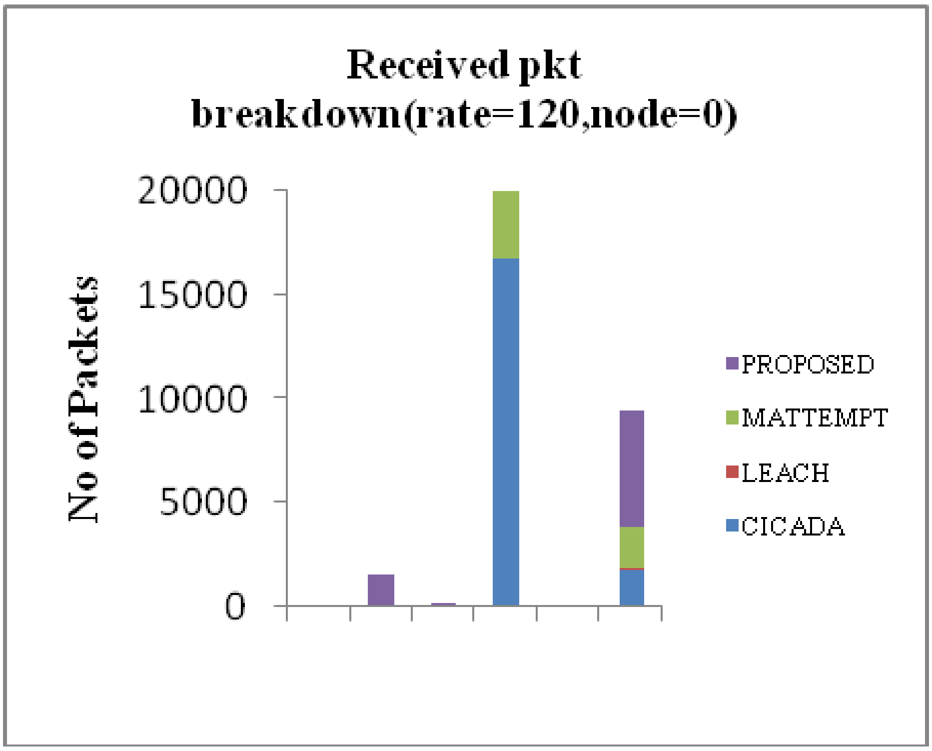

Figure 3.4: Number of packets received despite Interference

compared the growth of the cost function of our proposed protocol as compared to M-Attempt. This is shown in Figure 3.5.

The upper curve of the graph in Figure 3.5 is for M-Attempt and the lower curve is for proposed algorithm. The graph shows that the growth of cost in M-Attempt is more than the growth of cost in the proposed algorithm. This is so because in case of link breakage in M-Attempt, alternate path is chosen. For that, remaining energy and hop count changes. So, overhead is dependent on the remaining energy and the hop count. Again, for critical data single hop is chosen. So, hop count decreases and as a result more energy is used to transmit. Thus, remaining energy reduces and cost increases.

Figure 3.6 plots the overhead of the proposed algorithm and M-ATTEMPT. It can be seen that the number of topology changes are much less in the proposed algorithm. This is because every node whose temperature crosses a threshold leads to link disconnection and topology change in M-ATTEMPT. The proposed algorithm considers topology change only when body parts move.

3.5 Conclusion

In WBAN, there are heterogeneous sensor nodes which collect data and transfer it to the coordinator. The coordinator collaboratively transfers it to the Access Point which in turn sends the data to the doctors and paramedics via the internet. In the proposed protocol a node uses information such as location, id, velocity and remaining energy of its neigh-

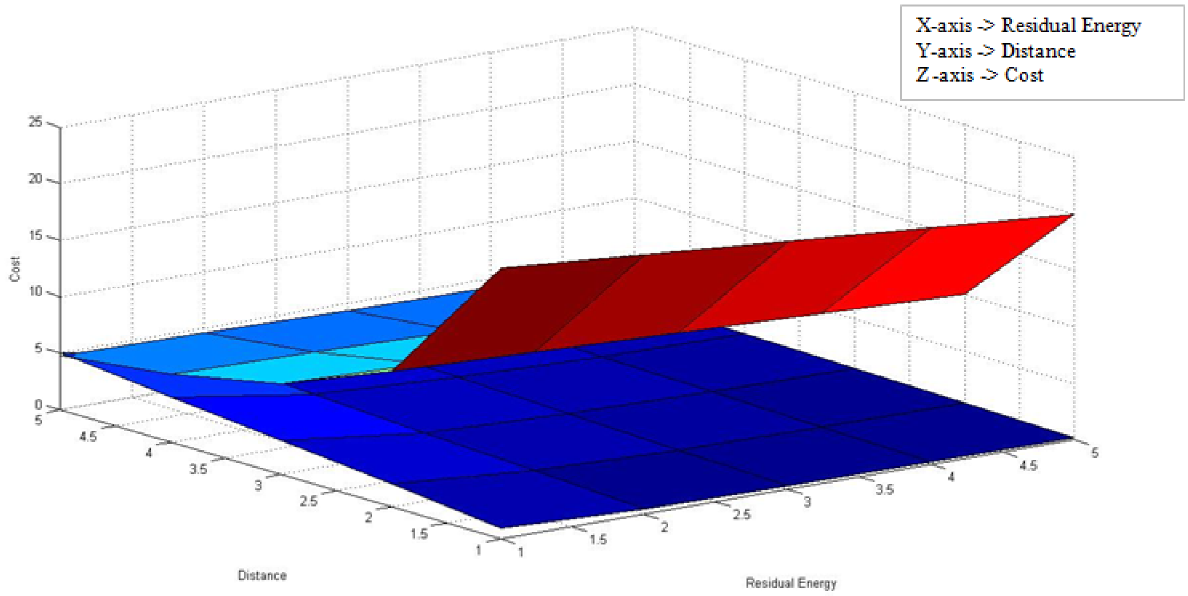

Figure 3.5: Growth of cost function

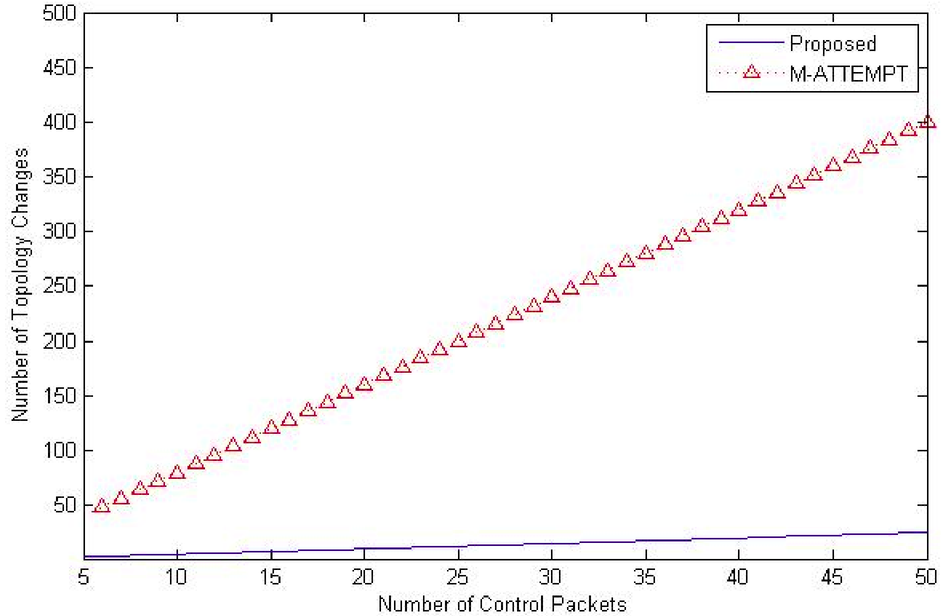

Figure 3.6: Overhead Comparison

bours to compute a cost function. Using the proposed cost function, each node selects an appropriate forwarder node. It has been shown via simulation that the proposed algorithm provides enhanced stability period and longer network lifetime than M-ATTEMPT.

Chapter 4

Impact on WBAN QoS for Twin Sinks

4.1 Introduction

We have already talked about WBAN technologies, WBAN components and the communication architecture. As already discussed, sensor nodes sense and transmit data via a wireless communication channel generally towards a sink node called coordinator or gateway node. This coordinator further forwards the data to a Personal Digital Assistance (PDA) which convey the data to a remote location based on the required application.

In WBAN, the maximum energy lost by a node is due to data transmission from sensor to sink. So, it is required to utilize the transmission energy pragmatically. This demands energy efficient routing protocol which support mobility. Though a lot of communication protocol is available in Wireless Sensor Network (WSN). There are some fundamental differences in WBAN with respect to network requirements. They are are already discussed in the Chapter 3. We just highlight here two salient distinctions.

1. Varying bandwidth of communication through body rather than space

2. Strict constraint for power consumption

These boundaries call for different set of protocols in WBAN. Usually, in WBAN architecture, a single sink is responsible to collect data from the sensors. Thus, sensors either have to increase power to maintain star topology to send their data directly to the sink or can relay the data towards the sink. Enhanced power for direct transmission will dissipate their energy faster resulting in low stability period. Forwarding the data will increase the hop count and hence, delay increases due to extra processing and relaying by other intermediate sensors. Moreover, the forwarder sensors also get over burdened and tend to lose already limited energy for this relaying process. To solve the problem of 'sensor-node-as-forwarder', special nodes called relay nodes can be incorporated. This solution still causes delay in data delivery which is fatal in case of emergency situations.

Another way to efficiently utilize the energy of the nodes is to use dual sink in the WBAN architecture. This is a common approach in WSN to forward the data to the nearest sink [93] in an Anycast manner. Though this approach is common in WSN, it is not so popular in WBAN systems. Therefore, we explore this approach and observe how the basic QoS parameters of WBAN like "Packet Delivery Ratio (PDR)", "end-to-end delay", stability period and energy consumption get affected.

In WBAN, high mobility leads to poor reliability. For efficiency in WBAN operations, the issue of optimum placement of the gateway nodes is also taken into account in this paper.

The chapter is organised as follows. Section 2 presents the related works specific to this work. The protocol for the proposed model in the next section. It is followed by simulation results in section 4 and conclusion is section 5.

4.2 Related Works

Different researchers have put their best to overcome the challenging requirements of WBAN. In paper [94], authors have used relay based cooperation to transmit critical data in emergency situation. Every intermediate node keeps a copy of the packet to reduce packet drop. This increases delay of the network which is unappealing. A protocol called DARE has been proposed in [95] which creates a scenario of a ward having eight patients. Each one of them is encompassed with seven sensors to monitor their vital parameters. This protocol is only aligned to optimize the net energy consumption, ignoring equally important other QoS parameters of WBAN. Authors in [96] have proposed a mathematical model to select cluster head in order to balance the energy utilization and enhance stability period. But, due to high mobility of WBAN, this protocol also failed to establish a benchmark. Multiple sink nodes have been used in different sides of a soccer game by the protocol THE-FAME [97] to measure the fatigue of the players. In this protocol direct transmission id enforced when the threshold is reached. This depletes the energy level of a node completely due to high power usage. As a result the node tends to 'die out' faster.

Authors in [34] put forwarded a protocol called LAEEBA where they have used both direct and multi hop communication based on path loss component to minimize only the energy consumption of the node. Authors in [57] have revised the LAEEBA protocol and proposed Co-LAEEBA. Cooperative knowledge of the path loss component, residual energy and intermediate distance between the sender and the coordinator helped to find a feasible route to the destination. Both [34] and [57] have unsatisfactory PDR for WBAN. In paper [92] a renowned thermal aware WBAN routing protocol called M-Attempt has been suggested. It looks for hotspot, bypasses data from the hotspot, and forwards data via a different path. Moreover, it supports mobility. But it keeps a node inactive which is below the threshold. Thus, data for that particular sensor becomes inaccessible. This may turn fatal in emergency situation.

Author in [98] initiated the modification of WBAN architecture by introducing dual coordinators. But they did not take into account the favorable placement of them on human body. Moreover, data is transferred to both the coordinators if in LoS of the sensor. This resulted in energy wastage and early dead node formation. The optimum placement of the coordinator in WBAN is a crucial issue which affects the PDR of the system. Few attempts have been made in the past to solve this problem.

In [99] relaying and cooperation were the two mechanisms used to maximize the network lifetime. They have not optimized the relay nodes. Thus, the positioning of relay nodes was fixed. [100] and [101] solved the problem of relay optimization using integer linear programming model. They have also proposed a routing algorithm minimizing the installation cost and energy consumption. However, in WBAN relaying is not an optimal solution because of high mobility of the patients. [102] and [103] designed their experiments to maximize the PDR of the system. The interval between the data communication of each node is considered as 8 seconds which is not appropriate in WBAN. [104] and [105] have used a mesh WBAN network where the subject was instructed to walk for 3 seconds in order to carry out the simulation. This duration was too less to represent the impact of their architecture on human mobility. None of the researches dealt with the ideal placement of twin coordinators on human body.

4.3 Proposed Protocol

4.3.1 Assumptions

Based on the following assumptions we have proposed a routing protocol.

1. All nodes possess group mobility only i.e, nodes possess a similar moving pattern as groups.
2. All nodes are intelligent enough to calculate their residual energy
3. All nodes can smartly compute link reliability between itself and neighbouring nodes

These assumptions ensure that nodes moving similarly get engaged to a closer relay or coordinator, providing a more stable topology. Intelligent nodes guarantees that they will not engage themselves in any route

4.3.2 Network Topology

In a WBAN, network mobility of a person is not restricted, though the parameters need to be strictly maintained. A WBAN has a single sink which collects vital signs from different sensors either in single hop or multi hop fashion depending on the presence of it within the transmission range of the sender. Thus, solitary coordinator gets overburdened and the risk of single point failure gets immensely higher using the traffic model of [106]. According to this traffic model, using a single coordinator, the trade off between star and tree topology is difficult as the later outperforms in terms of throughput, whereas the former is better in low end-to-end delay. So, we have proposed an architecture comprising of twin coordinators C1 and C2 with eight sensors. To find the optimum position, we have placed the gateways in two different set of positions on the body based on the Line-of-Sight (LOS). We have evaluated the performance metrics of WBAN for both the experimental setups to conclude that the second set of positions of the coordinators are better than the first.

4.3.3 Different Phases of the proposed Protocol

- Initialization Phase

  Initially both the coordinators C1 and C2 send 'HELLO' message having their Id and location. This location is fixed by the user as the coordinators are static. On receiving the packet, sensor nodes record them and broadcast their Node-Id, Packet-Id and residual energy level. Thus, all the nodes get aware of their neighbours.

- Next Hop Selection:

  When none of the coordinators are within the range of the sender, a node is selected having maximum cost based on Equation 4.1. To evaluate Equation 4.1 the equations 4.2 to 4.10 are used [107]. The node having maximum cost based on the equations is selected as next hop if and only if none of the coordinators are within direct range of the sender.

  When both the coordinators are in direct range of sender, then it uses Received Signal Strength Indicator (RSSI) model of [108] to calculate Equation 4.11. The coordinator, whose Pr value is maximum is chosen as receiver.

$$Cost_{ij} = C_E * (\frac{E_{res,j}}{E_{init,j}}) + C_L * LR_{ij} \tag{4.1}$$

$$LR_{ij} = (1-\lambda)LR_{ij} + \lambda * (\frac{Tx_{succ,ij}}{Tx_{total,ij}}) \tag{4.2}$$

$$E_{res,i} = E_{init,i} - E_{con,i} \tag{4.3}$$

$$E_{con,i} = E_{SB} + E_{SC} + E_{Tx} \tag{4.4}$$

$$E_{SB} = LR_{ij} * T_{SB} \tag{4.5}$$

$$E_{SC} = N_C * [P_{Rx-Tx} * T_{Rx-Tx} + T_C * P_{Tx} + P_{Tx-Rx} * T_{Tx-Rx}] \tag{4.6}$$

$$E_{Tx} = T_{Tx} * P_{Tx} \tag{4.7}$$

$$E_{DB} = LR_{ij} * T_{DB} \tag{4.8}$$

$$E_{DC} = (R+1) * [P_{Rx-Tx} * T_{Tx-Rx} + T_C * P_{Tx} + P_{Tx-Rx} * T_{Tx-Rx}] \tag{4.9}$$

$$E_D = E_{DB} + E_{DC} \tag{4.10}$$

$$Pr = Pt(\frac{1}{d})^n \tag{4.11}$$

Figure 4.1 refers the notations used for the proposed algorithm.

4.4 Routing

The flowchart of the proposed routing algorithm is given in Figure 4.2

4.5 Performance Evaluation

4.5.1 Setting and Configuration

The performance of the proposed protocol is studied and compared with ACIDS [98], LAEEBA [34], and DARE [95] in CASTALIA simulator [109]. Two main experiments are performed to assess the network. In each experiment, 8 sensors were deployed in 3×3 meter square body area with two coordinators. In Experiment 1,the first coordinator (C1) is located at the right lumbar and the second coordinator (C2) is situated at the left lumbar as shown in Figure 4.3. In Experiment 2, position of C1 remains unaltered whereas C2 is placed at the right collar bone instead of the left lumbar as shown in Figure 4.4. The simulation parameters used are shown in Table 4.1. The IEEE standard 802.15.6 is used for MAC layer and CSMA/CA mechanism is used.

4.5.2 Performance Metrics

To evaluate the performance of the proposed routing protocol, following metrics are used.

1. Stability Period:

   The duration of the operation of the network before the first node depletes all its energy is termed as stability period. In WBAN only one node is allowed to collect one particular physiological parameter. There is no backup for any node. If a node dissipates its entire energy and dies out, then its functionality will be stopped. This may be fatal in WBAN. Thus, high stability period is essential in this type of network.

$Cost_{ij}$	cost computed to select the next hop node
C_E, C_L	constant coefficients
$E_{res,i}$	residual energy of node i
$E_{init,i}$	initial energy of node i
LR_{ij}	link reliability between two nodes
$Tx_{succ,ij}$	number of packets successfully transmitted through the link between node S_i and S_j
$Tx_{total,ij}$	total number of transmission and retransmission attempts for all packets
$E_{con,i}$	energy consumed by node i
E_{SB}	average energy consumed at a node during backoff for a successful transmission
E_{SC}	average energy consumed at a node during collision for a successful transmission
E_{Tx}	average energy consumed at a node when transmitting packet
T_{SB}	average backoff time at a node for a successful transmitted packet
N_C	average number of collision for a packet successfully transmitted
T_C	average collision time
T_{Tx}	average time to transmit a packet
T_{DB}	average backoff time for a packet dropped
E_D	average energy consumed by a node due to a packet dropped
E_{DB}	average energy consumed at a node during backoff for a packet dropped
E_{DC}	average energy consumed at a node due to collision for a packet dropped
R	maximum number of retransmissions of a packet
Pr	wireless signal received power
Pt	power transmitted by wireless signal
d	distance between sender and receiver node
n	transmission factor between sender and receiver whose value is environment dependent

Figure 4.1: Notations used for Proposed Protocol

2. End-to-End Delay:

The time lag between sender node sending the packet and receiver node receiving it is termed as delay. As WBAN deals with health related data, delayed delivery may be

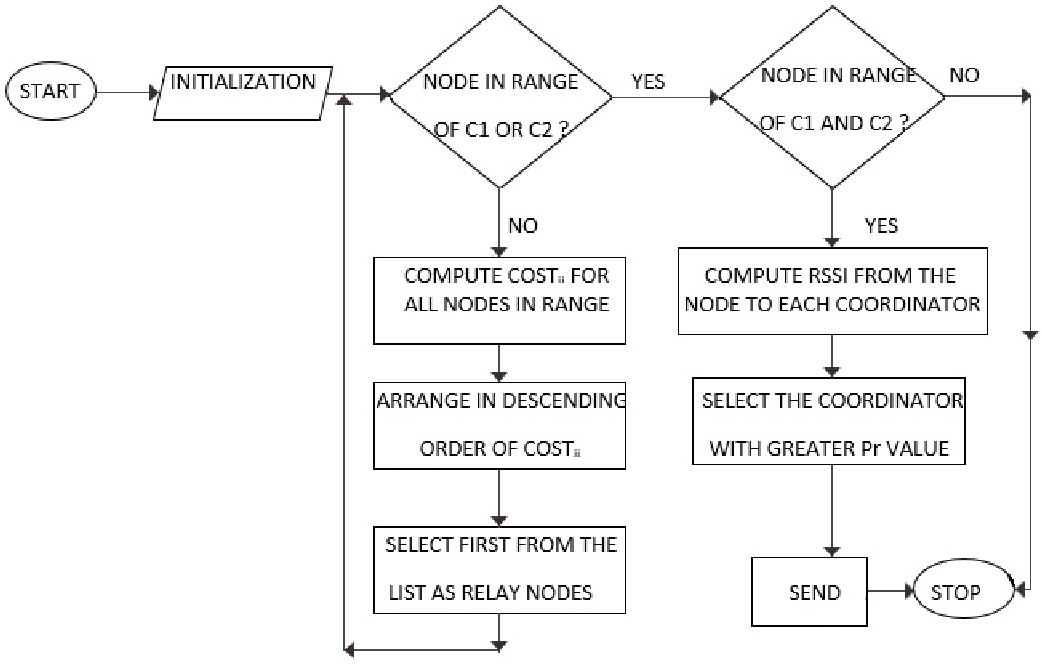

Figure 4.2: Flowchart for Proposed Algorithm

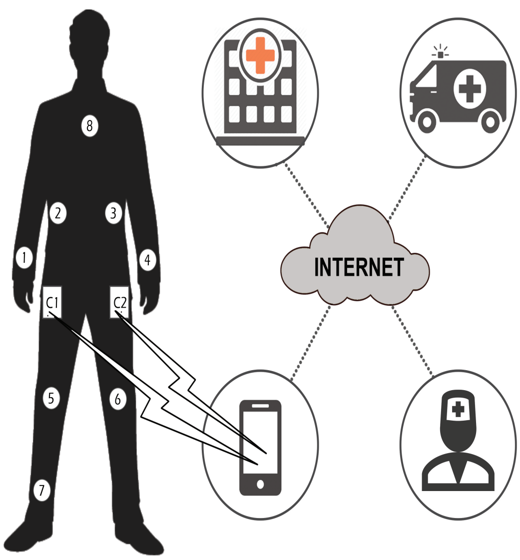

Figure 4.3: Setup for Experiment 1

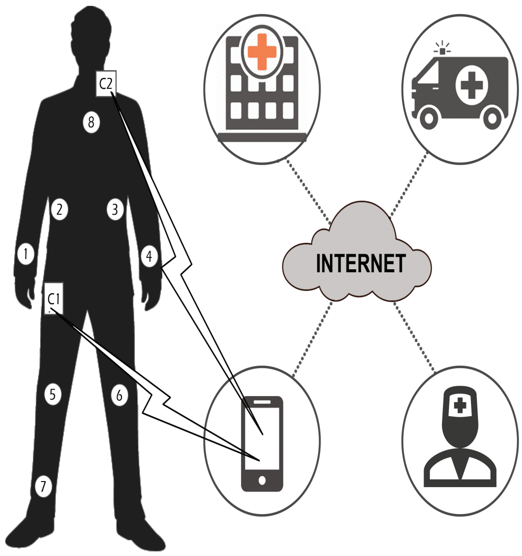

Figure 4.4: Setup for Experiment 2

Tx-Rx, Rx-Tx	0.02 s
Tx (power consumption)	3 mW
Rx (power consumption)	3 mW
Minimum supply voltage	1.9 V
Wavelength (λ)	0.135 m
Frequency (f)	2.4 GHz
Initial Energy (Eo)	18720 J
Battery capacity	560mAh

Table 4.1: Simulation Parameters

fatal. Thus, decreasing delay is a crucial factor in WBAN.

3. Packet Delivery Ratio:

   It denotes the ratio between the number of packets sent by the sender to the number of packets received by the coordinator. The higher the PDR value, better it is. This is because this type of network handles health data. So, packet drop is not desired at all.

4. Remaining Energy:

   The amount of energy left from the initial energy in a node is called remaining energy. This is a deciding factor whether the node can participate in the network. If a node gets inactive. the value of some health parameter will not be gathered. This may turn out to be disaster. So, energy of the nodes in WBAN should be used pragmatically.

4.5.3 Simultion Results

Figure 4.5 shows that the proposed protocol performs considerably better than LAEEBA and DARE. Its performance is at par with ACIDS till 9×10^3 seconds in the Experiment 1 and then outperforms ACIDS algorithm as well. In the Experiment 2, the number of active nodes in the network is much higher for the proposed protocol than ACIDS. This result was expected as in the proposed protocol each sensor sends the data to one of the coordinators with greater RSSI value unlike ACIDS which sends the data twice.

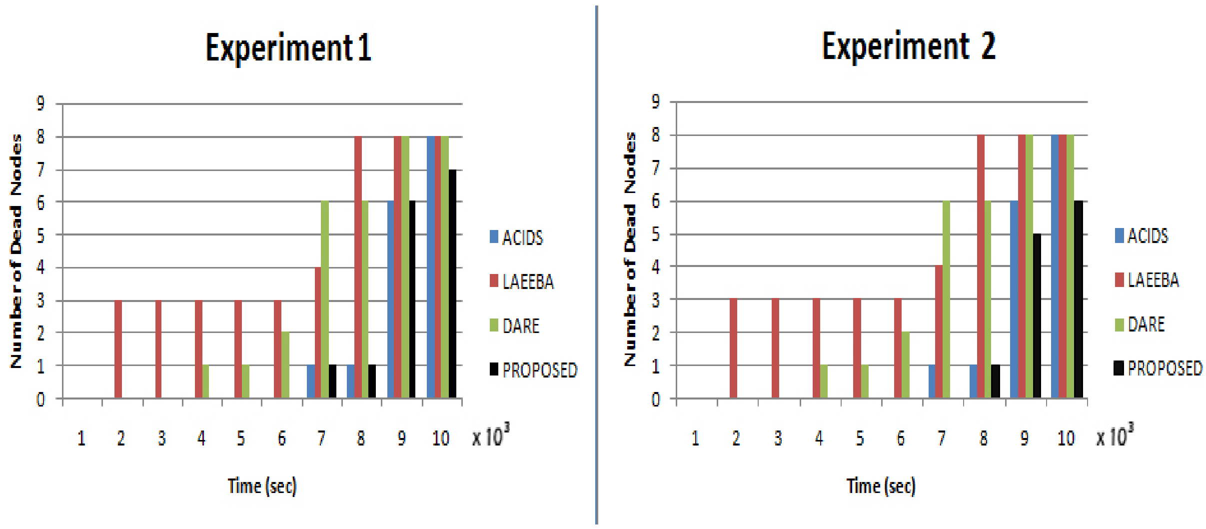

Figure 4.5: Stability Period wrt Time

Minimizing delay in WBAN is a much required QoS as it deals with human vitals. According to Figure 4.6, LAEEBA and DARE has higher end-to-End delay as they deal with only single sink. The presence of dual coordinators lower the delay both in ACIDS and the proposed protocol as most of the sensors are in direct communication range of the coordinators. In Experiment 1, initially ACIDS performs better than the proposed protocol. In the proposed protocol there are some extra calculations needed to send data to one of the coordinators. So, delay of the proposed protocols is initially higher than ACIDS, but later, they are almost at par. In Experiment 2, position of the second coordinator is better. Hence, the delay decreases.

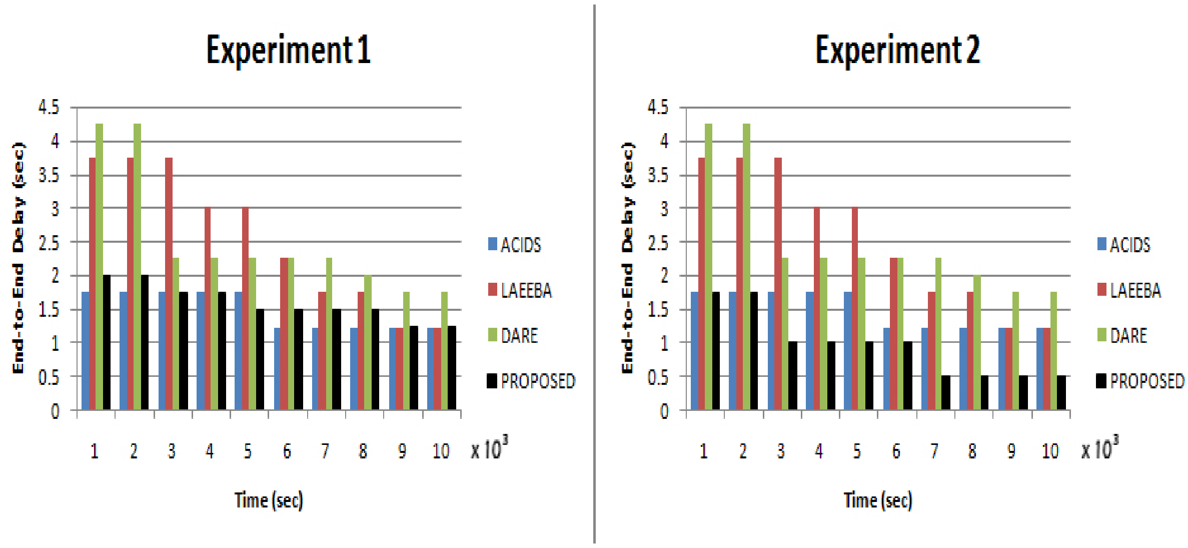

Figure 4.6: End-to-End Delay wrt Time

As ACIDS and the proposed protocol provides superior stability period compared to LAEEBA and DARE, their PDR is much higher in both the experiments as shown in Figure 4.7. In the Experiment 1, the proposed protocol is seen to be at least as good as ACIDS till $6 * 10^3$ seconds. Later, as the number of dead nodes in ACIDS increases, the PDR value decreases. In Experiment 2, the position of C2 is more favourable than Experiment 1. So, number of active nodes is higher. Thus, PDR of proposed protocol is significantly elevated.

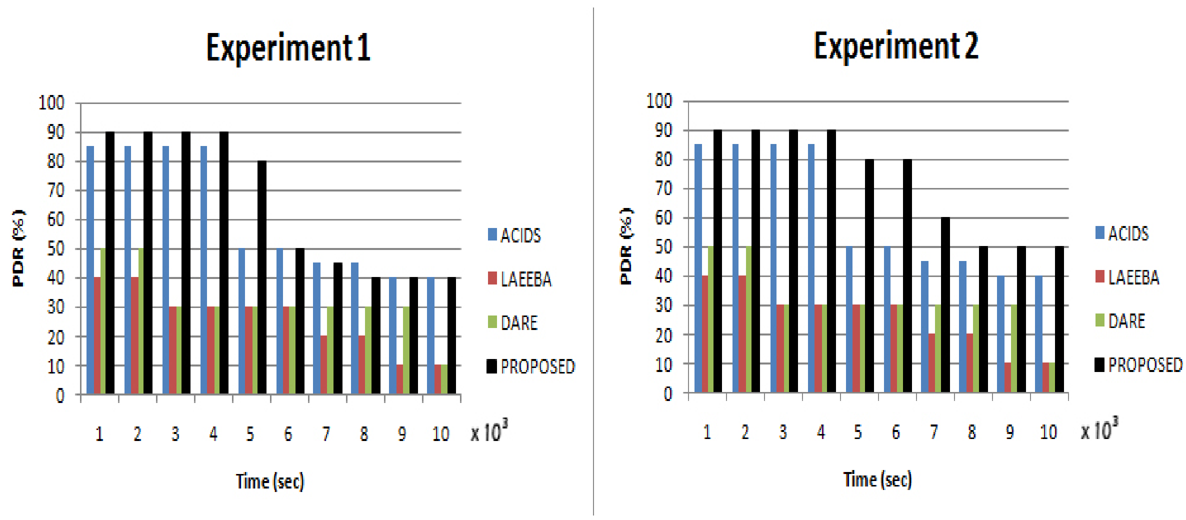

Figure 4.7: Packet Delivery Ratio wrt Time

As shown in Figure 4.8, DARE is the most energy efficient protocol whereas LAEEBA is the least in the list. DARE does not consider other basic parameters of WBAN like stability period, delay and throughput. Thus, energy parameters of others are comparatively lower as they come in trade off with the other parameters as well. In the proposed protocol, a sender sends the data to any one of the coordinator unlike ACIDS. So, it uses energy much more effectively as compared to ACIDS in both the experimental setups.

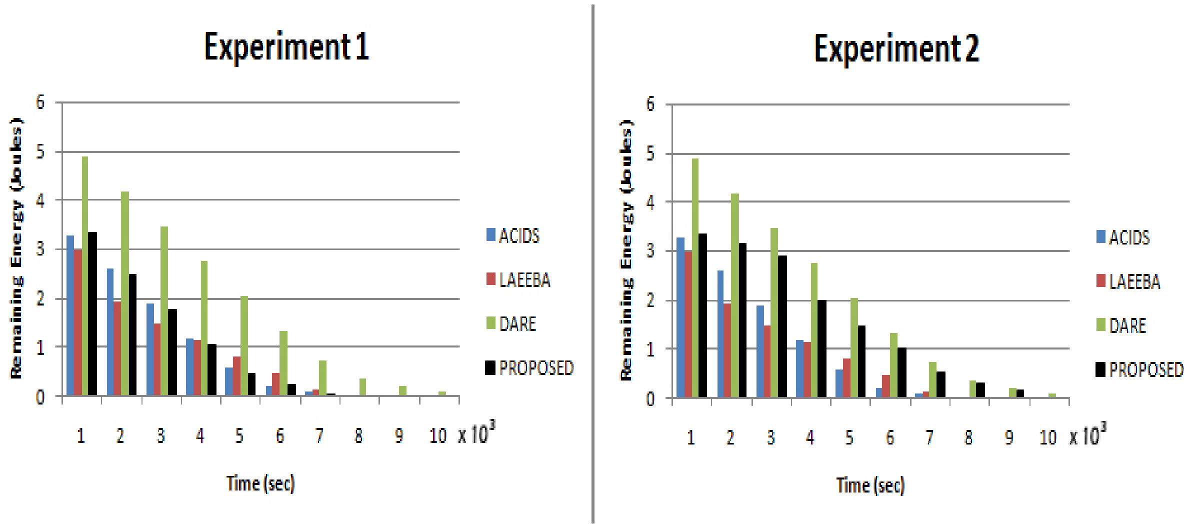

Figure 4.8: Remaining Energy wrt Time

4.6 Conclusion

This research focuses on increasing stability period, PDR and remaining energy while decreasing end-to-end delay by introducing dual coordinators in the network model. A modified concept of Anycasting is used to route data from a sender to the coordinator. We implemented the concept using two coordinators and eight sensors on human body.

To have an optimum position of the coordinators, we have simulated using two different configurations. We have compared the proposed protocol with state-of-the-art protocols like ACIDS, LAEEBA and DARE for both the setups.

Simulation results show that the setup of Experiment 2 is more favourable for the proposed protocol. It outperforms LAEEBA, DARE and atleast as good as ACIDS in terms of PDR, stability period and end-to-end delay. Due to availability of more than one coordinator, the sender can send data to the appropriate one. Thus, topologically most of the nodes come in star fashion to the sink. This results in better efficiency of the proposed protocol than others.

In some cases ACIDS performs better than the proposed one because of extra processing it has to do to choose between multiple sinks. But, overall performance is much better than that of ACIDS algorithm.

Chapter 5

A Bio-inspired Algorithm to Mitigate Interference in Multi-WBAN Scenario

5.1 Introduction

This chapter focuses on reliability and quality of service defined in terms of Bit Error Rate (BER) and Packet Delivery Ratio (PDR) for the messages delivered. It is shown that the proposed protocol ensures increased throughput of the network in terms of higher PDR value. Further, as WBAN sensor nodes are energy constrained, we have ensured the right balance of performance and power consumption by mitigating inter-WBAN interference effectively.

In order to ensure maximum throughput of health data packets, this chapter utilizes an emerging promising technology of wireless communication called Overlay Cooperative Cognitive Radio(OC-CR). This technology solves the problem of limited crucial spectrum allocation.

The contributions of this chapter are summarized as follows:

1. Allocate the available frequency channels fairly based on the criticality of the health data to be transmitted.
2. Optimize the transmission power in order to achieve higher channel gain by the cognitive users.
3. The proposed algorithm effectively avoids collision and hence enhance the throughput of the system.
4. Number of retransmissions to reframe the network as quick as possible is much less as compared to General 802.15.6.
5. The proposed algorithm outperforms 802.15.6, [110], and [111] in terms of probability of collision and throughput.

The chapter is organized as follows: Section 2 discusses the current state-of-the-art in this domain followed by an elaborate Design Model formulation of the proposed work. The proposed solution based on Particle Swarm Optimization (PSO) is discussed in section 4. In Section 5, the simulation results of the proposed algorithm are shown followed by Conslusion in Section 6.

5.2 Related Works

Research on enhancing reliability in WBAN by mitigating inter-interference is an active area. Categorization of interference is already discussed in detail in Chapter 2. In this section, we shall elaborate some algorithms which are specific to this work. There could be some repetitions which we have deliberately incorporated for easy reading.

Authors of [112] pointed out via experiments that increasing the number of WBANs adversely affects their PDR. This further degrades by mounting the data rate of the nodes in the network. Though the problem was well defined in that paper, the solution to this problem was not addressed. [113] analyzed co-channel interference among non-overlapping WBANs. In this paper, authors computed the least "network distance" which will have an acceptable level of Signal-to-interference-plus-noise ratio (SINR). They showed that the range of the least "network distance" is 7 to 12.5 metre. However, this solution restricts human mobility which is not desirable.

Different MAC schemes were investigated in [114] with respect to probability of collision, SINR and BER. This chapter showed that TDMA outperforms CDMA in co-channel interference mitigation with respect to BER and SINR. But FDMA is known to be the best solution for interference easing in uncoordinated WBANs. [115] discussed Cognitive Radio based intra-WBAN and inter-WBAN architecture and related issues. It presents an overview of these architectures. [76] used naive-Bayesian-supervised learning method to detect and predict coexisting WBANs. Packet Reception Ratio (PRR) and SINR are used for measuring parameters. But the issue of Quality of Service (QoS) is not addressed in this chapter.

According to the current state-of-the-art, different schemes to reduce inter-WBAN interference include power control strategies, MAC-based, Cognitive radio-based techniques and Ultra-wideband (UWB) based, Signal processing-based approaches. As WBAN sensors are energy constrained, reducing power consumption tones down transmission range and energy usage. As a result, this approach lowers the possible interference area and thus enhances the throughput and lifetime of the network. Proactive Power Update (PAPU) is discussed in [59] that applied game theory to find the optimum transmission power. Similar to [59], [64] proposed a game theory-based Power Control to maximize system throughput while minimizing power expenditure. Here nodes with high power usage are penalized. A reinforcement learning based on game theory is proposed in [116] for interference mitigation. In this paper, WBAN users transmit at the maximum data rate and the payoff function of one of the users is taken to be the reward function to select the best responding player. Whenever there is a change in the network, this reward function is updated and informed to every node in the network.

In [59], [64], [61] and [116], huge amounts of periodic message exchange takes place in the proposed algorithms to update the status of all nodes in the network. As WBAN nodes are highly mobile and energy constrained, this acts as an unbearable overhead for the lifetime of the network. [60] describes a Fuzzy Power Controller (FPC) system model that determines the level of transmission power based on SINR, current power of interference and a feedback channel of the current transmission power. The convergence time of the genetic-fuzzy system is based on the stability of the network. As WBAN is a dynamic system, the number of iterations needed to converge is very high. In [117] Bluetooth and acoustic wave technology are used to develop dynamic interaction graph in social network. Implementing this algorithm in a WBAN node is highly impractical because of energy requirement. In addition, the time to detect the distance between two WBANs using acoustic wave is not acceptable in this type of network. Moreover, accurate detection of the wireless channel state is still a research problem. [63] elaborates another scheme to lessen intrusion by maximizing the payoff of each WBAN. In reality, mapping each WBAN to a set of actions based on its type is a challenging issue. [118] describes a Cross Layer Interference Management (CLIM) scheme in which a WBAN adapts to another transmission rate and power whenever it detects interference. This scheme fails in a crowded network.

In [70] a QoS based MAC scheduling scheme has been described for healthcare monitoring. This approach considers coexistence of multiple WBANs. The interfering WBANs coordinate among themselves to schedule their transmission time. This is done by exchanging information among them. As WBAN users are highly movable, within the short duration of stability of the network, these extensive information exchanges become unrealistic. [119] uses a combination of CSMA/CA and TDMA to develop an Asynchronous Inter-Network Interference Avoidance (AIIA) algorithm. They have taken into account a less mobile network. In this method, some sections of a definite WBAN's active super-frame [120] are dedicated for coordination. Though it has better results in terms of coordination time, network capacity remains a challenge. [67] depicts a Continuous Frame Transfer (CFT) of radio module with ultra-low power characteristics. It senses the channel to control the transmission time. Thus, energy is greatly conserved in this method by limiting the number of retransmissions.

In Random Incomplete Coloring [111] authors have considered a hard assumption of perfect super frame synchronization to mitigate inter WBAN scheduling by graph coloring. In both of [67] and [111], delay is not considered at all which is a crucial parameter in healthcare. Two layer MAC (2L-MAC) protocol [68] uses a polling mechanism to avoid collision while transferring data. If the delay of the responder is higher than a threshold value, it switches to a backup channel. But neither channel's wobbliness nor the mobility of WBAN has been addressed. The end-to-end delay is also very high in a medium dense network. [110] mitigates interference by adaptive techniques based on Interference Mitigation Factors (IMF). Although the procedure is quite simple, it fails to assign priority of WBANs in different practical situations. Moreover, as in the IMF mechanism, there is no scanning of the channel; thus, collision in the physical layer is highly probable. [111] considered all nodes in a WBAN as a whole and all nodes in the same WBAN must work in the same time slot. This assumption is too unrealistic in health care domain.

A Clique Based WBAN Scheduling (CBWS) [121] is proposed to overcome the above problem. Each node in a WBAN has the capability of sleep or wake up. This enhances the network lifetime. But this protocol did not consider the channel quality or the priority of any WBAN coordinator based on the type of data. In [110] an Adaptive Inter network Interference Mitigation takes care of priority of each sensor node for orthogonal scheduling. This ensures the signal QoS at the receiver's end. But the end-to-end delay of the signal is considerably high because the sensor nodes can propagate in only one slot and then must pass the time for their next round. [73] describes another MAC approach called Cooperative Scheduling (CS) that has a high spatial reuse because they form clusters to lessen collision. However priority of sensor nodes and user mobility are not addressed. This approach takes a huge time to converge.

5.3 Design of the proposed algorithm

5.3.1 System Model

In this chapter, data generated from the body sensors are classified as Throughput-Sensitive (TS) and delay-sensitive (DS) based on their urgency of delivery. The WBAN coordinators which have DS data are classified as Primary User (PU) by the AP for that particular super frame transaction and the remaining WBANs participating in the network are Secondary users (SU). Thus, the tag of PU and SU dynamically changes in the network based on the type of data a WBAN intends to transmit.

At a particular time frame, channel gain is maximized by minimizing hindrances, maintaining coordination and collaboration among the network components. To deliver critical data with the best effort to the intended AP, the entire bandwidth available is distributed among the PUs only. The spectrum utilization of the PUs is not constrained so that the earliest delivery of critical data is possible. Here, a non-negotiation scheme is followed to optimize performance and quick convergence. However, each SU is aware of the possible collision with other users in the network by exchanging information among them.

This negotiation method enriches our proposed scheme to support dynamic environment. The average human torso is less than 3m by 3m. The longest distance an user has to cover to reach its AP is the diagonal of a 3m*3m square, which is $3\sqrt{2}$ m. To cover this distance, if an AP is not within the transmission range of the PU, it tends to increase its power; this is extremely undesirable in WBAN as it will not only dissipate energy faster, but also cause higher interference. To diminish the effect of interference, the SUs intend to utilize the gaps in transmission in the spectrum dedicated to a particular PU. Since multiple SUs compete to use the underutilized spectrum, possibility of collision exist. To solve this problem, AP makes a pseudo 2-Tier architecture. AP acquires appropriate information about the transmission power of the SUs and makes Actual-Level (AL) groups with the conflicting SUs. Any member of a group cannot be allocated in the same spectrum for that particular time frame. Thus, they form different Virtual-Level (VL) groups on the basis of the spectrum in which they are being allowed to transmit. In order to lessen the transmission power of the PU, these SUs forming VL groups may also act as relay nodes.

Total available bandwidth	B
Number of PUs at time ’t’	P
Number of SUs at time ’t’	S
Bandwidth allocated to i^{th} PU at time ’t’	$B_i(PU) = B/P$
Available resource information at time ’t’ $A_{i,j}(t)$	1/0 =1, when j^{th} SU cannot use i^{th} PU’s channel at time ’t’ because it is already been utilized by i^{th} P =0 otherwise
Channel assignment at time ’t’ $X_{i,j}(t)$	1/0 =1, when i^{th} PU channel is assigned to j^{th} SU at time ’t’, =0 otherwise
Transmission power of j^{th} SU on i^{th} PU channel at time ’t’	$T_{i,j}(t)$
Maximum transmission power of s^{th} SU	$Tx_{S_{max}}$
Channel gain of j^{th} SU if it is allocated to use i^{th} PU channel at time ’t’	$G_{i,j}(t)$
Maximum transmit rate of j^{th} SU on i^{th} PU channel at time ’t’	$r_{i,j}(t)$
Energy transmitted per bit/ Noise (SINR)	Y_b

Table 5.1: Notation

5.3.2 Formulation of an Optimization Problem

The notations used in the formulation are presented in Table 5.1.

The assumptions used in this chapter are as follows:

1. $\Sigma B_i(PU)$ less than or equal to The logical bandwidth of the wireless channel.
2. ΣX_{ij} less than or equal to 1 ; 1 less than or equal to i less than or equal to P and 1 less than or equal to j less than or equal to S;
   This indicates that at the most one SU is allowed to cognitively utilize a channel of a PU at time ‘t’.
3. The WBAN is under Additive White Gaussian Noise (AWGN) network using BPSK

amplitude modulation to maintain a tradeoff between the delay and the throughput of the received health data.

Maximum Transmit Rate of the j^{th} SU on i^{th} PU channel at time 't' is given by Equation 7.14.

$$r_{i,j}\left(t\right) = B_i log_2(1 + (T_{i,j}\left(t\right).G_{i,j}\left(t\right)/Q(\sqrt{2}Y_b) \tag{5.1}$$

where Q(x)= $(1/2\pi)\int_x^\infty e^{\frac{-x}{2}}$
Thus, the optimization problem to maximize throughput of an SU can be written as follows.

Max $\sum_{j=1}^{S}\sum_{i=1}^{P}X_{ij}(t).\mathrm{r}_{ij}(t)$
To complete the mathematical model, the following constraints must be satisfied.

$$\sum_{i=1}^{P} r_{i,j}\left(t\right) \geq r_0 \tag{5.2}$$

$$\sum_{i=1}^{P} T_{i,j}\left(t\right) \leq Tx_{Smax} \tag{5.3}$$

$$0 \leq T_{i,j}\left(t\right)\forall 1 \leq i \leq P and \forall 1 \leq j \leq S \tag{5.4}$$

Equation 7.15 illustrates that the transmission rate of the cognitive users must not go below the threshold value r_0. This ensures fairness in the spectrum allocation. Equation 5.3 refers to the transmission power constraints. It guarantees that the total transmission powers of all the SUs allocated in PU's channel must be less than or equivalent to the maximum transmission power of the SU's. This makes sure that the transmission power of the SUs are bounded. Equation 5.4 assures that the transmission power of a SU allocated to a PU's channel must not be negative. The channel allocation takes a discrete value, while the power constraint is of continuous nature. This represents a Mixed integer non-linear problem (MINP). Because of the complexity in solving this type of problems, this has been transformed into a Continuous Non-Linear Programming Problem (NLP).

5.4 Solution based on Particle Swarm Optimization (PSO) Technique

The optimization problem formulated is an NP problem. So the problem has been modeled by a biological evaluation process called Particle Swarm Optimization (PSO) [**wu2014low**] [73].

PSO is conceptually simple and is easy to implement. Its control parameters are robust and computationally it is much more efficient compared to other optimization techniques such as Genetic Algorithm(GA). In GA information are being shared among chromosomes. So the whole population moves like a single group towards an optimal area. PSO uses a uni-directional information sharing mechanism because only global best solution gives out the information to others. In every evolution, it tries to converge towards the best solution. Hence PSO tends to converge to the best solution quickly.

In PSO, each solution is denoted by a particle that has a position vector and a velocity vector. According to the aforementioned problem, a particle signifies a possible power and bandwidth allocation of the conflicting SUs at time 't'. The allocation focuses on interference mitigation by fair assignmnt of spectrum to avoid collision and thus enhances throughput of the system.

Moreover, PSO simulates the behaviour of flocking of bird. In our problem, incompatible SUs randomly explore frequency channels to propagate TS data to the intended receiver at time 't'. None of the SUs have any idea of the best channel. They only have the knowledge of the distance to the best solution in each iteration. All particles (SUs) determine their searching speed and direction within the search space based on their respective velocities. The performance of each particle depends on its fitness function which is determined by the objective function. The position of the particles at the convergence point gives the solution to the problem.

5.4.1 Notation

Notation used in this chapter for PSO technique are as follows.

- Q is the Number of particles.
- Position of particle $i(1 \leq i \leq Q)$ at the t^{th} iteration is denoted by
  $P_i(t) = \left[P_{i1}(t), P_{i2}(t), P_{i3}(t), ...P_{iD}(t)\right]$
  where D is the number of dimensions to represent the particle $d \in D$
- $P_i(t)$ is a probable solution.
- Velocity of particle $i(1 \leq i \leq Q)$ at the t^{th} iteration is denoted by
  $V_i(t)\epsilon \left[V_{i1}(t), V_{i2}(t), V_{i3}(t), ...V_{iD}(t)\right]$
  where $V\_iD(t) \in \left[-V_{max}, V_{max}\right]$
- Local Best Solution of the particle i until the t^{th} iteration is
  $P_{bi}(t) = \left[P_{bi1}(t), P_{bi2}(t), P_{bi3}(t), ...P_{biD}(t)\right]$
- Global Best Solution of the particle i until the t^{th} iteration is
  $P_g(t) = \left[P_{g1}(t), P_{g2}(t), P_{g3}(t), ...P_{gD}(t)\right]$
  The value of every bit in the particle is randomly generated in the initial phase. This scheme reduces the search space efficiently and thus the convergence time gets reduced.

- In every iteration the Velocity is updated as follows $V_{id}(t+1) = wV_{id}(t)+c_1r_1[P_{biD}(t)-P_{iD}(t)] + c_2r_2[P_{gD}(t) - P_{iD}(t)]$ where c_1 and c_2 are constants lying between 0 to 1. These are used to control the amount of variation in velocity. r_1 and r_2 are used to add randomness in the algorithm to explore the algorithm for varying degree.w is used to vary the priority of previous values and the current value. Too high a jump may cross the global maxima while too less a jump may take a long time to converge. Thus, we focused on balancing between exploration and exploitation in the evolutionary computing technique.

- In every iteration the position is updated as follows.
  $P_{id}(t+1) = P_{id}(t) + V_{id}(t+1)$
- The fitness function is calculated as follows.
  $F_{i,j}(t)$ = $\sum_{j=1}^{S}\sum_{i=1}^{P} X_{ij}(t)$.r$_{ij}(t)$ - the number of times the constraints has been violated.

5.4.2 PSO-based Spectrum Allocation Algorithm

1. 1. Propagate resource allocation matrix L, Channel Information matrix $G_{i,j}$, dimensions of each particle and the total number of population to SUs and subsequent APs.
2. 2. Initialize the number of iterations $t = 0$ and randomly generate $V_i(t)$ and $P_i(t)$ where $V_{iD}(t) \in \{-V_{max}, V_{max}\}$ and thus acquires $P_i(t) = \{P_{i1}(t), P_{i2}(t), P_{i3}(t), ...P_{iD}(t)\}$ for each $i(1 \leq i \leq Q)$
3. 3. Associate each $P_{id}(t)$ $(1 \leq i \leq Q)$ to $T_{i,j}(t)$ where (i, j) is the d^{th} element with $A_{i,j}(t) = 1$
4. 4. Compute Fitness Function of each particle in the population using the equation $F_{i,j}(t)$ = $\sum_{j=1}^{S}\sum_{i=1}^{P} X_{ij}(t)$.r$_{ij}(t)$ - the number of times the constraints has been violated
   Find Local Best solution $P_{bi}(t) = \left[P_{bi1}(t), P_{bi2}(t), P_{bi3}(t), ...P_{biD}(t)\right]$
   and Global Best Solution $P_g(t) = \left[P_{g1}(t), P_{g2}(t), P_{g3}(t), ...P_{gD}(t)\right]$
   where b indicates the particle with highest fitness value
5. 5. Set t=t+1
   and Update Velocity Vector using $V_{id}(t+1) = wV_{id}(t) + c_1r_1[P_{biD}(t) - P_{iD}(t)] + c_2r_2[P_{gD}(t) - P_{iD}(t)]$
   If the current value $V_{id}(t) \geq V_{max}$, set $V_{id}(t) = V_{max}$
   If the current value $V_{id}(t) \leq -V_{max}$, set $V_{id}(t) = -V_{max}$
6. 6. Update Position Vector using
   $P_{id}(t+1) = P_{id}(t) + V_{id}(t+1)$
7. 7. Computer Fitness Value of each particle in the population
   For each particle i, if Fitness Value $\geq$ Local best value, set the current fitness value as the local best solution i.e $F_{i,j}(t) = \left[P_{bi1}(t), P_{bi2}(t), P_{bi3}(t), ...P_{biD}(t)\right]$
   For each particle, if Fitness Value $\geq$ Global best value, set the current fitness value as the Global best solution i.e $F_{i,j}(t) = \left[P_{g1}(t), P_{g2}(t), P_{g3}(t), ...P_{gD}(t)\right]$

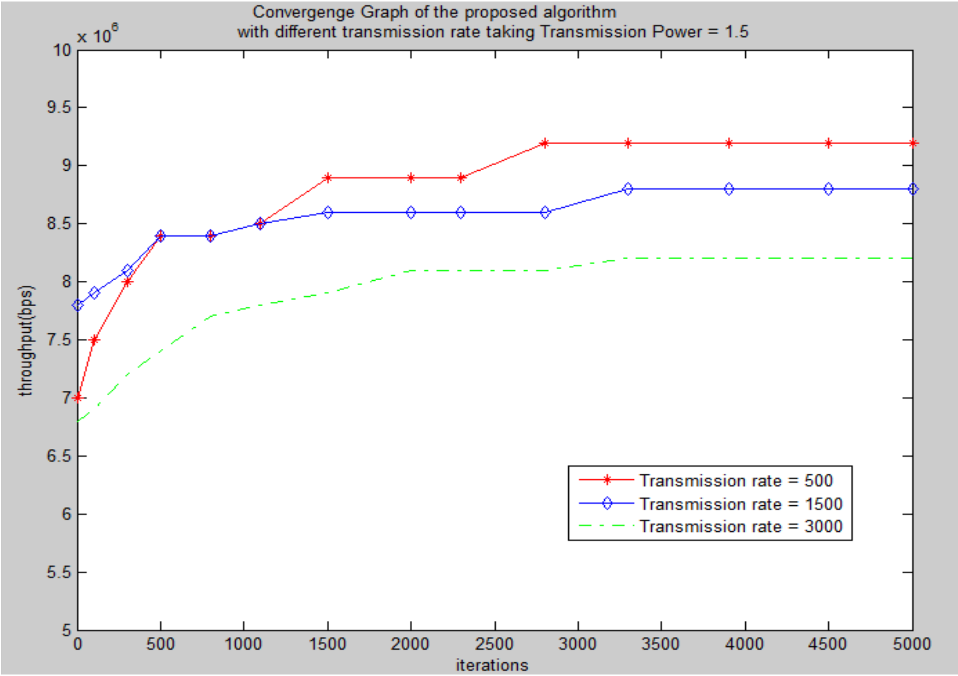

Figure 5.1: Convergence Graph for Transmission Power 1.5

8. 8. If t = max iteration value, then stop and output the Global best value $[P_{g1}(t), P_{g2}(t), P_{g3}(t), ...P_{gD}(t)]$ to $P_i(t)$
   Else goto Step 5

5.5 Simulation Results

To assess the proposed algorithm, it is simulated in Matlab. It is evaluated based on a cognitive radio system having 12 primary users and 10 secondary users using 6 MHz available bandwidth. The matrix of resource information is generated randomly. For a wireless link, the average channel gain of a cognitive user is randomly generated between 0 and 0.02. The interfering noise is 0.6 mW. The total number of particles in the population is considered to be 20. To conflow the amount of variation velocity possible, the variables $c1$ and $c2$ are taken as 2. The maximum velocity is assumed to be 5. The different transmission rates considered are 500 bps, 1500 bps and 3000 bps. To compare the transmission power, we have taken into account two cases with 1.5 mW and 2.5 mW.

The QoS parameters used for assessing are defined as follows.

- Convergence

  Mathematically, convergence is the property of approaching a limit more and more closely as an argument (variable) of the function increases or decreases as the number of terms of the series increases.

- Throughput

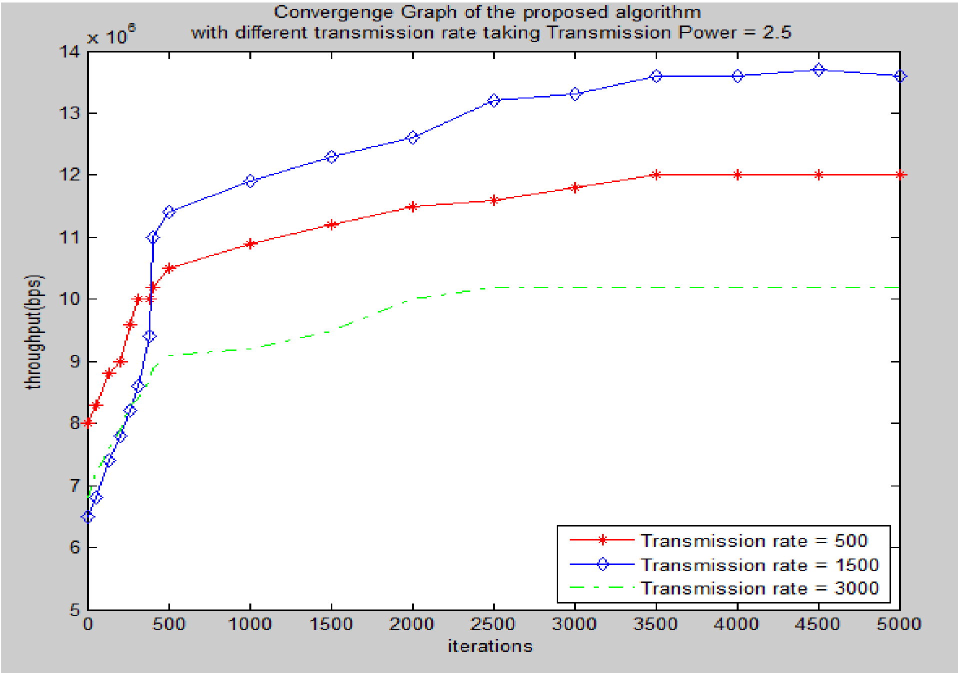

Figure 5.2: Convergence Graph for Transmission Power 2.5

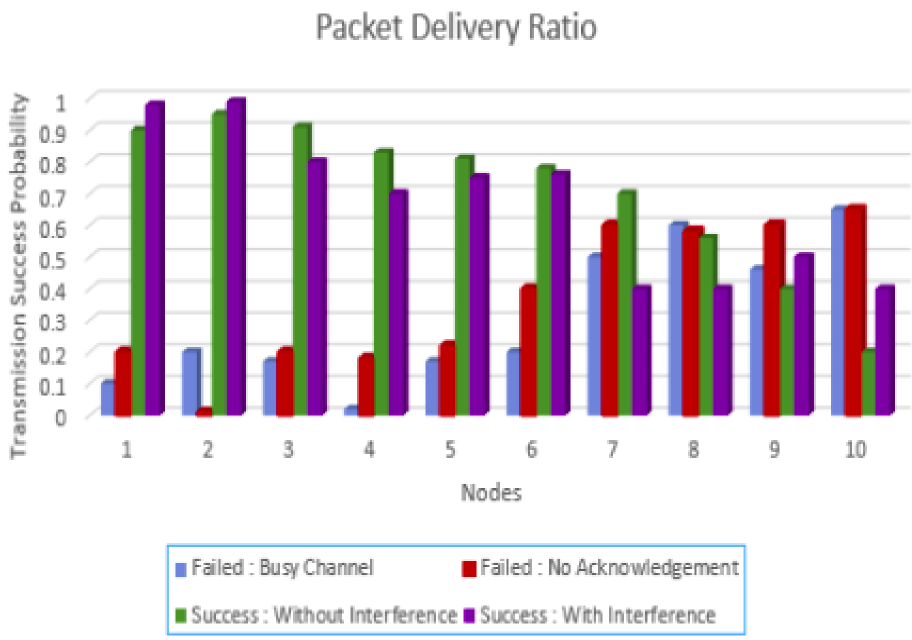

Figure 5.3: Throughput of 802.15.6

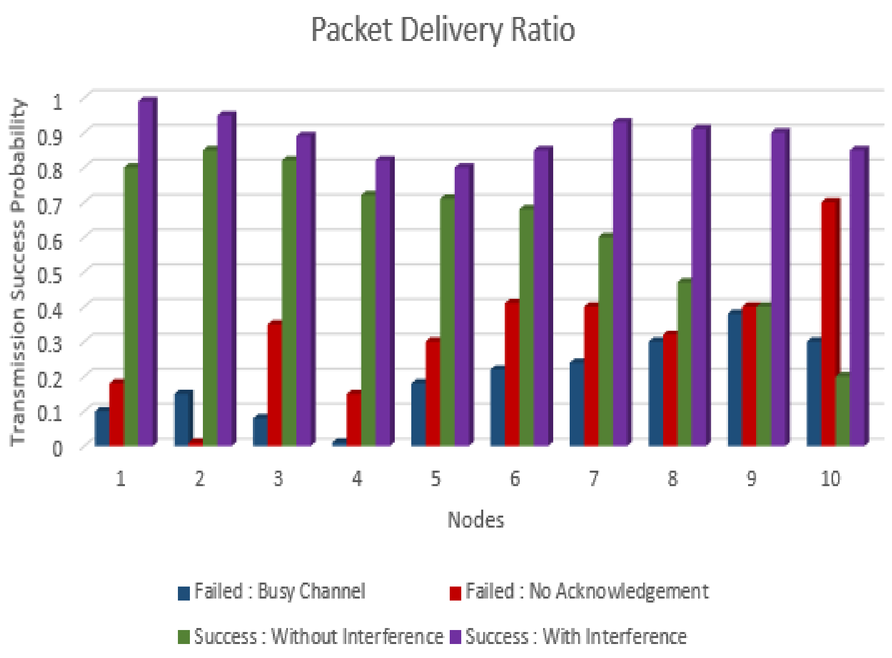

Figure 5.4: Throughput of Proposed Algorithm

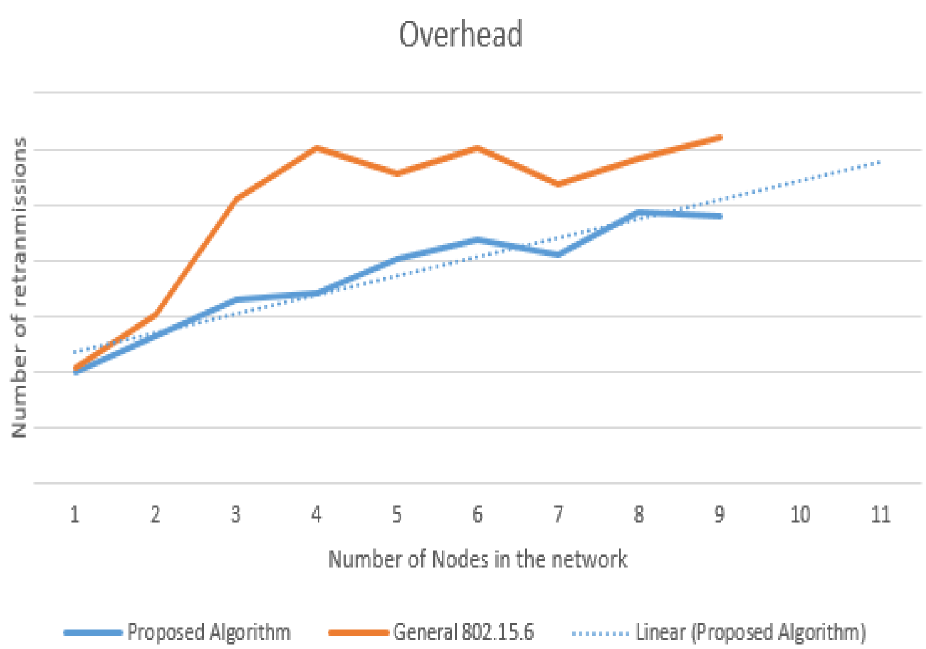

Figure 5.5: Overhead Comparison Graph

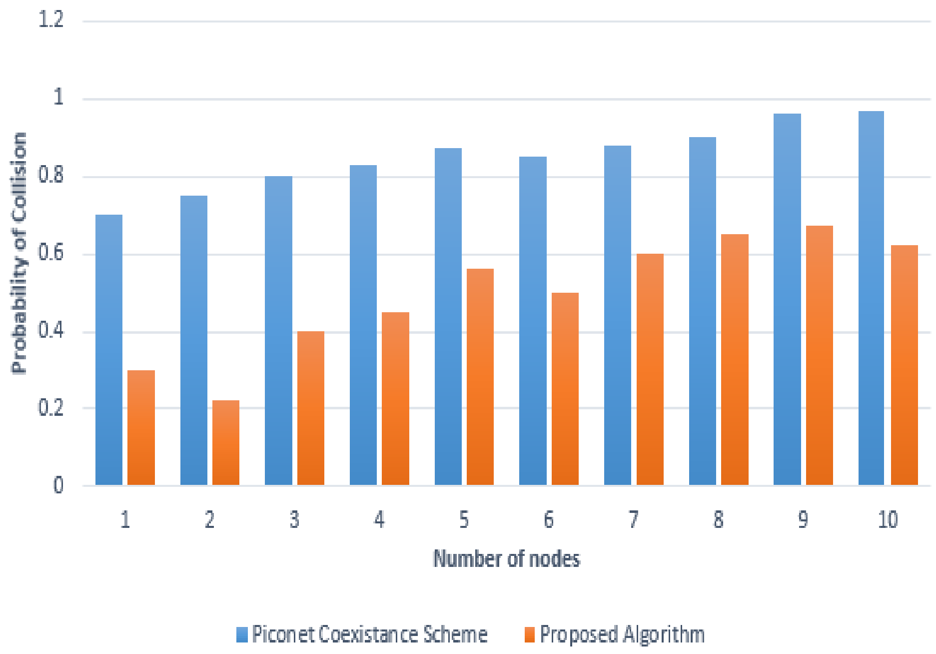

Figure 5.6: Probability of Collision

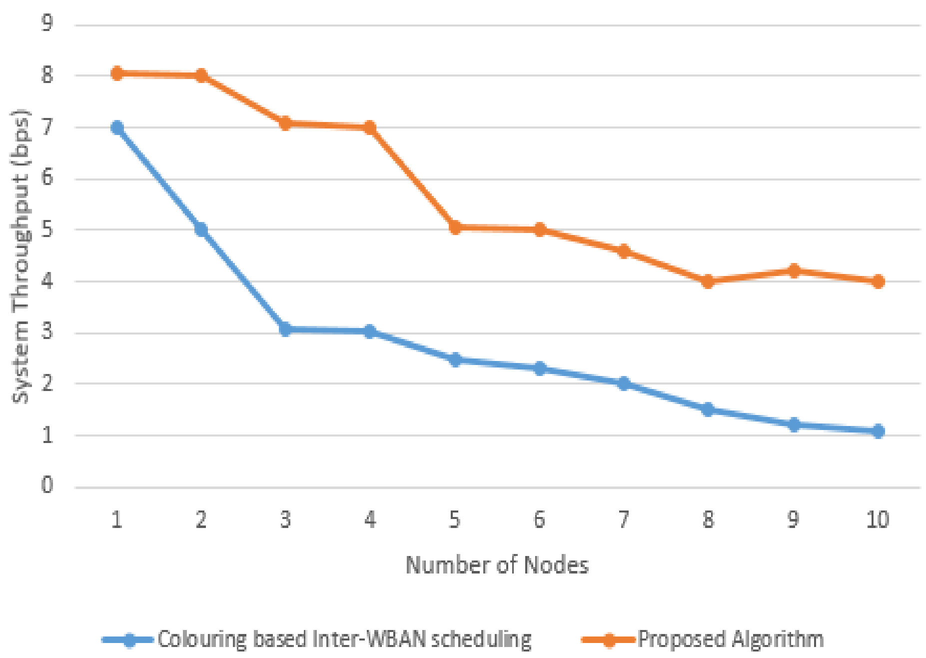

Figure 5.7: System Throughput Probability compared to Colouring based Inter-WBAN scheduling

Throughput is defined as the ratio of data packets received successfully at the destination to all the packets originated from the sources.

- Overhead

  The amount of resources used by every sensor node in the network such as bandwidth, energy etc.

- Collision probability

  Probability of collision is defined as the likelihood of more than one device attempting to send a packet on a network at the same time.

Both Figures, Figure 5.1 and Figure 5.2, demonstrate that the proposed algorithm gives very good near optimum results after 2500 iterations. From the figures we can also conclude that the throughput of the system does not vary only with the transmission rate. It is constrained by the power with which users are transmitting. Thus, cognitive users having higher channel gains are seen to be using more channels dissipating more power than users having less channel gain but more available power. Hence, the latter category can capture the remaining channels to transmit data. As a result, overall performance of the system improves increasing the throughput of the system.

Figure 5.3 shows graph of throughput vs. the number of nodes using a standard algorithm implemeting 802.15.6. It shows that as the number of nodes in the network increases, the probability of failure increases. Figure 5.4 shows that using our Overlay CR algorithm, the transmission success rate is almost constant irrespective of presence of interfering nodes. From the last two graphs we can conclude that the number of packets delivered to the receiver using our algorithm is at least 20% more than that of any standard 802.15.6 algorithm. This shows that our algorithm outperforms the general one to mitigate interference and hence increases reliable packet delivery.

The overhead of the proposed algorithm is also depicted in Figure 5.5 based on the number of retransmission of packets. From the graph it is clear that the number of retransmissions of packets in the proposed algorithm is comparatively much less than 802.15.6. This is also predictable since the SUs that have high remaining energy act as relay nodes; thus, the network becomes stable very fast even in the presence of high mobility.

Figure 5.6 compares the proposed algorithm with [110]. The probability of collision in [110] is much higher than the proposed one because the [110] considered adaptive schemes that performs better only in low populated channels. When the number of competitive users increases, the performance of their algorithm degrades. The proposed algorithm performs better in real life scenarios where the population varies dynamically.

Figure 5.7 demonstrates the system throughput of the proposed algorithm compared to [111]. As [111] maintained a perfect superframe synchronisation, there is no scope to support dynamic change in the environment. Thus, priority of health data has not been taken into account. On the other hand, our proposed algorithm prioritized the users as SU and PU. So the throughput of our system is better in terms of PDR.

5.6 Conclusion

In this chapter, we have proposed a bio-inspired model-based algorithm to mitigate inter-WBAN interference. In our algorithm, we have applied the concept of Overlay-CR system. As WBAN deals with a highly dense and frequently changing network, we have considered a AWGN network. To verify and validate the model, we have proposed an algorithm using PSO. Performance of the algorithm has been measured through simulations in MATLAB. Simulation results suggest that with 1.5 mW transmission power, when the transmission rate is nearly 3000 bps, the throughput of the system slows down. This result is expected because higher transmission rate ends up in data loss. But when the transmission power is increased to 2.5 mW and the transmission rate is 3000 bps, the throughput of the system increases by at least 20% as compared to the general 802.15.6. Moreover, the number of retransmissions of packets in the proposed algorithm is comparatively much less than 802.15.6 in high mobility scenarios.

Chapter 6

Routing Algorithm using Optimized Relays for Enhanced WBAN Lifetime

6.1 Introduction

WBAN comprises implanted, on-body or around the body sensors that monitor [122], [123], [124], [125], [126] and wirelessly transmit health data to a sink node called the coordinator. Deployment of a large number of implanted sensor nodes impose several challenges in positioning, maintaining and efficiently routing critical health data [86], [123], [87]. We have seen many challenges that WBAN systems face. Here, we list several other challenges that will be addressed in this chapter.

Electric and Magnetic Field (EMF) radiation is generated during transmission of data packets. This radiated energy gets transformed into heat. As a result, human tissues around the body sensor nodes may get damaged. If the temperature rise of the sensors is very high in a short span, tissues may get burnt or even cells may get mutated and that may lead to malignancy. The amount of heat absorbed by human tissues is measured by Specific Absorption Rate (SAR). SAR value is preferred to be less in WBAN. This can be ensured by optimizing the number of transmitted packets in the network. To achive higher success rate with limited transmission of packets, we cannot incorporate large number of relay nodes. The higner number of relay nodes will negatively effect the SAR value as the radiating field of them may get overlapped, damaging the tissues therein. Thus, optimization of the number of relay nodes is crucial to avoid tissue damage, enhancing the lifetime of the network by avoiding the formation of hotspot.

When more than one node comes in transmission range of one another, the risk of packet collision is higher. Since WBAN deals with health data, packet loss due to collision is not affordable. Data packets lost due to interference must be retransmitted, which increase the number of packets in the network and also deplete the remaining energy of the nodes. So, Signal-to-Interference-Noise-Ratio (SINR) should be increased to guarantee the Quality of Service (QoS) in WBAN.

Moreover, in-vivo sensor nodes are energy constrained. So, their battery power must be pragmatically utilized to enhance the lifetime of their functionality. This demands minimum energy consumption while performing activities. Relay nodes may take the responsibility of only forwarding data from the source towards the destination [127], [128], [129], [130], [131]. Thus, energy of the sensor nodes for relaying other's data is saved. However,optimum number of relay nodes should be deployed on the body for this task to ensure its positive effect overshadows.

Most researchers have focused on these issues individually. Several works have been done on WBAN routing based on energy efficiency [92, 132], interference [133], temperature awareness [131, 134]. But these protocols do not simultaneously focus on adverse effects of heating on human tissues, energy constraints and intra-WBAN interference. The objectives of the chapter are as follows.

1. Optimizing the number of relay nodes and positioning them in the network in such a way that the temperature rise of individual sensor nodes in the network is within a threshold value.

2. Minimizing installation cost.

3. Minimizing hop count for transmission of data packets from sender to the sink node that leads to low latency.

4. Network lifetime enhancement by homogeneously utilizing the remaining energy of the sensor nodes.

5. Minimizing energy consumption of the nodes which in turn minimizes specific absorption rate (SAR).

6. Minimizing intra-WBAN interference for reliable data transmission.

This chapter first aims to design a topology which has an optimized number of relay nodes and then proposes an efficient routing algorithm. Relay nodes are incorporated to frame the backbone of the connected wireless network so that all sensor nodes are coupled with at least one relay node and none of the nodes in the network remaining isolated. In the proposed method, the remaining energy of the in-vivo sensors are dissipated intelligently and homogeneously so that network lifetime is enhanced without compromising reliability. Moreover, in our method, multicasting has been used on to reduce the unnecessary packet transmissions. Our design also leads to minimum hop count from body sensors to the sink node.

The chapter is organized as follows. Section 2 discusses the state-of the-art solutions for the problems mentioned. Section 3 describes our WBAN design model using Mixed Integer Linear Programming (MILP)[135] [19] . Simulation results are discussed in Section 4. Finally, we conclude in Section 5.

6.2 Related Works

This section discusses the state-of-the-art solutions for the basic WBAN QoS parameters such as energy-efficiency, thermal awareness and interference mitigation. Authors in [130] have surveyed different WBAN research projects and its corresponding technologies, application scenarios etc. They have pointed out several open issues that still need to be addressed before applying WBANs for enabling ubiquitous monitoring of humans. Our work tries to address most of the issues simultaneously to provide an efficient WBAN model.

In [136], authors have proposed multipath routing for energy efficient recovery from failure in WSN. Simulation results show that braided multi paths have about 50% higher elasticity to independent failures. It also claims that the overhead for alternate path maintenance is better. However, this is just not adequate while dealing with critical health data in WBAN. Along with these issues our proposed model also takes into account various QoS parameters with equal importance to provide a better model. Similarly in [89] a comprehensive study on WBAN has been carried out. Authors in [89] have defined the term "green technology" as energy efficient techniques used in WBAN. Several energy efficient routing algorithms [137], [138] have been proposed. With respect to one of the QoS parameters, an optimal design of energy-efficient and cost-effective WBAN, energy-consumption was emphasized in [139]. The authors in this work have proposed a model to optimize relays to be deployed and for data routing towards the sinks. This minimizes network installation cost and thus energy consumed by wireless body sensor nodes and relays are also reduced. But, unlike our model, they failed to consider thermal issues, multicasting, interference mitigation and optimization of hop-count. In order to select next hop dynamically, the authors in [132] have proposed a routing protocol that uses maximum benefit function. They have considered energy, throughput, bandwidth and hopcount as the parameters to optimize. The approach dynamically adjusts the weight of the maximum benefit function to achieve timely and reliable transission of emergency data. Also, the QoS requirement of the periodic data is satisfied by this approach. But they did not consider the impact of the maximum benefit function on the SAR, which is a pivotal parameter in WBAN. Further, their approach did not consider the issue of interference that is crucial in case of reliable health data delivery system. Our proposed system considers these issues together. Authors in [140] ensured a reduction in the number of control packet on physical layer by reducing energy utilization. They have used block acknowledgment policy for data packets to get efficient power consumption in WBAN and prioritizing nodes according to transmission power and contension window size.

In [141], authors have proposed a Cooperative Energy Efficient and Priority Based Reliable Routing Protocol with Network Coding for WBAN. In this proposal, high priority nodes are non-cooperative and uses single hop communication with sink for data transmission. All other non-prioritized sensor nodes participate in the system as data generator and cooperative relay node forwarder. They have used enhanced Cuckoo Search Optimization Algorithm for relay node selection based on parameters like residual energy, distance between sender and sink and path loss. Similar to [132], their approach also bypassed two crucial factors - SAR and interference. Their method resulted in high throughput, but the appearance of dead nodes in the network is quite early compared to our proposed protocol.

Hence, the overall throughput of our system is better compared to [141].

Authors in [129] considered a star topology structure where each node has constant distance from the sink or the coordinator node. But they have not considered the fact that due to mobility issues distance of the nodes will change. This stringent constraint is handled in our model. In [128], authors have introduced a term *'link breakage rate'* with respect to mobility. The *link breakage rate* is quite high in WBAN topology due to movement of the patient. The energy consumption is also directly proportional to *link breakage rate*. Thus, the overhead due to the number of topology changes is also high as it is directly proportional to the *link breakage rate* [128]. We have proposed a system where this parameter is taken care of.

Wireless communication among implanted body sensors use radio signals that generate electric and magnetic fields. This absorbs antenna radiation and consumed power in node's circuitry causing rise in temperature. This have adverse effect on human tissues by reducing flow of blood [142], abnormal growth of different organs etc. Thus, SAR is defined as a measurement of the absorption rate of radiation energy by human tissue per unit weight. SAR = $\sigma|E|^2/2\rho$ W/Kg [142] where σ is the electrical conductivity of human tissue, E is the induced electric field due to radiation and ρ is human tissue density. In [131], authors used Particle Swarm Optimization algorithm to identify proper positioning of relay node to route data from source to destination having minimum SAR and improvised success rate of packet transmission. But, they failed to shed light on the interference caused by colocated components. This issue is resolved in our model and is compared with [131] as shown in Figure 6.11.

All the thermal aware WBAN routing protocols primarily aim to reduce the rise in temperature of implanted body sensor nodes. The basic metrics used are network rise in temperature, packet drop, delay, throughput, hop count and energy requirement. TARA [143] is the first thermal aware WBAN routing protocol to focus on overheating issue of implanted body sensor nodes. Though it performs better than Shortest Hop Routing (SHR) algorithm with respect to temperature rise reduction in the network but its withdrawal strategy increases the number of hop count and thus, energy consumption and packet delivery delay increase. LTR [144] and ALTR [144] were designed to overcome the problem of latency in TARA. They performed better in terms of energy consumption, Packet Deliver Ratio (PDR), delay and rise in network temperature. However, both these protocols do not guarantee that the direction of transmission of packets is always towards destination as they only address temperature rise in body sensor nodes. Moreover in ALTR, packets may be transmitted through hotspots instead of being dropped if hop count of packets crosses a threshold value. This results in significant temperature rise of the nodes. To overcome the disadvantages of LTR and ALTR, LTRT [138] handles temperature rise and delay together by focusing on end-to-end route temperature.

However, the average temperature rise metric used in LTR, ALTR and LTRT does not imply that the temperature of an individual node may not rise abruptly. Suppose a scenario where the remaining energy of all nodes in a network are not homogeneously used. In that case, a node may have actually exceeded its upper value of threshold temperature. But, because of the other nodes in the network, the average temperature may appear to be within safe limits. Thus, these over heated individual nodes remain hazardous for human health.

So, these algorithms are not appropriate for WBAN applications. To avoid this problem, TARA uses maximum temperature rise metric of the network which is more suitable. Our proposed model differs from these temperature aware WBAN routing algorithm by considering temperature rise of individual nodes rather than average of them. This makes the system more reliable, stable and safe.

In 2013, a thermal aware routing algorithm M-Attempt [92] which has been elaborated in Chapter 3.

Authors in [134] have proposed a trust and thermal-aware routing protocol for WBANs that is considering trust among the nodes as well as temperature of the nodes to isolate misbehaving nodes. The approach minimizes creation of frequent hotspots by evenly distributing traffic load in the network. Isolating WBAN nodes from a network, results in data loss. These data are health parameters. Loosing them may be dangerous. Thus, our proposed system aims to maximize throughput by keeping all the nodes integrated within the network.

Most papers in the literature on interference mitigation deals with intra-WBAN interference and inter-WBAN interference. Signal to noise plus interference ratio is a metric which is used as a measure of the rate of information transfer in wireless communication systems. It is mathematically formulated as follows:

SNIR= P_r / (N_0 + $\Sigma_{i \neq r}$ P_i) where N_0 is the additive noise power, P_r is the preferred received power and P_i is the unwanted power received from interfering relay node i. Commonly TDMA or CSMA are used. But, both these methods fail to mitigate collision when the traffic load condition is high. In high occupancy channels, most collisions occur while applying CSMA/CA in WBAN [145]. To diminish the negative effect of CSMA/CA Clear Channel Assessment (CCA) is preferred. However, CCA is ineffective in WBAN as its heating impact on human tissue is high [146]. TDMA is the other alternative as it solves interference problem. But, it consumes extra energy of the sensors to collaborate and synchronize control packets. In our manuscript we aim to solve this issue and effectively enhance the network lifetime which is calculated based on Equation 6.1 as given in [147].

$$Lifetime = \frac{E(N)}{Average\ of\ Total\ number\ of\ events} \tag{6.1}$$

In [148], authors presented a dynamic power assessment method which is intelligent enough to determine the transmission power required to send a packet through wireless link. The sender sends this power value to the receiver along with data packet. The receiver node adjusts the sender's power value after measuring the received power. This process is inefficient for WBAN as it consumes a lot of receiver node's energy for processing the sender's power. But, the delay incurred in this process is not considered. Our approach also deals with delay which is a vital WBAN parameter. Authors in [133] have proposed a tree-based WBAN topology using a set of relay nodes with stable commmunication. To reduce the effect of interference, two techniques from the literature called adaptive data rate and the adaptive duty cycle are used. This technique is also unproductive in WBAN because of the complexity of the receiver and the huge number of sensor nodes in the network. Further, nodes cannot periodically monitor the wireless channel conditions. Though this technique mitigates intra-WBAN interference, their method leads to number of packets being dropped. As a result, this algorithm has low throughput which has been taken care of in our system.

In [149] author has proposed a system to identify the elderly position in order to support pressure ulcer prevention. They have analyzed the self movements to make prognostications for bedsores and plan the caregivers interventions to decrease their burden in order to prevent bedsore. They tried to achive the goal by only leveraging the RSS measurements already available on small wireless communication devices. But the adverse effect of other parameters related to wireless communication on health related issues are not being taken care of in this work. Though it seems to be fine wrt indoor sensors, but in case of in-vivo sensors, SAR, delay and throughput should be taken into account simultaneously to design a realistic WBAN model.

In [147] authors have proposed protocol that chooses optimum routing path by determining the temperature of sensor nodes and by defining two threshold limits (minimum and maximum). It also considers the critical data signals to be sent when the temperature of node exceeds the admissible threshold limit. Here, the sensor nodes also act as relay nodes. Number of events encountered by each node is comparatively higher than our proposed algorithm.

Authors in [150] proposed a thermal aware, energy efficient and reliable routing protocol named thermal and energy aware routing where thermal and energy aware routing considers the weighted average of three costs while selecting the routing path: energy consumption, heat dissipation, and link quality (between communicating nodes).Here, packet collision is reduced by lowering RSSI. 70% of the nodes become heated due to which they have to transmit the data via alternative path to ensure throughput of the system. This resulted in high link breakage rate compared to ours.

6.3 Design of the proposed solution

In this section, we discuss the topology of WBAN that is considered in this work. Then, we shall develop the mathematical equations for the objective function and the constraints one after another. The objective function jointly minimizes the number and deployment cost of the relay nodes, energy consumption of the sensor and relay nodes, temperature rise of the sensor and relay nodes, hop count, angle between the sensor and the relay node, and specific absorption rate. It also maximizes the signal to interference and noise ratio. This objective is subject to some constraints like minimum connectivity of the nodes, flow balance for a relay node for all traffic towards the coordinator, capacity constraints of the forwarder nodes, integrity constraints for binary decision variables, temperature threshold value constraint of the nodes, electrical conductivity threshold value constraint, channel gain limit constraints etc.

6.3.1 Topology of WBAN

Let there be |S| number of WBAN sensor nodes located at some fixed positions on the body. Generally, in WBAN, there can be any number of sink or coordinator nodes, denoted by N. The relay nodes are installed at feasible positions called the candidate sites denoted by P.

Our proposed model considers a single coordinator, though it has the potential to serve multiple sink nodes. The sensitivity and position of all the organs in the body are considered equal to maintain the individual threshold of temperature rise of the nodes in proposed model. The effect of even one sensor going beyond threshold temperature is adverse and highly unwelcome.

6.3.2 Mathematical Modelling Using Mixed Integer Linear Programming (MILP)

Our model has 3 types of nodes with different functionalities.

1. sender: These sensor nodes have the capability of sensing and sending vital stats.
2. relay/forwarder: These nodes have the duty of receiving and transmitting data from sender or other relays to the sink nodes. They are incapable of sensing data.
3. destination/coordinator/sink: These nodes act as gateway of the body. They are the collectors of all the sensed data. Thus, they can only receive data from other components of the body.

The functionalities of the three types of nodes in the model are different. The parameters related to energy consumed by each type is thus distinct. Our proposed model has three possible use cases.

1. Usecase I:

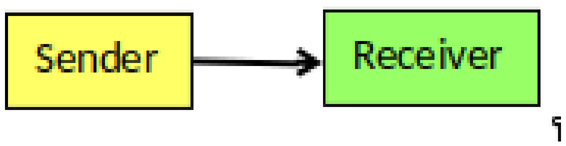

Figure 6.1: Usecase I: Sender transmits packets directly to the receiver

According to Figure 6.1, total energy consumed is dependent only on the sensor and receiver nodes. The parameters involved are the volume of traffic generated ($traf(i)$), number of packet loss due to transmission ($\alpha(i)$), energy consumed by the transmitter to transmit via the link between the sender and receiver ($E_{amp}(n_{ij})$) and the distance between the two nodes (D_{ij}).

2. Usecase II:

Figure 6.2: Usecase II: Sender transmits packets to the receiver via a relay node

In case of Figure 6.2, the sensor node is not within the direct range of the coordinator. So, the data reaches the destination via a forwarder node. Total energy consumed in this case is the sum of the parameters involved for cost of relay node installation ($cost(j)$), energy consumed by sensor nodes to relay data to forwarder node (Eq.6.3), consumed energy by the forwarder node to receive data from sensor node (Eq.6.4) and relay it to the coordinator node and the energy consumed by the coordinator to receive the data from the forwarder node (Eq.6.7).

3. Usecase III:

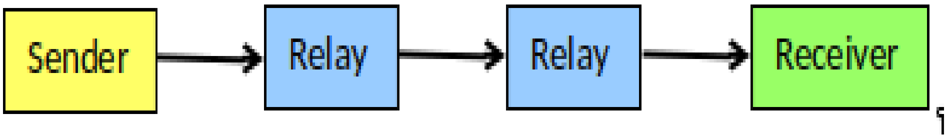

Figure 6.3: Usecase III: Sender transmits packets to the receiver via two relay nodes

In Figure 6.3, the first relay node needs to use another relay node to transmit data from the source to the destination as the destination is not within direct range of the first relay node. Unlike Figure 6.2, the first relay node consumes energy to receive data from sender and transmit data to second relay node (Eq.6.5). The second relay node consumes energy for receiving data from the first relay node and transmitting it to the coordinator (Eq.6.6).

Our work uses the propagation and energy models as given in [139]. Accordingly, packet loss is modeled in several equations (Equation 3, Constraints 5, 6, 7 and 8) to build the objective function and the constraints.

Objective Function

To build a WBAN, all relevant parameters need to be considered together. The proposed objective function, cooperatively minimizes the deployment cost of the relay nodes, energy consumption of the sensor and relay nodes, temperature rise of the sensor and relay nodes, hop count, angle between the sensor and the relay node, interference and noise. This objective is subject to some constraints like minimum connectivity of the nodes, flow balance for a relay node for all traffic towards the coordinator, capacity constraints of the relay node, integrity constraints for binary decision variables, temperature threshold value constraint of the nodes, channel gain limit constraints etc.

Our objective function is to minimize the following factors:

1. Relay node Installation Cost
$$\Sigma_j cost(j) z_j \tag{6.2}$$
$cost(j)$ is the cost of deploying forwarder node at the j^{th} relay node. z_j is the j^{th} relay node installation variable i.e., it decides if the j^{th} relay will be deployed or not.

2. Total Energy Consumed by all sensor nodes to relay data towards a forwarder node
$$\Sigma_{i,j}(traf(i) - \alpha(i))x_{ij}(E_{TX} + E_{amp}(n_{ij})D_{ij}^{n_{ij}} \tag{6.3}$$
$traf(i)$ is the traffic generated, $\alpha(i)$ is the packet loss due to transmission from sensor i towards the coordinator. x_{ij} is the WBAN sensor assignment variable i.e., the connectivity from the i^{th} WBAN sensor to the j^{th} forwarder node. E_{TX} is the energy needed by the transmitter. $E_{amp}(n_{ij})$ is the energy consumption for transmitting data from the node i to a relay node j. $D_{ij}^{n_{ij}}$ is the distance between the i^{th} WBAN sensor node and the j^{th} relay node.

3. Total Energy Consumed by all forwarder nodes to receive data from a sender node
$$(\Sigma_j f_{Total}(j) + \Sigma_{jl} f_{jl} b_{jl}) E_{RX} \tag{6.4}$$
Node j is connected to the coordinator node. $f_{Total}(j)$ is the total traffic of data through the forwarder node j towards the sink. f_{jl} is the amount of data transmitted through the link of the j^{th} and the l^{th} relay node. b_{jl} is the connectivity parameter for the intermediate forwarder node i.e, the j^{th} forwarder node. E_{RX} is the energy needed for the receiver to receive one bit of data.

4. Total Energy Consumed by forwarder nodes to transmit data to another forwarder node
$$\Sigma_{jl} f_{jl} b_{jl}(E_{TX} + E_{amp}(n_{jl}) D_{jl}^{n_{jl}}) \tag{6.5}$$
$E_{amp}(n_{jl})$ is the energy consumed for transmitting data from the relay node j to another relay node l. $D_{jl}^{n_{jl}}$ is the distance between the j^{th} relay node and the l^{th} relay node.

5. Total Energy Consumed by forwarder node to receive data from other forwarder node
$$((\Sigma_{jl} f_{jl} b_{jl}) - w_1(\Sigma_l \Sigma_j \neq_l q_{jl} + n_0)) E_{RX} \tag{6.6}$$
w_1 is the multiplying factor for white noise power at the receiver m. q_{jl} is the channel gain between transmitter j and receiver l. n_0 is the white noise power at the receiver m.

6. Total Energy Consumed by forwarder node to transmit data to coordinator

$$\Sigma_j f_{Total}(j)(E_{TX} + E_{amp}(n_{jk})D_{jk}^{n_{jk}}) \tag{6.7}$$

Node j is connected to the coordinator node. $E_{amp}(n_{jk})$ is the energy consumed for transmitting data from the relay node j to the coordinator. $D_{jk}^{n_{jk}}$ is the distance between the j^{th} relay node and the sink node k.

Thus the objective function is as follows.

Min {Eq.6.2 + Eq.6.3 + Eq.6.4 + Eq.6.5 + Eq.6.6 + Eq.6.7 + $\Sigma_i\ ts_i$ + $\Sigma_j\ tr_j$ + $\Sigma_i\ hop_{ik}$ + Σ_i $|angle|_{ik}$ + $w_2(\Sigma_m(((1/B)\Sigma_n \neq_m q_{nm}P_n) + n_0))$}

where i ∈ S; j,l ∈ P; k ∈ N; m ∈ (P ∪ N) and n ∈ (S ∪ P)

1. $\Sigma_i ts_i$ is the sum total of the temperature rise in all sensor nodes.
2. $\Sigma_j tr_j$ is the sum total of the temperature rise in all relay nodes.
3. $\Sigma_i hop_{ik}$ is the sum total of all hop counts between the i^{th} sensor and the k^{th} coordinator.
4. $\Sigma_i |angle|_{ik}$ is the sum total of all angles between the i^{th} sensor and the k^{th} coordinator.
5. $w_2(\Sigma_m(((1/B)\Sigma_n \neq_m q_{nm}P_n) + n_0)$) is the sum of interference and noise of all relay nodes and the coordinator node. w_2 is the weight factor for the interference and the noise. B is the bandwidth of the channel. q_{nm} is the channel gain between transmitter n and receiver m. P_n is the transmission power of the node n.

Constraints

1. $\Sigma_j x_{ij} > 0$; j ∈ P and ∀ i ∈ S

   For each sensor node i, there is at least one relay node j in the network. This ensures the minimum connectivity of a sensor node to a relay node i.e, at least one relay node will be connected to every sensor node.

2. $\Sigma_i x_{ij} > 0$; i ∈ S and ∀ j ∈ P

   For each relay node j, there is at least one sensor node i in the network. This ensures the minimum connectivity of a relay node to a sensor node i.e, at least one sensor node will be connected to one relay node.

3. $\Sigma_l b_{jl} > 0$; l ∈ P; ∀ j ∈ P and j ≠ l

   For each relay node j, there is at least one relay node l in the network. This ensures the minimum connectivity of a relay node to another relay node i.e, at least one relay node will be connected to another relay node.

4. $x_{ij} \leq z_j a_{ij}$; j ∈ P and ∀ i ∈ S

   This makes sure that WBAN sensor i is under the coverage of the forwarder node j if and only if the forwarder node is deployed at the j^{th} position of the candidate site and the WBAN sensor i is connected to the forwarder node j. a_{ij} is the WBAN sensor coverage parameter i.e., the i^{th} WBAN sensor node has a link with the j^{th} forwarder node.

5. $\Sigma_i(traf(i) - \alpha(i))x_{ij} + \Sigma_l(f_{lj} - f_{jl}) - w_1(\Sigma_l \neq_j q_{lj} + n_0) - f_{Total}(j) = 0$; i ∈ S; ∀ j ∈ P; l ∈ P and j ≠ l

   It ensures the flow balance for the relay node j for all traffic towards the coordinator. $\Sigma_i(traf(i) - \alpha(i))x_{ij}$ total data generated by WBAN sensor node i for the coordinator. $\Sigma_l(f_{lj} - f_{jl})$ shows the difference between the received and transmitted packets at j^{th} forwarder node. f_{lj} is the amount of data data transmitted through the link of the l^{th} and the j^{th} relay node. $w_1(\Sigma_l \neq_j q_{lj} + n_0)$ is the packet loss due to interference and noise. q_{lj} is the channel gain between transmitter l and receiver j. $f_{Total}(j)$ is the total amount of data sent through j towards the coordinator.

6. $f_{jl} \leq \Sigma_i(traf(i) - \alpha(i))b_{jl}z_j$; $f_{jl} \leq \Sigma_i(traf(i) - \alpha(i))b_{jl}z_l$; i ∈ S; ∀ j ∈ P; l ∈ P and j ≠ l

   It signifies that the link between forwarder node j and k exists iff the forwarder nodes at j and k are deployed and they are connected. z_l is the l^{th} relay node installation variable i.e., it decides if the l^{th} relay is deployed or not.

7. $\Sigma_l f_{lj}$ = min(v_j - Σ_i ($traf(i)$ - $\alpha(i)$) x_{ij}, $data_l^{forward}$); i ∈ S; ∀ j ∈ P; l ∈ P and j ≠ l

   $\Sigma_i(traf(i) - \alpha(i))$ is the total amount of data input from all the sensors to the relay node j. $\Sigma_l f_{lj}$ is the total amount of data input from all relay nodes to the relay node j. For every forwarder node j, the total amount of data serviced by the node is the sum of the two parts already explained and should never exceed its capacity v_j. $Data_l^{forward}$ is the amount of data to be forwarded by the node l.

8. $f_{Total}(j) \leq \Sigma_i(traf(i) - \alpha(i))c_j z_j$; i ∈ S and ∀ j ∈ P

   If the forwarder node j is not covered by the coordinator, it forcefully nullifies data flow between the j^{th} forwarder node and the coordinator. Total data from the relay j to the coordinator node should be less than or equal to the total data inflow into the relay node j minus the packet loss. c_j is the coverage parameter of the coordinator for the j^{th} forwarder node.

9. x_{ij}, a_{ij}, b_{jl}, z_j ∈ 0,1; ∀ i ∈ S; ∀ j ∈ P and ∀ l ∈ P

   This ensures the integrity constraints of binary decision variables.

10. $1 \leq ts_i < (105 - ts_i^{curr})$; ∀ i ∈ S

    The temperature rise of the i^{th} sensor node should be less than $(105 - ts_i^{curr})^0$F. 105^0F is taken as the maximum temperature that a normal human being can sustain. ts_i^{curr} is the current temperature of the sensor i.

11. $1 \leq$ tr$_j$ $<$ (105 - tr$_j{}^{curr}$); $\forall$ j $\in$ P

    The current temperature rise of the j^{th} relay node should be less than (105 - tr$_j{}^{curr}$)^{0}F as 105^{0}F is taken as the maximum temperature that a normal person can sustain. tr$_j{}^{curr}$ is the current temperature of the relay j.

12. $2 \leq$ hop$_{ik}$ ≤ 3; $\forall$ i $\in$ S and $\forall$ k $\in$ N

    The number of hops between the i^{th} sensor node and the k^{th} coordinator node should be either 2 or 3. This is required in order to reduce delay of health data delivery.

13. $0 \leq |angle|_{ik} \leq 90$; $\forall$ i $\in$ S; $\forall$ j,l $\in$ P and k $\in$ N

    The angle between the i^{th} sensor node and the k^{th} coordinator node should be between 0^0 and 90^0. This constraint makes certain that health data should only be sent towards the direction of the intended coordinator node.

14. $256 \leq q_{nm} \leq 300$

    The channel gain between transmitter n and receiver m should be greater than 256 and less than 300. The channel gain has been set based on the knowledge of signal to interference and noise ratio as mentioned in [117] and [59].

15. $D_{ij}^{n_{ij}} = D_{jl}^{n_{jl}} = D_{jk}^{n_{jk}} = q_{jk}^{-1/4}$
    This constraint is used to calculate the distance between the nodes.

Decision Variables

The decision variables are $|P|$ i.e., the number of relay nodes, a_{ij}, b_{jl}, x_{ij}, z_j, $D_{ij}^{n_{ij}}$, $D_{jl}^{n_{jl}}$, $D_{jk}^{n_{jk}}$, $angle_{ik}$, f_{jl}, f_{lj}, $f_{Total}(j)$ and q_{jl}.

6.3.3 Solution of the MILP using Python

A program has been developed in Python to solve the MILP. We have taken the value of the parameters from the papers [139], [117] and [92]. The values are given in Table 6.1. It is seen that the formulation gives optimum solution for 2 relay nodes i.e. $|P|$ = 2. If the number of relay is 1, we are getting an infeasible solution. While testing with 3 relay nodes, no optimum solution was obtained. This can be justified as follows. Average human structure is 6 feet. WBAN sensors transmit data with less power in order to avoid interference and manage their remaining energy pragmatically. Again, increasing the number of relay increases the deployment cost. Thus, the optimum number of relay nodes is 2.

6.3.4 Physical Positioning of Relay Nodes, Sensor Nodes and Coordinator

In the proposed WBAN design, deployment of an optimum number of relay nodes minimizes its installation cost. The design leads to minimum temperature rise for sensor nodes

cost(j)	10 momentary units
traf(i)	110 bits/sec
$\alpha(i)$	10 bits/sec
E_{TX}	16.7 nJ/bit
$E_{amp}(n_{ij})$	1.97 nJ/bit for n_{ij}=3.38
E_{RX}	36.1 nJ/bit
$\|N\|$	1
$\|S\|$	7
v_j	770 bits/sec
B	128
P_n	1.556 microWatts
n_0	0.0389 microWatts
w_1	0.01
w_2	1000
Initial energy of a node	0.5 J

Table 6.1: Simulation Parameters

and relay nodes. Thus, the overall temperature rise of the patient will get checked.

6.3.5 Proposed Routing Algorithm

The proposed algorithm is based on the following steps.

i. Sensor nodes (S_n) that wishes to send data to the coordinator (C_n), first sends an RTS with adequate power level so that its nearest relay node (R_n) can receive it. This relay node sends an acknowledgment immediately. If the coordinator also receives the RTS, it will also send an acknowledgment. If the sender sensor node receives acknowledgment from both the relay node and coordinator, it sends data packet to the relay node with the assumption that along with the relay node, the coordinator also receives it. This is depicted in Figure 6.4.

ii. If the sensor node has only received acknowledgment from the relay node, sensor node sends data packet to the relay node. The relay node transmits the packet with an adequate power so that either the coordinator node or the relay node which is one hop away from the coordinator receives it. After the coordinator has received the packet, it sends the $P_{ack,c}$ back to the sending relay node as shown in Figure 6.5.

iii. If the sensor node has not received the $P_{ack,r}$ or $P_{ack,c}$ within a predefined time period, it repeats the entire procedure.

NODES	POSITION
Sensor 1	head
Sensor 2	neck
Sensor 3	chest
Sensor 4	left arm
Sensor 5	right arm
Sensor 6	stomach
Sensor 7	left knee
Sensor 8	right knee
Sensor 9	left foot
Sensor 10	right foot
Coordinator	waist

Table 6.2: Physical positioning of nodes

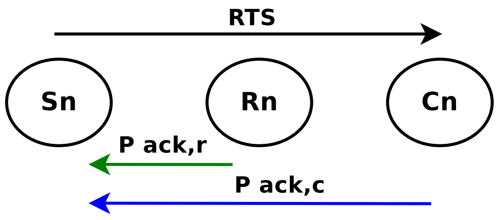

Figure 6.4: System Model of Usecase I

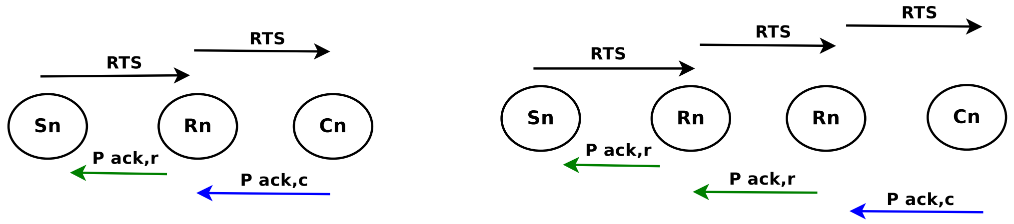

Figure 6.5: System Model of Usecase II and III

We have shown the flowchart of the system in Figure 6.6.

Proposed Routing Algorithm

Input: Distance between sensors and relays
Distance between relays
Distance between relays and coordinator node
Power level of sensors
Power level of relays
Output: Hopcount
1: **for** each sensor
2: **if** (the power level of a sensor is such that it can send to the nearest relay node) **then**
3: send data to the nearest relay node;
4: **if** (the relay node found in step 2 has enough power to send to the coordinator node) **then**
5: send data to the coordinator;
6: report the hopcount as 2;
7: **else**
8: find the nearest relay node from the relay node found in step 2;
9: **if** (the power level of the relay node found in step 2 can send to this relay node) **then**
10: send data to the nearest relay node;
11: **if** (the relay node found in step 9, has enough power to send to the coordinator node) **then**
12: send data to the coordinator;
13: report the hopcount as 3;
14: **endif**
15: **endif**
16: **endif**
17: **endif**
18: **endfor**

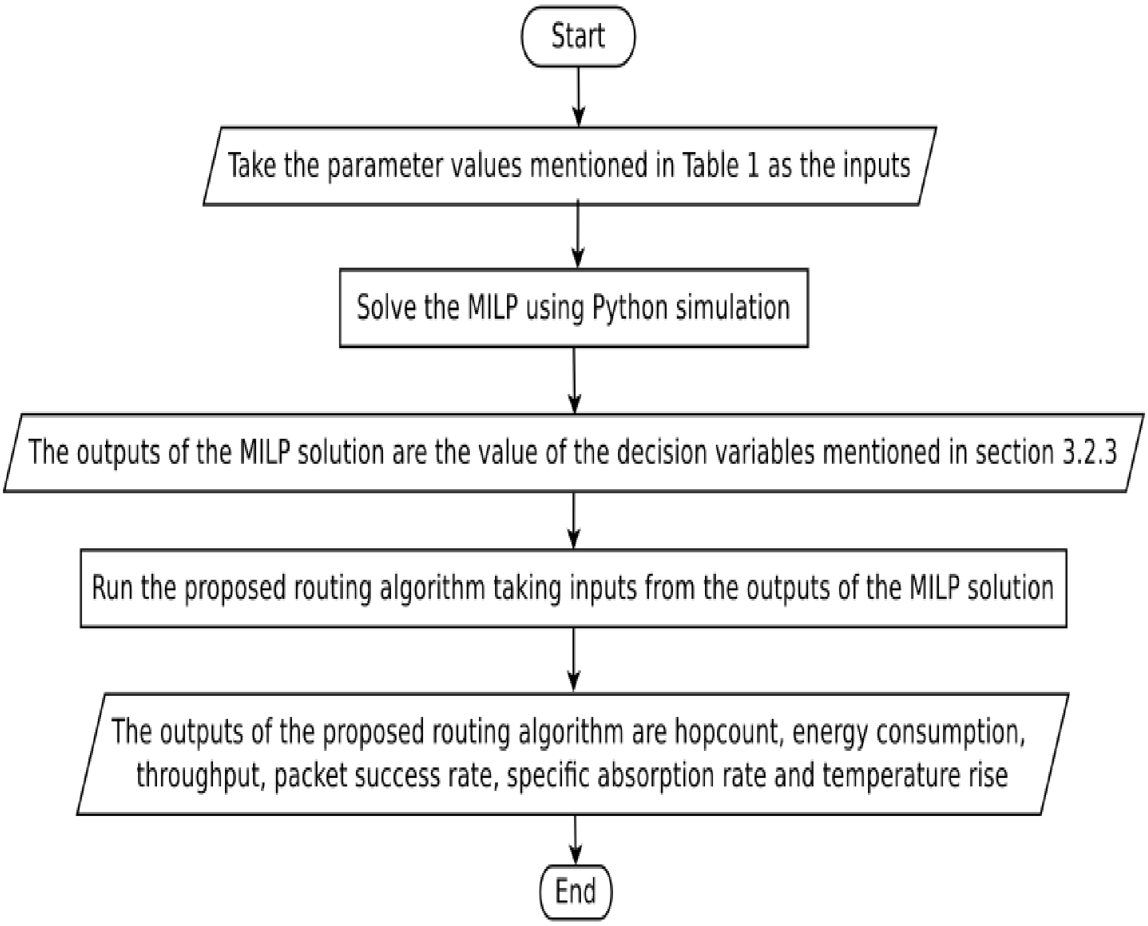

Figure 6.6: Flowchart of Proposed System

6.4 Simulation Set-up and Performance Evaluation of the Routing Algorithm

The deployment of body sensors is depicted in Table 6.2. Relay nodes are deployed one by one on the body based on the maximum coverage and LOS (Line of Sight) of sensor nodes and coordinator in such a way that they form the backbone for transmission from any sensor node to the coordinator and all sensor nodes are connected with at least one relay node. We have evaluated the proposed algorithm by simulating the same in MATLAB. The metrics used to evaluate the performance of the proposed algorithm are as follows:

1. Number of topology changes of the network
2. Number of hops
3. Network lifetime of the system
4. Throughput of the system

5. Specific Absorption rate (SAR)

6. Average temperature rise

6.4.1 Parameters

We have seen in section 6.3.3 that the formulation gives optimum solution when number of relays is 2. So, the number of relay nodes ($|P|$) is taken as 2 for the experiments. The solution of MILP in Section 6.3.3 gives value of the different decision variables (section 6.3.2). These values are taken as input of the routing algorithm to run the experiments.

6.4.2 Simulation Results of the Proposed Routing Algorithm

We have taken the parameters as fixed values for our simulation run. Due to mobility, the exact positions of sensor nodes, relay nodes and the sink change in every iteration altering the network topology. Each position is considered as a round. Generally, there is a pattern in human mobility. Thus, variations in alteration of network topology is limited, but frequent. Figure 6.10 shows the number of packets delivered to the sink in $10 * 10^3$ rounds. The MILP solution gives us the optimum value of our decision variables for all rounds. The number of sensors is taken as 12 in Figure 6.8.

Overhead of the Proposed Routing Algorithm

The overhead of an adhoc network routing protocol is due to frequent topology changes. Rate of topology changes depends on link breakage rate of the network as mentioned in [151]. The proposed algorithm is independent of the previous network topology while sending its current data. In Figure 6.7, we have compared the overhead of the proposed algorithm with M-Attempt algorithm [92] and [140]. M-Attempt is chosen for comparison as it is a renowned protocol. However, the proposed algorithm incurs less topology changes than M-Attempt algorithm [92]. Authors in [140] used block acknowledgment to reduce the overhead due to control packets and thereby achieve efficient power consumption. For each posture, every sensor node will broadcast control packets. All nodes reply after receiving a control packet from another node. Link table is updated (by incrementing the number of links) if ACK is received. A node with maximum “link” value in the link table send data to the sink node in the selected posture. Frequency of human mobility is high. So, the link breakage rate remains high in this case as well. This results in very high overhead in terms of average packet transmission as shown in Figure 6.7 for [140]. In the proposed protocol, forwarder nodes are used to maintain a well connected system. From the figure Figure 6.7 we can conclude that the overhead of the proposed algorithm is much less than that of [92] and [140].

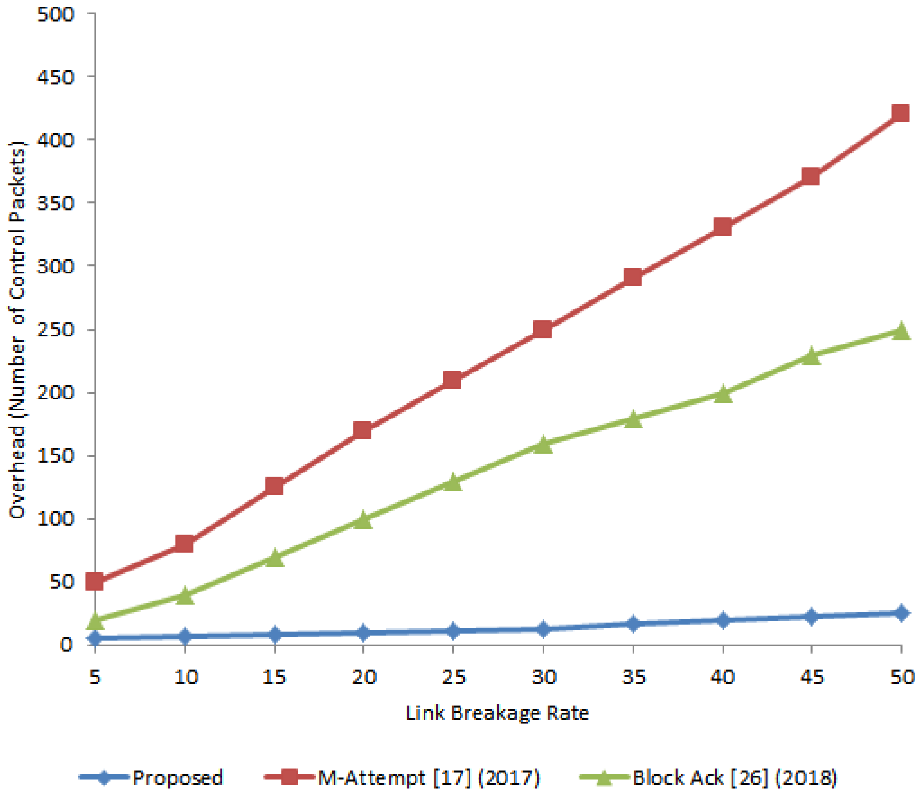

Figure 6.7: Number of Control Packets

Hop Count Minimization Graph

In Figure 6.8, the number of hop counts from each sensor node to reach the coordinator is shown. In the proposed routing algorithm, the sender always sends data intelligently with the motive of delivering data to the intended receiver at the earliest. This result shows that 83.33% of sender nodes can send their critical health data to the destination node in two hops. Thus, we can claim that latency of delivery for critical health data is low.

Enhancement of Network Lifetime

The network lifetime is taken to be the time duration till the last node in the network is alive. This is interpreted in terms of remaining energy of the network with respect to number of rounds. All nodes in the proposed algorithm send data if and only if their power level is above the threshold. Thus, the remaining energy of all nodes in the network are homogeneously utilized enhancing the network lifetime. [92], [132], [133] and [147] are some of the current state-of-the-art algorithms that aim to enhance network lifetime. The graph in Figure 6.9 shows that the proposed algorithm has better network lifetime than its competitors. As the total energy of the network completely drains out in less number of rounds in M-Attempt [92], it has very poor lifetime. In [132], the high priority data is transmitted first. As packet loss is more in [132], less packets are received at the receiver. Hence, energy consumption is less in each round than the proposed algorithm. In [147], authors

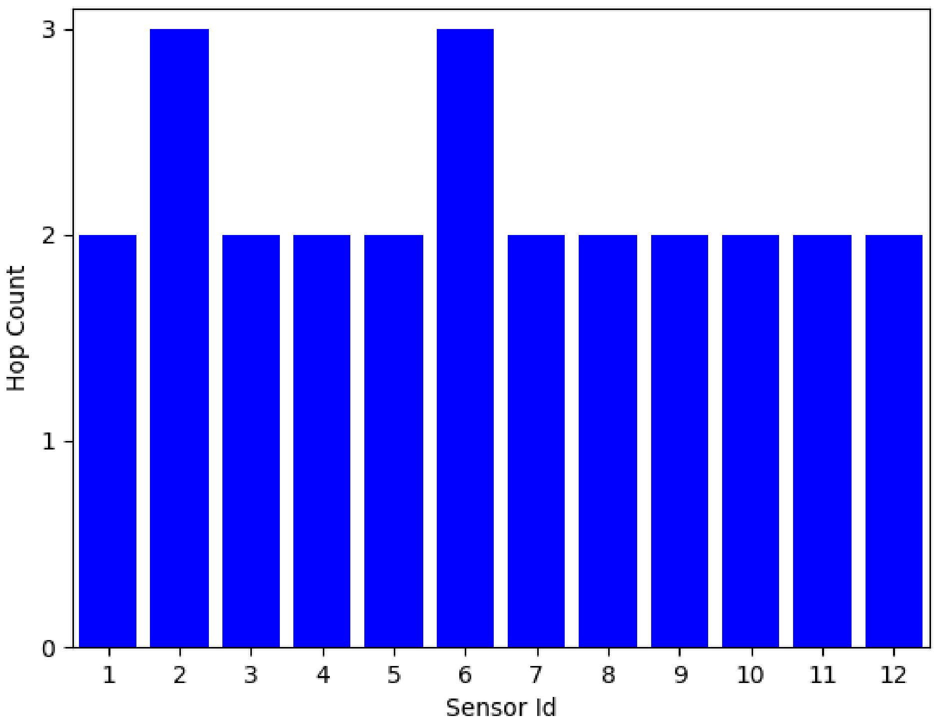

Figure 6.8: Number of Hops

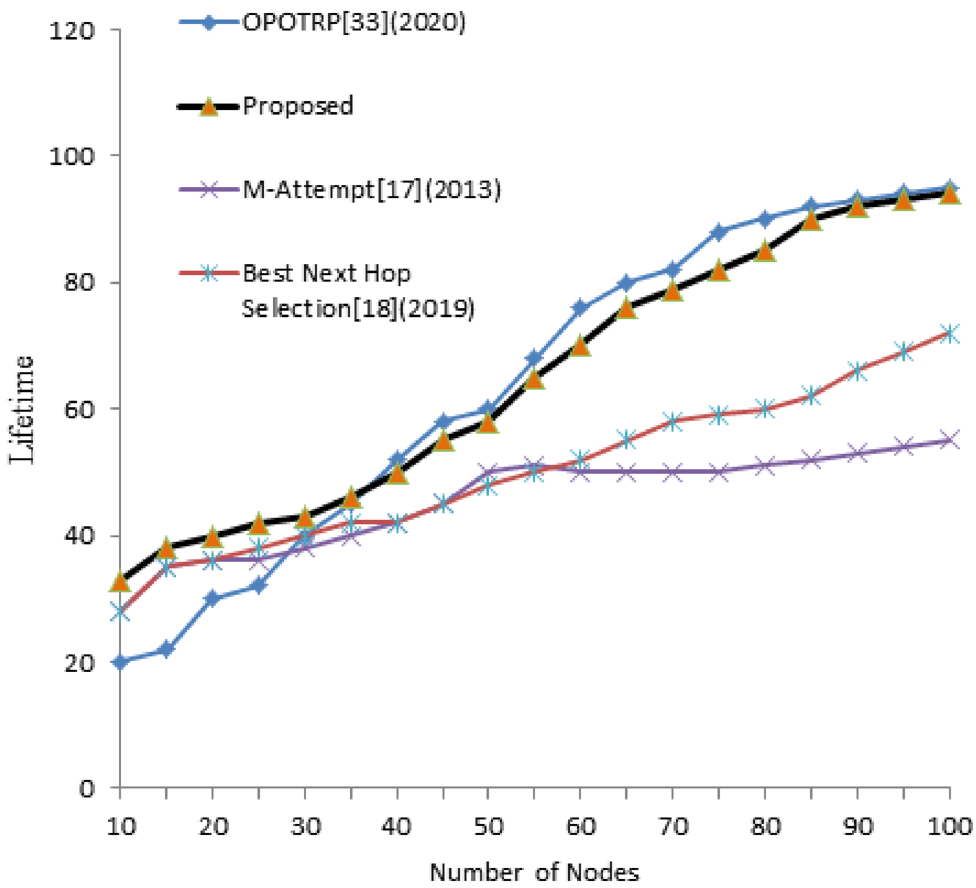

Figure 6.9: Network Lifetime with increasing nodes

have limited the transmission rate of heated nodes only for critical data. In our protocol, the responsibility of forwarding data is handled by various relay nodes well connected with the sensors. So, the energy of the sensors are primarily used for data collection and forwarding its own data. Hence, unlike [147], remaining energy of a node in our system is comparatively higher, enhancing the lifetime of our network using Equation 6.1. According to Figure 6.9, when the number of nodes is initially less, the lifetime of our network outperforms than the rest. But, as it increases, its lifetime is almost as good as [147].

Number of Packets Delivered to the Coordinator

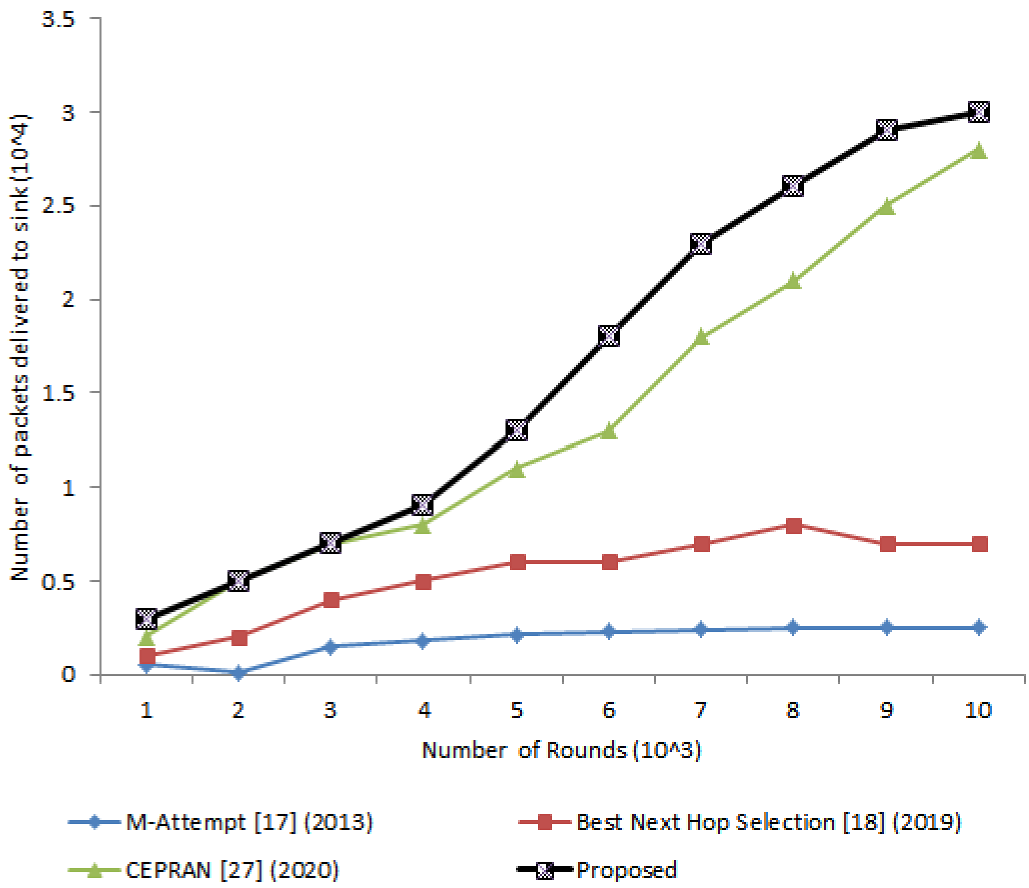

Figure 6.10: Number of packets delivered per round

M-Attempt algorithm [92] has a very poor throughput as shown in Figure 6.10. In [92], packets are transferred to the destination avoiding hot spot but the algorithm has high overhead because of huge topology changes as shown in Figure 6.7. So, latency of data transfer becomes high and throughput becomes low. In the proposed algorithm, more number of packets are delivered to the coordinator per round as shown in Figure 6.10. So, it . This protocol takes multiple parameters of the network into account, such as residual energy, transmission efficiency, available bandwidth and the number of hops to the sink to construct a benefit function that delivers the best next hop. The protocol in [132]also fails to deliver the best throughput as it encounters dead nodes at an earlier stage because nodes do not utilize their energy homogeneously. Further, this protocol [132] lack thermal awareness of the system. In [141], authors have proposed an algorithm that considers distance, energy, and path loss as the major parameters to decide which among the existing nodes can function as the relay node. Initially, this protocol performs at par with our proposed scheme, but after 4000 rounds, our proposed scheme works better. This is because our method considers relays only as forwarders which enhance the throughput of the system as shown in Figure 6.10.

Packet Success Rate in comparison with the PSO Algorithm

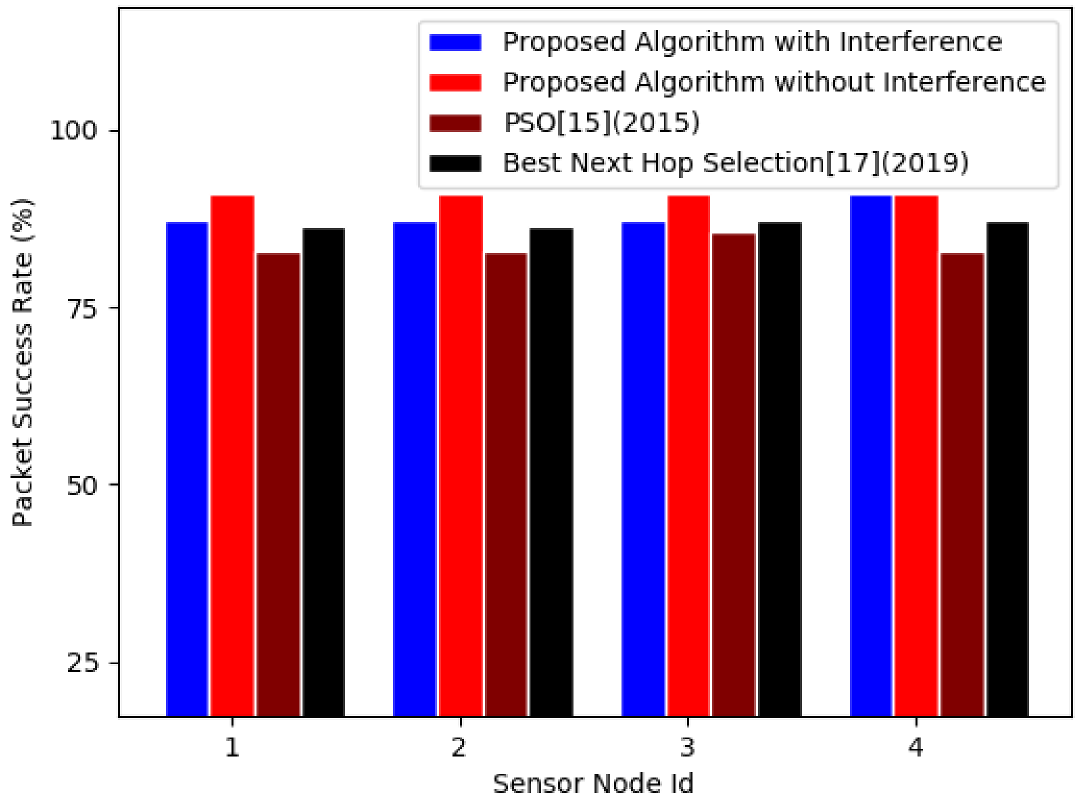

Figure 6.11: Packet success rate

Figure 6.11 depicts that the average packet success rate per round in our algorithm is better than [131, 132]. Figure 6.11 shows that our proposed algorithm has around 91% success rate if there is no interference. The packet success rate of [131] is around 85% in the same scenario. In presence of interference, our protocol supports a packet success rate of around 87%. As the throughput in [132] is less than the proposed algorithm, the packet success rate is less. It needs to be mentioned here that in [131] the packets were distributed per node in a non-homogeneous manner. Our algorithm ensures that all nodes are uniformly utilized for packet forwarding and consequently packet success rate becomes higher.

Specific Absorption Rate in Comparison with PSO Algorithm

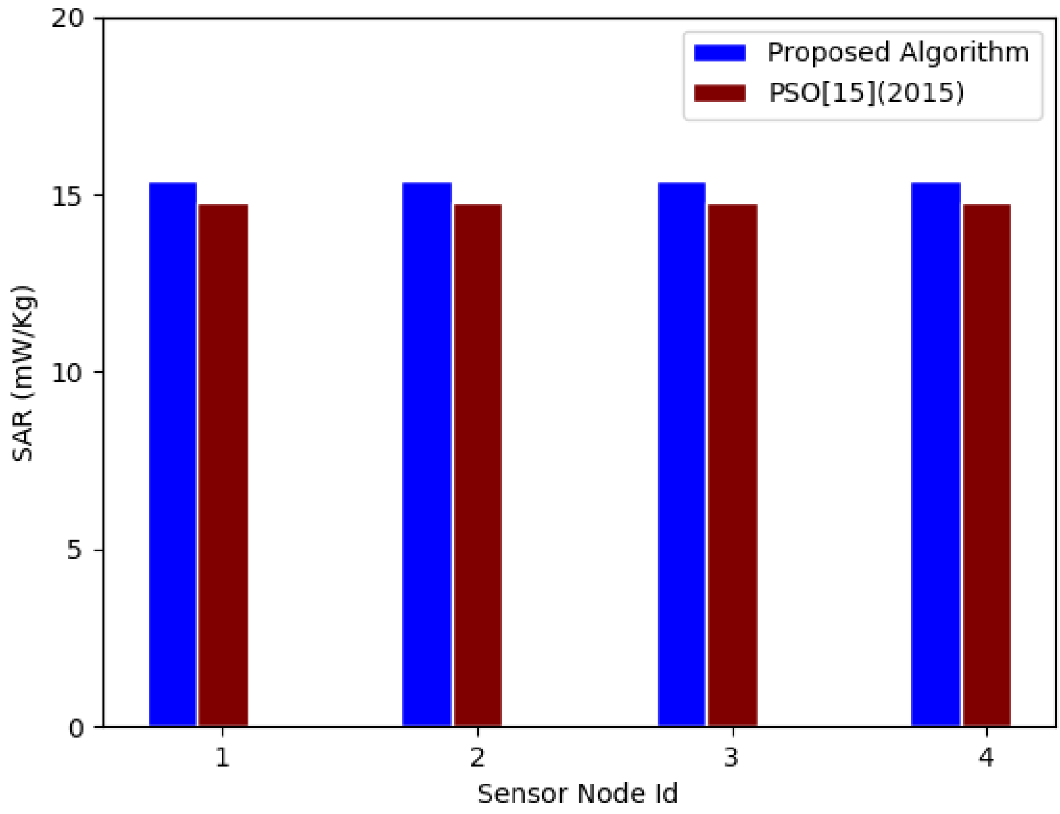

Figure 6.12: Specific Absorption Rate

Figure 6.12 shows the SAR of each sensor node of the network. SAR signifies the absorption rate of human tissues. The higher the value, the heating effect of the tissue is more. Lower SAR value is desirable for this type of network. Though our proposed routing algorithm has SAR value within the threshold, it has little more SAR value than the algorithm mentioned in [131]. This is because our algorithm minimizes interference by increasing the distance between the nodes and chooses an optimum distance between the nodes. Whereas, the existing algorithm given in [131] is not mitigating interference by increasing the distance between the nodes. Thus, the distance between the nodes may not be smaller than the distance obtained by [131]. As a result, energy consumption of our approach increases by a little amount due to inteference mitigation. Hence, the SAR value increases a little than the approach given in [131].

Average Temperature Rise wrt Data Rate in comparison with current state-of-the-art

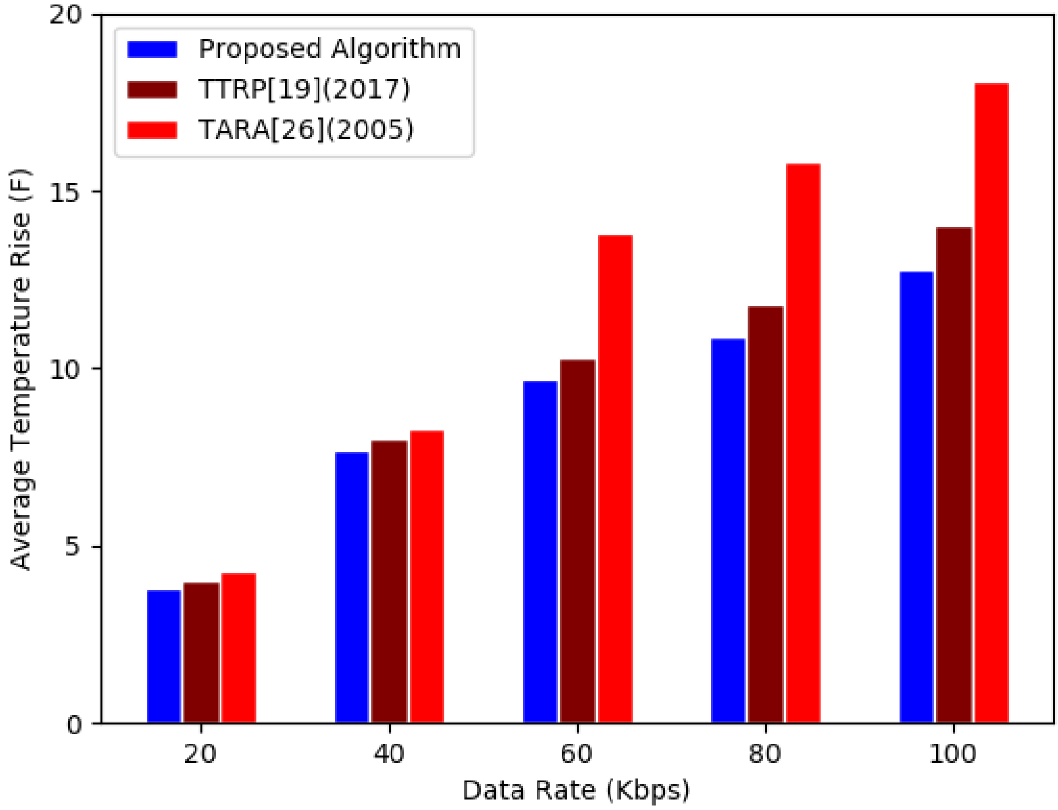

Figure 6.13: Average Temperature Rise wrt Data Rate

Figure 6.13 indicates the average temperature rise of different protocols at various data rates. In [143], average temperature rises to find an alternate path using retransmission in presence of hotspot on the route. Moreover, the packet withdrawn policy also has a negative effect on it. TTRP [134] has used weighted system to distribute the packets evenly in the network, minimizing the creation of hotspot. In our approach, individual sensor and relay has a temperature threshold. Our proposed routing algorithm preforms at par with [134] when the data rate is low. During high data rate, our proposed algorithm outperforms [134] as we have prevented the formation of hotspot.

6.5 Conclusion

In this work, a novel approach has been proposed to optimize the number of relay nodes which effectively minimizes the overall deployment cost of the network keeping the temperature rise within a threshold value. Our proposed routing algorithm cooperatively minimizes energy constraint, thermal issues and intra-WBAN interference. Evaluation results show that the average remaining energy of the body sensors are high for our routing algorithm. It also maximizing the PDR, throughput and network lifetime. Further, this routing algorithm ensures delivery of more than 83.33% critical health data from the sensors to the coordinators in just two hops. It has also been shown that it outperforms current state-of-the-art in terms of average temperature rise of the network.

Chapter 7

Achieving Energy Efficiency and Impact of SAR in a WBAN through Optimal Placement of the Relay Node

7.1 Introduction

Wireless Body Area Network is one of the most promising in the health-care and assisted living paradigm. A WBAN node has a very tiny lithium (Li-ion) battery for both in, on, or around the body communication. The battery lifetime is small and cannot always be changed unobtrusively. This is one major obstacle to the large-scale deployment of WBAN. A WBAN architecture comprises sensors that send its data along with forwarding others to a centrally located point called the coordinator. As we have already mentioned these sensors are energy-constrained. Transmitting other parameters become tedious and energy-consuming. So, this job is being transferred to a special node called to relay that functions only by forwarding the health database from sensor to coordinator if required. Now, with the introduction of relays in the network, the major concern is where to deploy them to have efficient communication. Deployment of relay (R) nodes optimally between the source (S) and the destination (D) is one of the prime solutions to address the issue of maximizing the network lifetime.

Authors in [152] reduced the energy consumption of cooperating WBANs by using an optimal packet size. They did not consider any particular MAC protocol. Authors in [153] evaluated optimal packet sizes for different WBAN communication scenarios. They concluded that based on the acknowledgment policy used, packet size selection has to be considered for energy-efficient communication in WBAN. Delay incurred because of the selection process has not been mentioned. In [154], WBAN nodes incur variable path loss caused by shadowing as the nodes are mobile. In [155] authors constrained the outage probability and allocated optimal power to improve the energy efficiency of WBAN. Authors have compared the outage performance and energy efficiency of star topology in WBAN in [156]. They have considered both single and multi-hop relay cooperative schemes. Authors in [157] evaluated the impact of different components like beacon order, super-frame order, and back-off exponent on network performance in WBAN. In [158], the authors further studied the influence of the position of the coordinator, the formation of the tree for an association, and guaranteed time slot allocation on a network. The authors in[159] considered beacon collisions while forming a piconet by more than one device.

The WBAN is mainly used for the collection of biomedical data based on tiny sensors, the authors [160] discussed different aspects of information security in wireless body area networks, but they have ignored the energy optimization of WBAN networks. Similarly in [161] the authors discussed the performance issue of WBAN networks without considering the importance of SAR on body network. Here the authors [162] applied WBAN networks and different machine learning algorithm approaches to take the valuable information to predict the early information of the coronavirus.

All the cooperative network enhances reliability at the cost of data rate and energy consumption [163]. The connectivity-based mechanism adapts transmission power for each link and performs well for a distributed network [163]. In a star topological network like WBAN where the number of nodes is less, this mechanism is unfruitful. The overhead delay incurred in the PRR-based network in [164] is unsuitable for a healthcare network like WBAN. The RSSI-based prediction model of [165] is inappropriate for WBAN due to the high link breakage rate for mobility. The link-state which is defined by path loss, fading, and shadowing in WBAN changes dynamically due to motion in the human body. In [166], the authors performed experiments to measure RSSI variation for different postures. The authors varied the transmission power by comparing the average RSSI value with a predefined threshold determined from the experiments.

In [64], a game-theoretic approach is used. This is impractical in WBAN as it requires extensive packet exchanges among themselves. Authors in [167] proposed a heuristic approach to enhance WBAN network lifetime by using a few relay nodes. Since the positions of the relays are fixed beforehand, the total cost of the network is not minimal. In [168], authors considered human mobility while determining stable links for a relay-based WBAN structure. Similar to [167], the number of relays is fixed and their positions are pre-determined and static. This is a major problem in optimizing the overall network cost. Zhang et al. In [169] developed a reliable routing protocol to enhance the network lifetime by dynamically calculating the coordinates of relay nodes. However, the cost is not minimized due to a fixed number of relay nodes.

In [100], authors have proposed another framework to minimize the relaying cost while maximizing energy efficiency. They also have considered only stationary positions for relay nodes. Later, in [101] authors have considered different body postures for a realistic dynamic approach. In [170] the authors investigated the optimal location of the relay based on two-hop WBAN scenarios but they neglected the optimal payload and the thermal impact on the human body.

The thermal impact of sensors on human body tissues cannot be neglected while designing for WBAN. The successful design of WBAN and its impact on the healthcare domain will be realistic only when we consider effects of SAR on human body. [171], [172] represents some current state of the art on the investigations of SAR. These papers have studied the physical design of the antenna and the effect of EMF radiation on the human body. Whereas in [173] the authors work with TCDMA-based algorithm techniques to achieve better throughput and packet delivery ratio [174] without considering the effect of SAR on the human body.

In [172], the authors investigated the effect of different input powers of UWB antennas on SAR value. It is observed that tissues with high water content (like muscles and fat) get heated up faster. During packet transmission, the distance between the source from the observing point and transmission power significantly affects the rise in temperature causing the SAR level to cross the threshold. Improvised MAC and routing layer along with intelligently designed physical layer can reduce the impact of SAR and [175] focused on human body communication (HBC). They compared various models of the human body like the Muscle Model, 2/3 Muscle Model, and Layered human body model to analyze the Finite Difference Time Domain (FDTD). The authors in [176], propose a MAC protocol that opportunistically schedules transmission based on the predicted channel fluctuation.

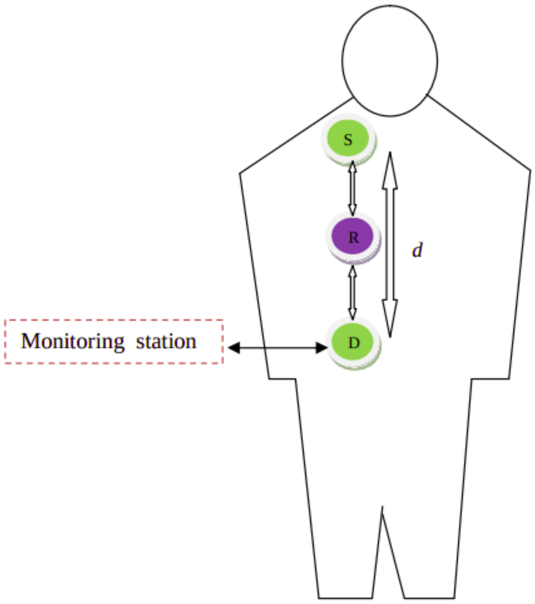

Figure 7.1: A Linear WBAN System Model.

Though a lot of research work is still on, there is no significant contribution to the impact of positioning relay node deployment in WBAN architecture.

The contribution of this chapter is as follows.

- Find the best location of the relay for on-body WBANs based on the linear and non-linear model.
- Investigate the effect of different design parameters; like distance (d), payload (L), an end to end outage probability ($\mathcal{O}$), and different modulation schemes in the WBAN network.

- Analyze the process to mitigate the harmful effect of a specific absorption rate (SAR).

In this chapter, we examined the optimal relay location for energy-efficient WBANs. We justified the reason for the importance of optimal relay deployment instead of the middle position between two nodes for the linear and non-linear system models. We have considered a non-cooperative system model and its works over well accepted Rayleigh fading channel as shown in Fig.1.

The remaining chapter is structured as follows. The background information on the proposed work is described in Section II. The proposed energy power consumption model is explained in Section III, which is followed by analytical and simulation results in Section IV. Lastly, Section V concludes the article.

7.2 Related Works

We have considered a linear topology of a single source (S) and destination (D) node pair in our WBAN network. Positioning the deployment of a relay (R) node in between these two is the primary objective of this chapter. As in-vivo WBAN nodes are installed to the uneven structure of the human body, we have also examined the best location of the relay-based on a non-linear 3D coordinate topology model.

In the process, we have shown that the energy consumption of the sensor nodes is reduced and hence lifetime of the WBAN network is enhanced if the relay nodes are deployed correctly. As the sensors are battery-operated, the power model plays a vital role. We have analyzed the positive impact of the prime deployment of the relay, like enhancing the battery lifetime and minimizing the effect of harmful specific absorption rate (SAR), which deals with the effect of radiation on body tissues. In this section, we also touch upon the communication model, the law related to battery power usage, and specific absorption rate, a metric that is used to measure the effect of radiation on body tissues.

7.2.1 The Communication Model

As per IEEE 802.15.6 standard, devices can be operated in various frequency bands using various channels. On-body sensors can transmit data in frequency bands 13.5, 50, 400, 600, 900 - 950 MHz, 2.4, 3.1 −10.6 GHz using CM3 Radio channel link to the coordinator across tissues in the human body. In this chapter, CM3 is used in a 900 - 950 MHz frequency band for communication between the on-body sensor and the coordinator. We also note that the volume of traffic towards the coordinator in a WBAN is more than the volume of data in the opposite direction [177]. So, we have adopted half-duplex communication in this work. In a WBAN, sensors perform in a duty cycle mode comprising ACTIVE, SLEEP, and TRANSIENT modes [178]. Switching time from sleep to active mode is negligible as the duration of active mode [177] [179] is much more.

The ACTIVE mode time (T_{ac}) depends on the frame format of IEEE 802.15.6 as shown in Figure 7.2 along with the size of payload (L) and ACK/NACK frames. We have assumed

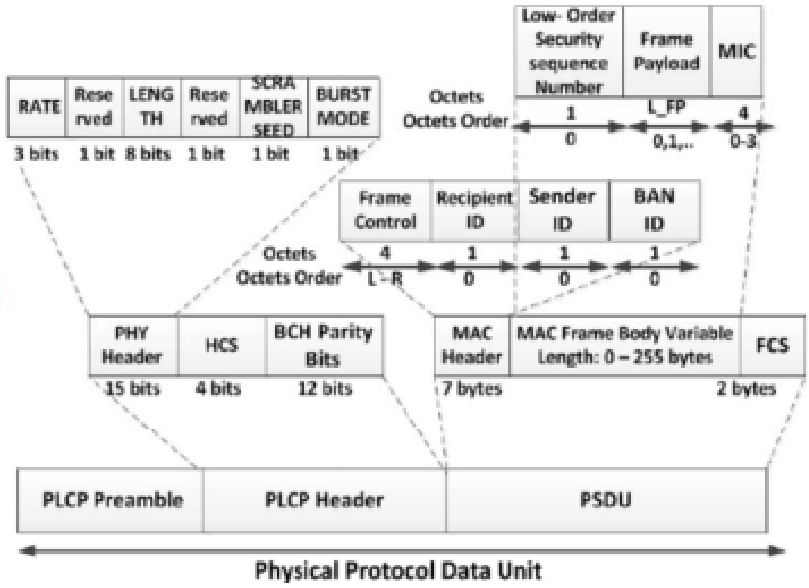

Figure 7.2: Standard Physical and MAC Frame Format of 802.15.6

a stop and wait for ARQ protocol. Once a data packet is sent, the receiver will send either an ACK frame if it has received the packet successfully or it will send a NACK frame. After transmitting the sensed data, the transceiver switches to SLEEP mode for a duration of T_{sl} time. So, the energy required to transmit a frame is the sum of ACTIVE mode power consumption (P_{ac}), transition period energy (P_{sl}) from both sleep mode to active mode and reverse, and SLEEP mode power consumption. We have neglected the very small value of SLEEP mode power consumption [180].

7.3 Linear and Non-Linear WBAN System Model

Primarily we have investigated the optimal relay location for a simple linear three-node model shown in Fig. 7.1, where the relay position (d_{SR}, 0) is located in the same line between the source (0, 0) and destination (d, 0). Based on this model, we have examined the best deployment location of the relay, determining optimal payload as well as analyzed SAR. Due to the uneven structure of the human body, linear relay node deployment is practically difficult to implement. We examined another topology to investigate a non-linear relay deployment position and investigate an optimal relay position based on the $3D$ coordinate system [101]. The relay position can change in three directions. Based on the coordinate system, position of source is taken as $(0, 0, 0)$ and that of destination is $(0, 0, d)$ as shown in Fig. 7.3. This indicates that source and destination nodes are placed d distance apart in terms of the depth of human tissue. Optimal relay location not only can maximize the network lifetime of WBAN but, it can also reduce the possibility of damaging body tissue by energy assimilation. In our non-linear system model, the X-axis represents the distance between the source (S) and the destination (D). The relay can be deployed based on the Y-axis from $-d$ to $+d$ distance. The distance of two nodes is calculated using Euclidean formula $\sqrt{((x_1-x_2)^2+(y_1-y_2)^2+(z_1-z_2)^2)}$. X and Y-axis represent the coordinates of a $2D$ plane. Z coordinate represents the third dimension to represent the depth of the human body as shown in Fig. 7.3 and Fig. 7.4. This depth of the human body is correlated to body position and movement. We have examined the optimal location of the relay considering all three axes and provided guidelines to deploy the relay at a prime location to maximize WBAN lifetime and minimize SAR.

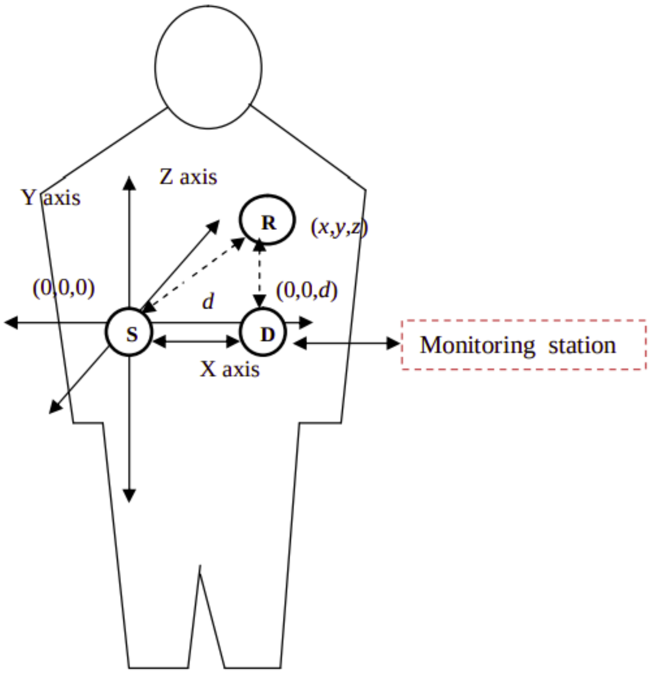

Figure 7.3: 3D Representation of Non Linear WBAN System Model

7.4 ENERGY CONSUMPTION MODEL

Based on the Physical and MAC protocol used in WBAN and the assumptions mentioned in the earlier section, the energy consumed to complete one cycle (including ACK/NAK) of frame transmission is given by 8.1.

$$E_F = P_{ac}T_{ac} + 2P_{sl}T_{sl} \tag{7.1}$$

Here factor 2 is taken for the transition period (T_{sl}) considering both the source and destination node.

The power consumed in ACTIVE mode is a combination of power amplifier power P_{PA} and constant circuit power P_C according to the following expression [178].

$$P_{ac} = P_{PA} + P_C \tag{7.2}$$

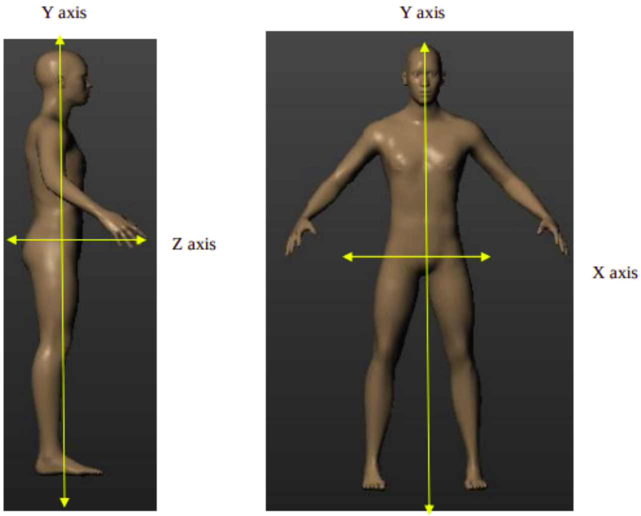

Figure 7.4: 2D (X-Y axis) Representation of Non Linear WBAN System Model

The power amplifier power depends on the transmission power P_t, the ratio of peak to average ratio (PAR) and drain efficiency ρ in the following manner.

$$P_{PA} = \frac{PAR}{\rho} P_t \tag{7.3}$$

In the WBAN on-body network model, the path loss values and parameters depend upon the distance between nodes and the frequency band. In this chapter, we have considered the frequency band to be 950 MHz [181]. Based on that the path loss model an be expressed as follows.

$$PL[dB] = a\_loss\ lg\ d + b\_loss + N\_loss \tag{7.4}$$

a_{loss} and b_{loss} are coefficients of linear fitting, d as the distance between $Tx - Rx$, and N_{loss} denotes distributed variable with standard deviation σ_N in dB.

The average transmission power P_t in terms of the received signal power P_r can be written as [178] Equation 8.4.

$$P_t = P_r 10^{\frac{b\_loss + N\_loss}{10}} d^{\frac{a\_loss}{10}} \tag{7.5}$$

The received signal power (P_r) at the receiver end in Equation 8.4 can calculated from the required energy per bit at receiver (E_b) and bit rate (R_b).

$$P_t = E_b R_b 10^{\frac{b\_loss + N\_loss}{10}} d^{\frac{a\_loss}{10}} \tag{7.6}$$

In this chapter, QPSK modulation is used as a standard for WBAN. The Bit Error Rate (BER) for QPSK at the receiver is expressed as

$$P_b = Q(\sqrt{2\gamma_0}) \tag{7.7}$$

here $Q(\cdot)$ represented as the Gaussian Q function and $\gamma_0 = E_b/N_0$ denoted as the signal to noise ratio (SNR). The requisite E_b can represented as

$$E_b = \left(\frac{N_0}{2}\right)\left[Q^{-1}(P_b)\right]^2 \tag{7.8}$$

here $Q^{-1}(.)$ is denoted for inverse Q function and $N_0/2$ represented as two-sided thermal noise power spectral density (PSD) .

In a WBAN, the successful packet transfer rate depends on the signal-to-noise ratio (SNR). In the receiver end, output fading is one of the crucial causes of a change in SNR value. We have adopted a well-accepted Rayleigh fading model to take care of this aspect in our energy consumption model. Based on Rayleigh fading, outage probability is defined as the unit time when the average SNR (γ) falls below the minimum required SNR (γ_0). The average SNR (γ) is represented as the ratio of required bit energy (E_b) and one-sided noise power spectral density (N_0). The outage probability can be expressed as follows [182].

$$\mathcal{O} = \mathrm{P_r}[\gamma < \gamma_0] = 1 - \exp\left(-\frac{\gamma_0}{\bar{\gamma}}\right) \tag{7.9}$$

From 7.9, the required average SNR can be represented as, $\bar{\gamma} = -\gamma_0/\ln(1-\mathcal{O})$. From 7.9, the required bit energy is as follows, where N_f is the receiver noise figure.

$$E_b \geq -\frac{N_0 N_f \gamma_0}{\ln(1-\mathcal{O})} \tag{7.10}$$

7.4.1 Frame Outage and Fading

In IEEE 802.15.6, a frame can be successfully transmitted if an outage does not occur while forwarding the data frame or acknowledgment frame. The frame outage probability O_F is represented as follows [152] .

$$\mathcal{O}_F = 1 - (1-\mathcal{O})^{L_s} \tag{7.11}$$

Where, $L_s = L_t/\log_2 M$ (M = modulation order) symbols are sent in one transmission cycle per frame and L_t denotes the total number of bits transmitted including ACK or NACK frame during one transmission cycle.

The end-to-end outage probability [152] along the entire relayed path is given by Equation 7.12.

$$O_R = \mathcal{O}_F + (1-\mathcal{O}_F)\mathcal{O}_F = 2\mathcal{O}_F - \mathcal{O}_F^2, \tag{7.12}$$

7.4.2 Energy Consumption per bit Calculation

The power consumed in the active mode for transferring a frame through the relayed path is given by Equation 7.13.

$$P_{bt,relay} = \mathcal{O}_F \left(\frac{P_{PA,SR} + P_{TX} + P_{RX}}{R_b} \right) + (1 - \mathcal{O}_F) \times \left(\frac{P_{PA,SR} + P_{PA,RD} + 2P_{TX} + 2P_{RX}}{R_b} \right), \tag{7.13}$$

Where, $P_{PA,SR}$ and $P_{PA,RD}$ are active mode transmitting power for S-R link and R-D link receptively. We can derive its value from equation 7.3 and 7.6, and the $P_{PA,SR}$ and $P_{PA,RD}$ are represented as follows.

$$P_{PA,SR} = \frac{PAR}{\rho} E_b R_b 10^{\frac{b\_loss + N\_loss}{10}} d_{SR}^{\frac{a\_loss}{10}} \tag{7.14}$$

$$P_{PA,RD} = \frac{PAR}{\rho} E_b R_b 10^{\frac{b\_loss + N\_loss}{10}} d_{RD}^{\frac{a\_loss}{10}} \tag{7.15}$$

Average energy consumption per bit for successful transmission over the relay path is denoted by Equation 7.16.

$$E_{suc} = \frac{1}{8L} \left[4P_{sl}T_{tl} + \frac{P_{bt,relay} L_t}{(1 - O_R)} \right] \tag{7.16}$$

The first part of the equation represents the total required power of transition period energy, where four times transition period energy need for two hops (S-R and R-D) and the second part represents the data transmission period energy including retransmissions because of outage $(1/(1-O_R))$. Next, to analyze the result of SAR, we have applied equation 7.16 to calculate the discharge current (I_i).

The most energy efficient optimal position of relay d_{SR}^* can achieve by evaluating E_{suc} in 7.16 as a function $(f(d_{SR}))$ of d_{SR}, where, $d_{RD} = d - d_{SR}$, and in the next step differentiate E_{suc} with respect to d_{SR}.

The solution can represent as, $\partial E_{suc}/\partial d_{SR}|_{d_{SR}=d_{SR}^*} = 0$, and the optimal location of relay expressed as,

$$d_{SR}^* = \frac{d}{1 + (1 - \mathcal{O})^{-1/(a_{loss}/10-1)}} \tag{7.17}$$

Table 7.2 represents the Parameters of the Path Loss Model Covering Frequencies of 950-956 MHz for On-Body Communication [181].

Parameters in a Room for On Body Communication link CM3 [**Chenfu2015transmission**] are shown in Table 7.3.

P_b	BER at receiver for OQPSK
b	Modulation level
B	Bandwidth
N_0	2(power spectral density of noise)
N_f	Received noise
PAR	Peak-to-average ratio
β	$\frac{PAR}{\rho} - 1$
ρ	PA drain efficiency
E_{bit}	Energy consumed per bit
L	Size of payload
R	Data rate

Table 7.1: Notation

Parameter	Hospital Room	Anechoic Chamber
a_loss	15.5	28.8
b_loss	5.38	23.5
δ_N	5.35	11.7

Table 7.2: Parameters of the Path Loss Model Covering Frequencies of 950-956 MHz for On-Body Communication

Parameter	Values
f_c	950 MHz
B	400 KHz
d	1m
P_{sl}	0.5 mW
P_b	10^{-5}

Table 7.3: Parameters of a Room for On Body Communication link CM3

7.4.3 Estimation of Battery Life

To compute the energy consumption in this chapter, we have used the Peukert law to estimate the battery lifetime. Peukert's Law tells us exactly how long a lead-acid battery of a node in the WBAN will last under any load. This Law expresses mathematically that as the rate of discharge increases, the available capacity of that battery decreases. The mathematical expression of this law is as follows.

$$L = \frac{aC}{I^b} \tag{7.18}$$

L = battery lifetime in hours C = rated capacity at that discharge rate in Ampere-hours I = actual discharge current in Amperes, a is a constant ($a <= 1$) and b is a constant ($b = 1.05\ 1.8$).

Where discharge current,

$$I = \frac{E_{suc}}{V * T} \tag{7.19}$$

The total time (T) to transmit a single bit is the addition of active mode time (T_{ac}) and transit mode (T_{sl}), here the required voltage (V) is considered as 3V and E_{suc} represents the energy consumption per bit for successful transmission.

7.4.4 Specific Absorption Rate (SAR)

Our system is modeled to transmit the data from the sender to the receiver via the relay node positioned adaptively to minimize SAR so that less harm is caused to human health. SAR [173] is the rate of absorption of electromagnetic energy (W) per unit mass of tissue in units of watts per kilogram, measured in W/Kg as given in 7.20.

$$SAR = dm\frac{d(dW)}{dt} \tag{7.20}$$

where, W = power in watts (W), m = mass in Kilograms (Kg) and t = time in seconds (sec). Table 7.4 represents the simulation parameters of SAR [173] along with their corresponding values used.

$$SAR = \frac{\sigma\mu\omega}{\rho_1\sqrt{\sigma^2 + \epsilon^2\omega^2}}((\frac{I_i dl \sin\theta \exp^{-\alpha\Re}}{4\pi})(\frac{1}{\Re^2} + \frac{\mathrm{mod}\ \gamma}{\Re}))^2 \tag{7.21}$$

SAR is calculated using Equation 7.21 whose notation are given in Table 7.1. The attenuation constant is given by Equation 7.22.

$$\alpha = \omega\sqrt{\frac{\mu\epsilon}{2}}[\sqrt{1 + (\frac{\sigma}{\omega\epsilon})^2} - 1]^{\frac{1}{2}} \tag{7.22}$$

SAR is used to measure the amount of EMF radiation a human body absorbs from the heat and electromagnetic radiation generated from the WBAN sensors attached or implanted in the human body. International SAR measurement standards vary based on different body parts and countries. As specified by FCC, the most generally accepted SAR

Parameter	Notation	Values
σ	body temperature conductivity	.866 $\frac{S}{m}$
μ	permeability	$4\pi X 10^7 \frac{H}{m}$
ω	frequency band	950Mhz
ρ_1	density of tissue	1040 $\frac{Kg}{/} m^3$
ϵ	relative permittivity	52.73 $\frac{F}{m}$
dl	length of antenna	1m
$\Re$	distance from source to observation point	0.1m
θ	angle between the observation point and xy plane	90

Table 7.4: Parameters of SAR

limit for public exposure to EMF radiation is 1.6 W/Kg. Here, discharge current (I_i) is also derived from the total amount of energy dissipated for successful bit transmission. Similar to the previous section, the required voltage is 3v and the total time to transmit each bit is the addition of active mode and transition mode. Average energy consumption per bit for successful transmission over the relay path is derived later in Equation 7.16.

7.5 Algorithm for Data Retransmission at the node

In a WBAN IEEE 802.15.6 frame K, $Node_i$ have regular data with seq. no. j to be transmitted and retransmission is applied based on NACK;

Begin Algorithm

Step 1:

Node wake up from sleep mode to active mode (T_{sl}) and keep in active mode for T_{ac} time slot (depends on payload size and frame format),
transmit data with seq. no. j ;

Energy spend in this step: $P_{ac}T_{ac} + P_{sl}T_{sl}$
Step 2:

After transmitting sensed data, transceiver switches to SLEEP mode for a duration of T_{sl} time

Energy Spend in this Step: $P_{sl}T_{sl}$

Step 3:

if the packet is received,
then send ACK frame,
go to Step 1,

transmit data with seq. no. $j+1$ in frame $K+1$

else

send the $NACK$ frame

go to step 1

Step 4:

Total Energy Spend to complete one cycle (including $ACK/NACK$) of frame

$P_{ac}T_{ac} + 2P_{sl}T_{sl}$

End Algorithm

7.6 Results and Discussions

Parameters for path loss, parameters of a Room for on body communication link CM3 and parameters for SAR used in the simulation setup are tabulated in Tables 7.2, 7.3, and 7.4 respectively. It justifies the reason for taking the optimal relay location for a linear $S{-}R{-}D$ path instead of the middle position of the $S-D$ path in the linear WBAN system model. Based on this model, we compare the energy consumed per bit for communication through the relay (dual-hop) (E_{sucR}) with that for communication without the relay (single hop) (E_{suc}). The analytical results are established from the mathematical models, which are plotted using MATLAB, and the simulation result is shown using Castalia-3.2 (baseline MAC for WBAN) based on realistic CM3 communication link parameters.

We analyze the best location of the relay (d^{*}_{SR}) considering different distances between source and destination, where the nodes are situated on the body. We have also examined the optimal payload value for two positions (middle and optimal) of the relay node in non-linear WBAN. Next, we compare the energy consumed per payload bit for different end-to-end outage (O) values. We compare energy consumption per payload bit for the best position of the relay and the traditional middle position [152] between the $S - D$ path. We have investigated the energy consumed per successful bit for different payload (L) values and examined the effect of SAR for optimal relay location. In all cases, we can't apply the linear WBAN topology model, especially to the human body. Finally, we have examined the optimal zone of a relay to enhance the lifetime based on a 3D coordinate system model.

7.6.1 Comparing energy consumption with and without relay

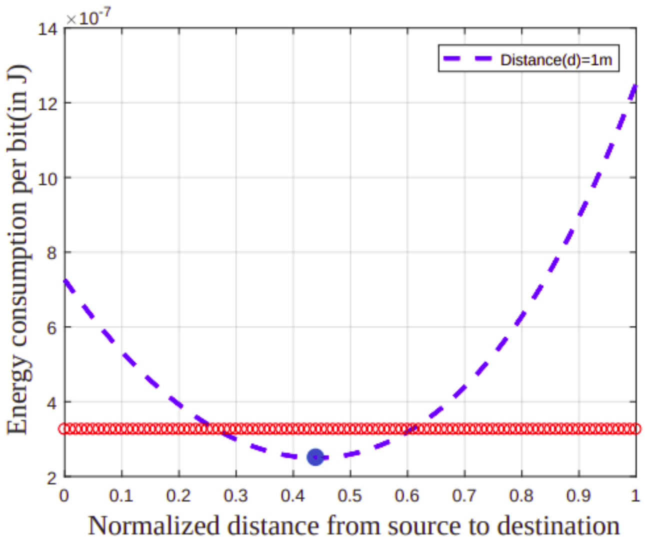

Figure 7.5: Comparison of energy consumption in Dual-hop and Single-hop WBAN Network.

In Fig. 7.1 average energy consumed per bit for successful transmission has been plotted against the distance between source and destination. It is seen that when the length of the $S - R$ link is between 28-60 cm the energy consumption is better along the relayed path. The best performance is obtained when the relay position is 44 cm from the source in the $S - R$ link. We have determined the optimal location of the relay for different distances (d) between source and destination placed on the body where linear placement is possible. It is also observed that the lifetime of WBAN is enhanced by deploying the relay in the optimal location which is not the middle of the line joining S amd D [152].

7.6.2 Optimal location analysis for different end to end outage (O) values

Fig. 7.6, shows the plot of optimal relay location for different different end to end outage values. We have represented the distance between two nodes (S and D) based on normalized form (d^*_{SR}/d). The X-axis represents the energy consumption per bit (J). We have

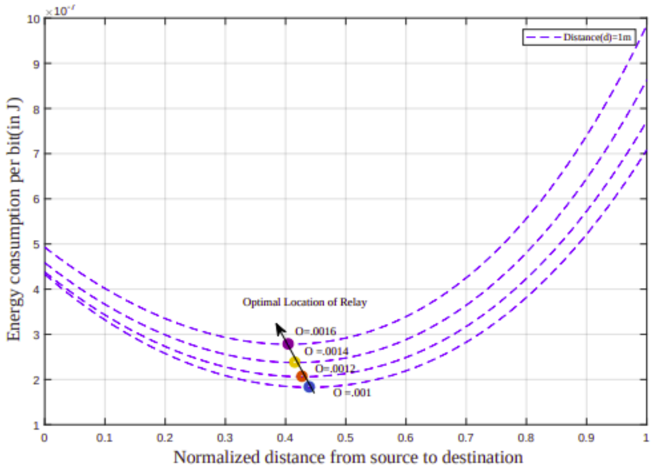

Figure 7.6: Optimal relay location by varying the distance (d) between source and destination.

plotted the normalized distance on the $Y - axis$ keeping the path loss and other systems parameters constant varying the end-to-end outage (O) values. From Fig. 7.6 we can say that for all the cases, the optimal location (in terms of energy consumption) of the relay is not the middle position in the $S - D$ path. When the outage value is high (.0016 and .0014), the optimal location is closer to the source, whereas for lower values (.0012 and.001) the optimal location is closer to the middle position of the $S - D$ path. We can conclude from these results that the optimal location of the relay in WBAN is heavily dependent on the end-to-end outage between the source and the destination node.

7.6.3 Energy efficiency variation with payload (L)

In Fig.7.7, we have compared energy consumption per successful communication of bit varying payload for two different cases (relay in the middle and relay at the optimal location). The red line shows the variation of payload when the relay is placed in the middle position of the line joining the source and destination nodes for a given low end to end outage value (.001). Greenline signifies the payload variation when the relay is deployed in the proposed optimal location (44cm). In this case, the distance between the two nodes is 1m. The result demonstrates some interesting facts. When the outage value is .001, the optimal payload value range is 38-47. The optimal relay position is more energy-efficient compared to the relay in the middle. This optimal payload depends on an end-to-end outage value; when the outage value is .0012 the optimal payload position shifts to 32-41 cm.

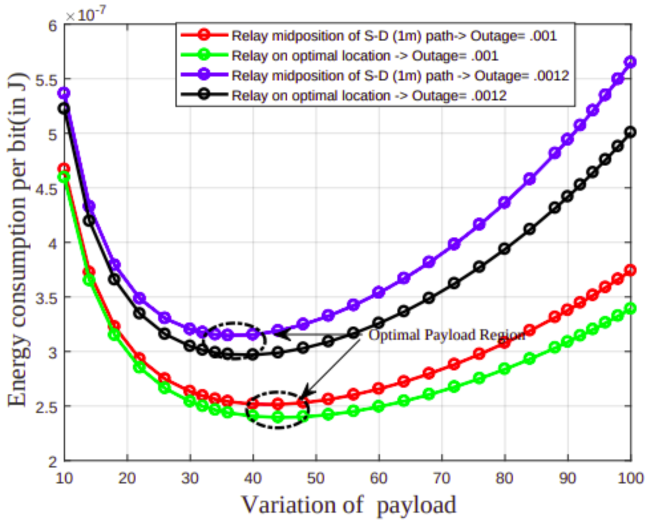

Figure 7.7: Compare middle relay position and optimal relay position with payload (L) variation.

Based on this, we achieve some guidelines of optimal data payload range to get the energy optimization instead of analysis with arbitrary data payload values [170].

The battery life for two different positions of the relay is examined in Fig.7.8. We have calculated the lifetime of the network based on peukert law. Primarily, the actual discharge current (I) is calculated from energy consumption per bit and applied to this value to evaluate the lifetime from equation 7.18. Battery capacity is considered as 560 mah [183]. Fig.7.8 shows that when the payload is less (within 78), the battery consumption of the relay node remains the same irrespective of its position. As the payload increases, the optimal location of the relay node outperforms the relay in the middle in terms of battery longevity. Thus, from Fig.7.8 we can state that when relay node is deployed at the proposed optimal location, the battery lifetime is enhanced by 13% compared to conventional relay in the middle deployment. In Fig.7.9, we analyze the optimal range of payload value based on total energy consumption (in joule) of the network. We can say that energy consumption heavily depends on the size of the payload. Fig.7.9 shows that at the payload value of 100, it takes maximum energy. This result is the same irrespective of the position of the relay node. However, if the payload is more than or less than 100, the energy consumption of optimal relay deployment position performs better compare to relay deployment in the middle position of the S-D path.

7.6.4 Comparison of SAR value for two different relay positions varying payload (L)

In a WBAN, sensor nodes are generally placed on different parts of the human body or within the body. During packet transmission from one node to another node, an electric and magnetic field (EMF) radiation is generated, which may affect the human body cells

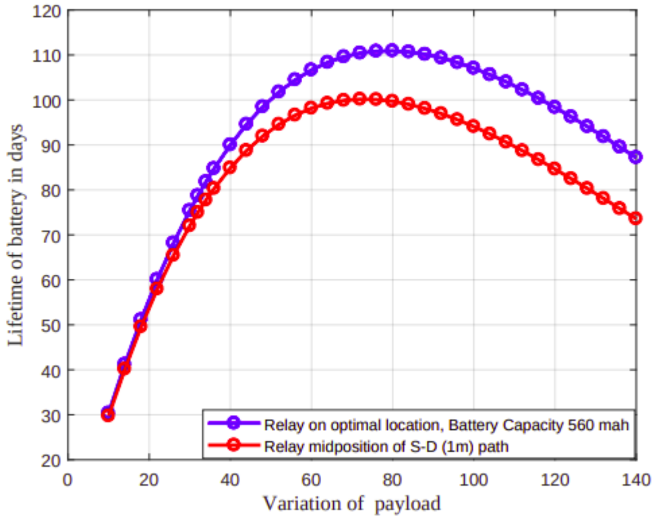

Figure 7.8: Compare battery lifetime with payload (L) variation for middle relay position and optimal relay position.

or tissues. The radio frequency absorption by human tissue per unit mass is defined by a specific absorption rate (SAR). A higher SAR value is not desirable as it may harm the healthy tissues. In most of the previous research work, [152, 183] of WBAN neglected the effect of SAR on the human body. In this chapter, we have investigated the effect of the optimal location of the relay on SAR value. In Fig.7.10 we have examined the SAR values for optimal relay location and relay in the middle deployment for different payloads. The SAR values mainly depend on the distance between the observation point and the source and the current required to transmit the signal. In this chapter, we have taken a constant value of the distance between the observation point and the source. We have varied the payload values which reflect the required current values. Fig.7.10 reveals some interesting results. We can say that for low payload values (less than 55) the SAR value is almost the same for both deployments of relay nodes. If the payload value is more than 55, SAR values for optimal relay location (blue line) are much less compared to mid-position relay deployment (red line).

7.6.5 Optimal relay position analysis for nonlinear 3D coordinate system model

In Fig.7.11 and Fig.7.12 we have analyzed the most energy-efficient region for relay deployment based on 3D coordinate system, shown in Fig.7.4. This WBAN 3D topology [101] supports, the sensor node can deploy in different body parts of a human body. We have analyzed the energy saving for optimal relay deployment on the human body, with respect to direct transmission(without a relay). We assumed that the relay can be deployed anywhere on the body. In Fig.7.11 we have determined the optimal location based on the X-Y plane, whereas the Z-axis value is unchanged. From Fig.7.11 we can say that the most optimal location region is the smaller boundaries region, where the X-axis value is from 35 cm to

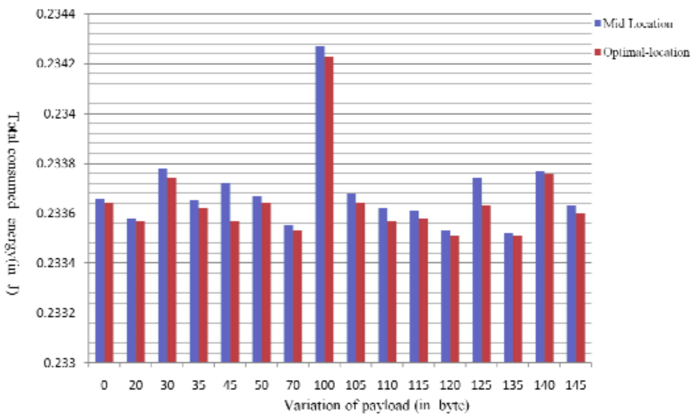

Figure 7.9: Total consumed energy compare with middle relay position and optimal relay position with payload (L) variation.

54 cm, and the Y-axis value is from +30 cm to -24 cm. We have also examined that we can save near to 53 percent of energy if we placed the relay in that region. In Fig.7.12, we have evaluated the optimal location based on the X-Z plane keeping Y fixed. The best boundary region location can save 75 percent of energy. This boundary region is given by Z values between +8 cm to -7 cm, and X values between 35 cm to 50 cm. Finally, in Fig.7.13 we have represented the energy consumption per bit for a relay-based WBAN network based on a 3D coordinate system model. The bar value represents the energy consumption per bit. We can say that the prime location for relay deployment is near to the left side of the center position of the 2D plane which is shown as a blue color in Fig.7.13. It is attractive to note that the optimal location of the relay is not in the center either in a 2D or a 3D plane.

7.7 Conclusions

In this chapter, we have analyzed the optimal location of the relay in a WBAN in terms of energy consumption and lifetime. We have examined the energy consumed per successful transmission of a bit for different payload values, along with the energy efficiency of a relay-assisted WBAN compared to different distances between the source and destination, different modulation schemes, and different payloads. We have considered relay placement for 2-D and 3-D WBAN. From the experiments, we may conclude that the optimal position of the relay is not at the center of the source and destination nodes. If the relay is placed at the optimal location, the lifetime of the WBAN is greatly enhanced.

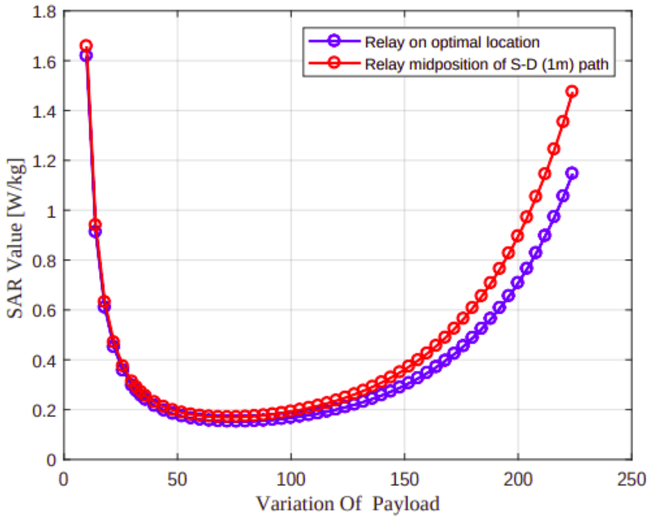

Figure 7.10: SAR Compare for Middle relay position and Optimal relay position with payload (L) variation .

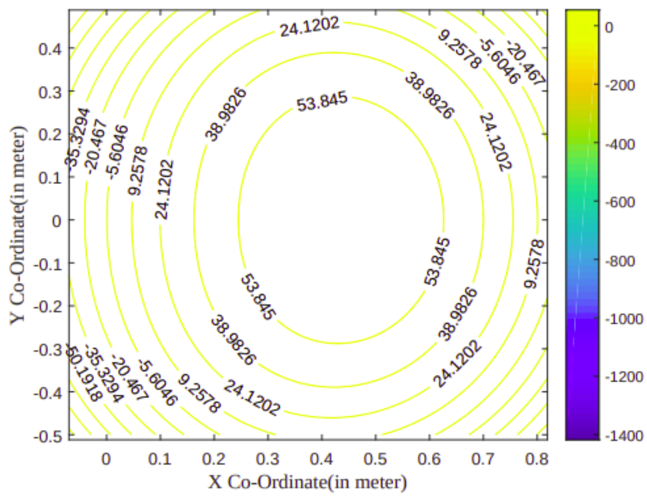

Figure 7.11: Optimal relay position based on X-Y plane .

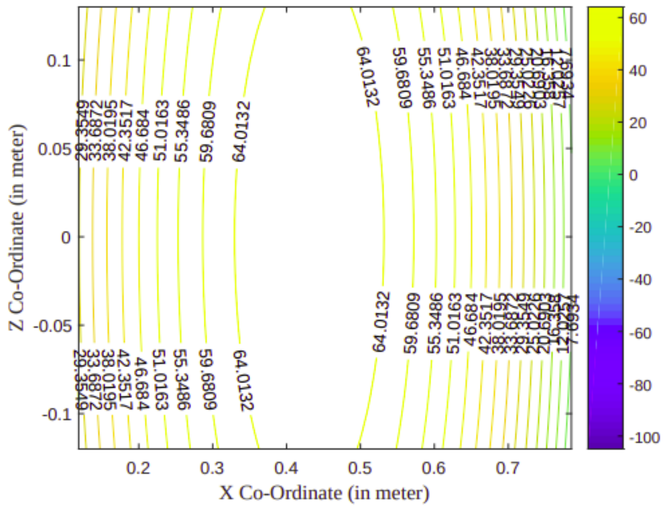

Figure 7.12: Optimal relay position based on X-Z plane .

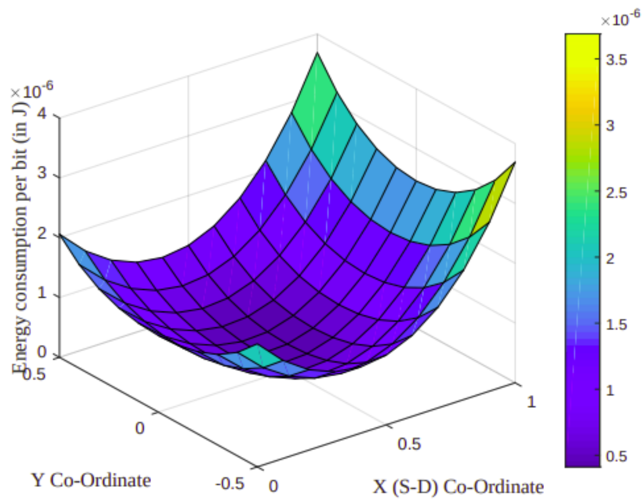

Figure 7.13: Optimal relay position based on X-Y plane 3D view .

Chapter 8

WBAN to BBN Architecture to Restrain Epidemic Spread

8.1 Introduction

Health data acquired by a WBAN is capable of making users aware about one'S own vital stats. During a pandemic situation, where a disease is infectious in nature, propagating information of one's health can provide a positive societal impact. This can also curb the spread of disease. This issue raised the invention of another network where health data from one WBAN is propagated to and through other bodies. Thus introduction of Body-to-Body (BBN) solutions to transmit each WBAN's data via its network of cooperating WBAN has great social benefits.

Currently, our society demands a system which can convey the health status of each individual to others, This ensures that the individual as well as those who are in contact are aware of the critical consequence of being in close proximity. The individual also can take measures accordingly for being safe and quarantined. Thus, real time interactions among cooperative WBANs in a BBN network may allow every person to be considered as a good citizen to auto-prevent the spread of Covid-19 like epidemic. We consider the scenario to reduce epidemic spread in an enclosed crowded area. We assume that each person in that area is WBAN enabled. The coordinator of each WBAN participate in the BBN network in a cooperative manner. BBNs are natural choice to connect collaborating WBANs in close proximity. by involving them in mutual interactions and cooperation [184]. These data collected by the WBANs of individuals are considered as sample inputs. Substantial success has been made in deep learning producing systems to be able to learn without explicit programming, but by building models from the sample data collected as input. The inherent requirement for large scale high quality well structured data necessitates providers to move to electronic health record.

The main contributions of this paper are as follows.

- Help in a low epidemic spread of the disease in an enclosed area by minimising contact between non-affected and affected WBANs. Use quarantine strategies to prevent the diffusion of the disease to the population.

- An unsupervised coloring algorithm for spectrum allocation is used for a BBN network having multiple cooperative WBANs that can effectively separate the WBANs into non-overlapping clusters. The cluster heads are responsible for efficiently transmitting data with minimal interference to their nearest authorities to ensure proper analysis of the health status.

The rest of the chapter is organised as follows. Section 8.2 details our state-of-the-art related to this contribution. Section 8.3 describes the model. Section 8.4 gives an overview of Inter WBAN Interference Mitigation scheme in this work followed by Section 8.5 that provides an insight to the performance evaluation of our model. Finally, we conclude the chapter in Section 8.6.

8.2 Related Work

Authors in [185] highlight the limitations of the current information transfer system in healthcare scenario for epidemic control. Precise estimations for epidemic situations are not conveyed in a timely and efficient manner by hospitals and health workers due to delay in information systems. In this paper, authors have developed a new information system called EPIC that uses Social Networks for pandemic control. EPIC algorithm combines health data collected from WBANs and social interactions available in social networks. This approach predicts the spread precisely and on-time. But this proposal does not address priority based sensor data transmission which is the need of any epidemic condition to control. It also handles the data inefficiently as the WBANs are non-cooperative and the quarantine strategy is solely handled by the authorities. Thus, susceptible individuals ignore the epidemic threats around them.

One more technique to reduce interference in a dense WBAN deployment, like ours, is cooperative communication. Cooperative communication uses in spatial diversity. When a large distance has to be travelled from the source to the destination, or wireless medium becomes adverse cooperative communication can lead to improved reliability and energy efficiency [186].

In 2013, the same authors proposed another which integrates WBANs technology for health data and mobile phonesfor social information [187]. Authors have designed a mobile phone capability driven hierarchical social interaction detection framework integrated with WBANs. With this framework, they have proposed a set of epidemic source tracing and control algorithms to effectively identify pandemic sources and inhibit the propagation of a pandemic. In some pandemics, like COVID-19, there exists an intermediate status between susceptible and infected. During this phase, a person though infected, is not a carrier. He stays in this latent period for sometime before being infected. Unlike [187] we have considered an effective epidemic control model by considering this intermediate state, so that an appropriate strategy for quarantine can be planned even before the patient is declared as infected.

Moreover, anticipating the quarantine strategy is not enough to control epidemic spread. All WBANs in a BBN network need to cooperate to transmit this information in a timely and efficient manner. Thus, a methodical inter-WBAN routing algorithm is required to effectively transmit data through the BBN architecture.

We have already discussed challenges posed by inter-WBAN interference. Some more major challenges for interference mitigation of a dense system of WBANs are listed in the following.

- Their distribution in space
- They do not exchange any data with their neighbors
- They undergo block fading, i.e., the interference channel gain may remain constant for a slot but varies from slot to slot

Only some research works have addressed routing among WBANs. Some of them are discussed as follows.

Authors in [188] proposed a multiple cluster-based hybrid security framework that supports both intra-WBAN and inter-WBAN communications. Authors have ensured secure cluster formation by using electrocardiogram (EKG)-based key agreement scheme and energy is used efficiently as multiple clusters are formed. Highly dynamic and random EKG values of the human body for pairwise key generation and refreshment. This work is scalabel and has a reduced network overhead.

Authors in [74] proposed a dynamic resource allocation scheme where each WBAN in the network exchange information to efficiently interprets an interference region with others in a close vicinity. The nodes in this region are later allocated orthogonal sub-channels, while non-interfering nodes can transmit in the same time slot. Here the authors have assumed a minimum interference level. As WBAN deals with critical health data, during epidemic situation this assumption becomes impractical.

Authors in [111], [**Ma2021coloring**] proposed a random incomplete coloring to achieve a fast and high spatial reuse inter-WBAN scheduling. It can always provide fast convergence with time-complexity $O(e^{w(2\log n)/2})$ in any spatial reuse requirement. Furthermore, it can support an increase of up to 90 percent of spatial reuse over the conventional complete coloring using chromatic $X(G)$-colors, which is known to be the optimal coloring of complete coloring. But, the strict assumptions made in this paper, such as perfect superframe synchronization, make this method unsuitable for our real life use case.

Authors in [189], proposed a social group interaction power control game model. New utility and cost functions accommodate both convergence speed and quality. This work proves that only one Nash equilibrium (NE) point exists for this game model, which ensures the algorithm converges quickly. Thus it mitigates interference between WBANs.

In [190], a new coexistence mechanism is described to reduce the interference between a number of WBANs. The scheme is based on adjusing transmission power of the participating WBANs depending on their motion.This leads to efficient use of energy.

In [191] authors have formulated the channel selection of the coexisting WBAN coordinators for interference mitigation in a time-varying environment as an exact potential game. The utility is the weighted aggregate interference. It has been shown that the channel selection (action) profile which globally minimizes the interference is a pure strategy Nash Equilibrium (NE) of the game. They have considered two distributed learning method to converge the NE. This method do not requite any information exchange among the WBANs. Our use case is a time-varying network topology where the number of active WBAN users varies. This method is unsuitable for the dynamically changing network.

An Optimal Backoff Time Interference Mitigation Algorithm (OBTIM) is proposed in [186]. The proposed algorthm reschedules or switches channels when WBAN performance becomes less. Simulation study demonstrates that itutilizes channel better. Naturally throughput, collision probability, energy efficiency improve a lot.

8.3 Framework

The goal of this framework is to provide a low epidemic spread of the disease in an enclosed area. Health data must be ensured to reach the destination in a timely and efficient manner.

Our system consists of the following.

- Cooperative WBAN users in an enclosed area
- Health Portal that authorities of the enclosed area use to find out close interactions.
- Data repository in which the information gathered or created using a BBN network is stored.

8.3.1 Terminologies Used

- *Cooperative Handshaking among WBANs*

  Whenever a WBAN enabled individual is in the range of another user, their coordinators perform a 'digital handshake'. Here, they exchange encrypted data such as tempID, mutual health data including status and the strength of the wireless signal.

  The encryption is such that anyone is able to view data but only a trusted person will be able to access data using the key.

  The probability two persons are within 1.5m from each other is computed using RSSI (Received Signal Strength Indicator) and Tx Power (Transmission Power). However, closeness is computed using RSSI

- *Encrypted TempID*

  The temporary identifier (tempID) is used to ensure privacy of the user-data. The tempIDs are created in a periodic manner and they become useless after an expiry time. They are nothing but random unique elements. Using TempID, a person can

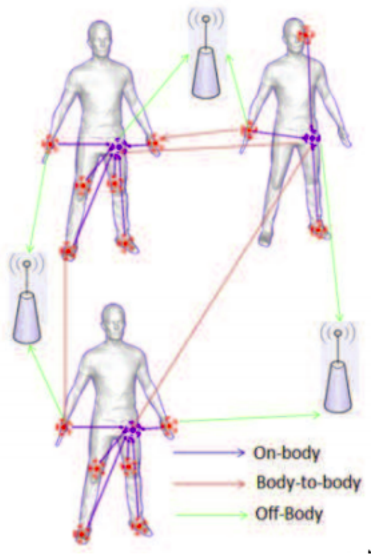

Figure 8.1: BBN Architecture

be identified as a participating user of the BBN network without his /her personal details.

- *Encounters*

  An encounter is a digital handshake between two WBAN-enabled individuals . Encounters are used to find out the period of close contact where one user is already positive. Based on this information, additional advices are given.

8.3.2 Epidemic Spread Control Model for BBN architecture

In this section, we describe all the phases that we have considered to control the spread of epidemic situation. We have considered a 2 tier BBN architecture with cooperating WBANs as shown in Figure 8.1. This ensures self-restrained WBANs and quarantine strategies decided by authorities of the enclosed space of our use case that uses the BBN architecture.

In this system, we have considered a dynamic framework where a person can enter and leave the network at his/her own pace. Real time health information is exchanged between cooperative WBANs of the network via their respective coordinators. Using K-means++ algorithms, WBANs form non-overlapping clusters to coordinate efficiently, minimising interference. The authority intercede and provides quarantine strategies based on the exchanged health data preventing infectious people to come in contact with others. We have divided the entire working time into τ continuous aeons. Authorities of the enclosed area keep a count of the *Encounters* during each aeon to accurately determine the period of close contact.

Every epidemic is divided into four stages as shown in Figure 8.3. They are as follows.

- *Sensitive Stage* This phase is responsive to external conditions or simulations. An

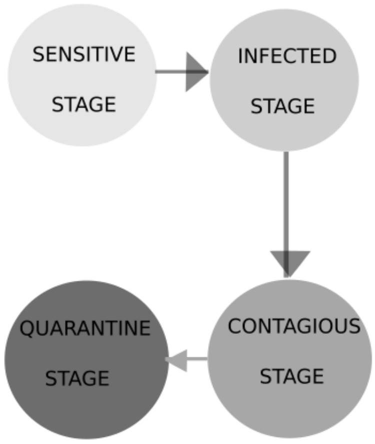

Figure 8.2: Phases of Epidemic Disease

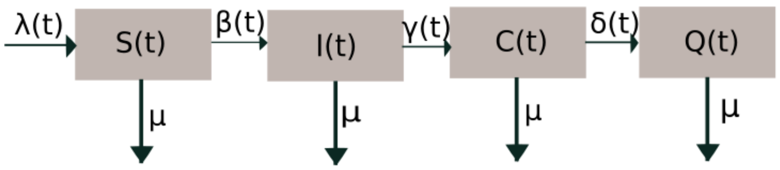

Figure 8.3: Epidemic Flow Model

individual is vulnerable and thus considered to be exposed to contagious people, but herself not yet infected; may be asymptomatic.

- *Infected Stage* In this phase, an individual is considered a confirmed positive case, but not infectious and communicable.
- *Contagious Stage* In this stage a person is considered to be infected, infectious and transmissible.
- *Quarantine Stage* This stage indicates those individuals who has been identified correctly and been sent to isolation.

The annotations shown in Figure 8.3 are explained in Table 8.1 at t^{th} epoch.

In our work, we aim to ensure detection of the epidemic outbreak during the initial phase when it has not yet propagated fully.

The mathematical formulation of the stages is given by Equation 8.1.

$$N(t) = S(t) + I(t) + C(t) + Q(t) \tag{8.1}$$

In our use case, we have assumed the difference between rate of arrival and departure is negligible. Thus at time t, where $t \in \tau$, there are N number of total individuals in an

Symbols	Meanings
$\lambda(t)$	Arrival Rate
$\beta(t)$	Close contact/Infectious Rate of Sensitive people with Infected people
$\gamma(t)$	Transmission Rate
$\delta(t)$	Rate of Isolation
μ	Departure Rate

Table 8.1: Notations

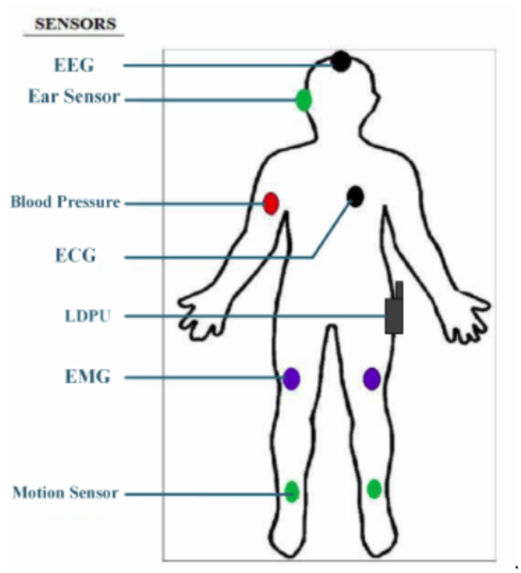

Figure 8.4: Intra WBAN orientation

enclosed area. According to Equation 8.1, $S(t)$, $I(t)$, $C(t)$ and $Q(t)$ denotes the subset of all individuals present in *Sensitive Stage*, *Infected Stage*, *Contagious Stage* and *Quarantine Stage* respectively at time t.

8.3.3 Assess Health Status

In this work, each $WBAN_i$ $i \in N$ is assumed to be able to detect the status of his/her health from attached sensors and transmit it to its own coordinator as shown in Figure 8.4. The correlated sensor data received for $WBAN_n$ is denoted by Equation 8.2.

$$\Gamma_n(t) = \gamma_i(t), \forall i_{sensor} \in WBANn \tag{8.2}$$

$$H_n(t) = f(\Gamma_n, t) \tag{8.3}$$

This $\Gamma_n(t)$ is transmitted to second tier of the architecture mitigating inter-WBAN in-

Clinical Evaluation of COVID-19	Measurements	Early Warning for COVID-19
Respiratory Assessment	RR Lung/ Heart Sound SpO2	$\geq 20bpm$ Crackles $\leq 94\%$
Cardiovascular Evaluation	ECG/HR Cuffless BP	Arrhythmia, $HR \geq 100bpm$ $\geq 140/90mmHg$
Clinical Symptom Monitoring	Body Temperature Cough	$\geq 38°C$ Dry cough

Table 8.2: Epidemic Threshold for Wearables

terference and is received by the authority level. Now, using Equation 8.3, authorities define health status of $WBAN_n$, which is denoted by H_n, at time epoch $t \in T$. Authority matches the received $\Gamma_n(t)$ of $WBAN_n$ with Table 8.2 to determine her H_n. The values of this are considered as threshold values denoted by EP_{th}. To keep our model simple and practical, the health status is represented by discrete levels as follows.

$$H_n(t) = \begin{cases} 3, iff(\Gamma_n, t) \geq EP_{th}; Contagious\, WBAN(C) \\ 2, if \epsilon < f(\Gamma_n, t) \leq EP_{th}; Infected\, WBAN(I) \\ 1, otherwise; Exposed\, WBAN(S) \end{cases} \tag{8.4}$$

8.4 Inter WBAN Interference Mitigation

Our model is efficient only if all data transmissions take place effectively, reliably and timely. Using clustering to allocate spectrum is a very typical choice to reduce interference. If an applications does not need any fixed infrastructures, one can use a coloring algorithm. to cluster. Most coloring algorithms require the location of the user, which can be provided by the WBAN application. For WBANs, it is possible that the coloring algorithm is deployed on a server. As mobility leads to changes in topology, considerable computing and transmission resources are required. Again, tf there are errors in location and position information, may adversely affect the quality of clustering.

For these issues, a coloring algorithm is designed that aligns with the capabilities of a WBAN node. Distributed interference-avoidance scheduling of wireless networks can be modeled by the notion of distributed graph coloring, which is commonly adopted in sensor networks or MANET [192], [193], [194]. But, coloring speed is found to be the key factor that affects the performance of inter-WBAN scheduling.

In our system, machine learning is used to improvise the learning process. [195] demon-

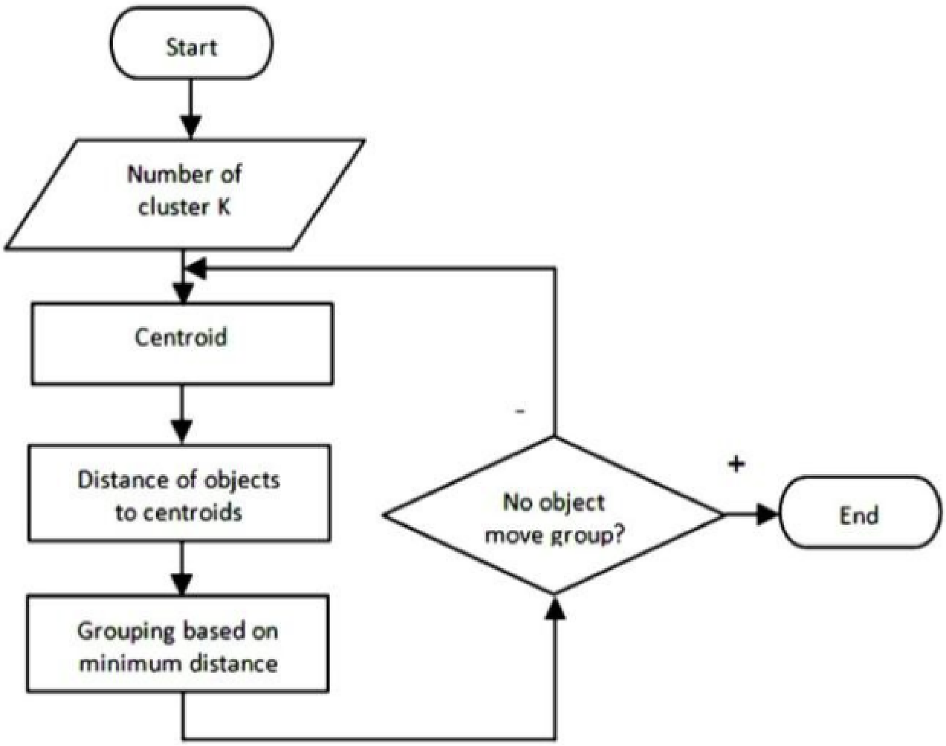

Figure 8.5: K-means Algorithm Flowchart

strated that healthcare offers a different form of data. Different master learning algorithms such as supervised, unsupervised, and enhanced algorithms are used for analyzing this variety of data to increase prediction that can be analyzed using different performance parameters such as exactness, sensitivity, specificity, precision, F1 scoring, and Curve region.

In this work, we have used an unsupervised learning method to refine the method of coloring to reduce the complexity of the algorithm. More accurate features like distance are extracted by the learning algorithm. Thus, we have developed a K-means++ algorithm for WBANs. This method automatically clusters the WBANs. Welsh Powell algorithm ensures minimal number of clusters maximising effective spectrum allocation. This algorithm ensures a smarter initialization of the centroids and improves the quality of the clustering.

Initially, a random WBAN is selected as cluster center. From this center, shortest distance between other WBANs of the network is calculated. The further a WBAN is from existing cluster center, the higher is its probability to be chosen as the next cluster center. This method maximizes the distance from the recently computed cluster center to the previous cluster center. The flowchart of the algorithm is given in Figure 8.5.

The advantages of this procedure to choose cluster center are as follows.

- Based on the density of the area, it can perform adaptive clustering.
- Effective spectrum allocation is ensured as cell characterisation are based on distance.

Although the initialization in K-means++ is computationally more expensive than the

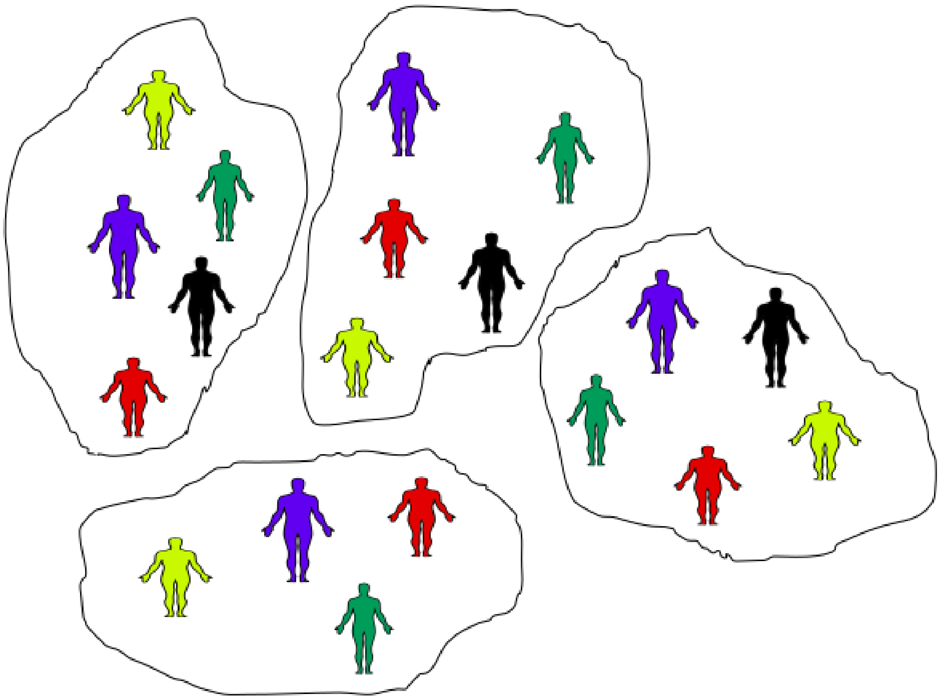

Figure 8.6: Intelligent partitioning of WBAN using K-means++ Algorithm

standard K-means algorithm, the run-time for convergence to optimum is drastically reduced for K-means++. This is because the centroids that are initially chosen are likely to lie in different clusters already. Moreover, to minimize cost to compute fall outs for topological changes, optimization is performed at local level too. The channels which are not adjacent are grouped differently. The vertex coloring algorithm is used to find out the channel groups for each cell to use. Assignment of spectrum is dynamic in nature so as to mitigate interference among collaborating WBANs.

Clustering of WBANs is performed by the Algorithm K-means++. Assignment of spectrum is performed by Welsh Powell algorithm as shown in Figure.

8.5 Performance Evaluation

In this section, first we have described experimental setup which is followed by results obtained.

Castalia-3.2 simulator [196] is used to for evaluation of the routing protocol in BBN networks.

8.5.1 Experimental Setup

In this work, we have considered two use cases as described below.

- Case 1: All the cooperative WBANs in an enclosed area are randomly distributed. The distance between two WBANs is not less than 0.5 m. If a WBAN is within a distance of 1.5m from another WBAN, it is considered to be in close proximity of each other.
- Case 2: All the cooperative WBANs in an enclosed area are evenly distributed, like a cinema hall, where the distance between two WBANs is 0.8 m.

Data traffic is classified based on Equation 8.4. $C(t)$, $I(t)$ and $S(t)$ represent data from Contagious WBAN, Infected WBAN and Exposed WBAN respectively.

We have considered transmission power of all devices as P_t. Total number of interfering WBANs in a BBN network is considered to be n which are placed at a distance r_k.

Intervention of the system is calculated using Equation 8.5 which measures total interference power.

$$I = \sum_{k=1}^{n} P_t r_k^{-4} \tag{8.5}$$

To ensure efficient bandwidth utilization, effective clustering is required. This incorporates a better spectrum allocation with minimal signal-to-interference ratio as given by Equation 8.6.

$$SIR = \frac{P_t r_0^{-6}}{I} \tag{8.6}$$

where I is given in Equation 8.5. Smaller value of I indicates better interference mitigated system.

We have assumed a 200m X 200m enclosed area. To understand the effect of coloring algorithm used, we have considered a BBN network with three different densities such as 200 WBANs, 150 WBANs and 100 WBANs for each use cases.

In case of our use Case 1, where mobility is high, probability of maintaining the position of WBAN unaltered is taken as 60% for an epoch. The number of channels is taken as to be 24. Average of 10 experiments is taken to calculate interference value in each cycle. If the difference between two consecutive iterations is less than 10^{-5}, the iteration is stopped.

Authors in [197] proposed a Reliable Routing Technique (RRT) [198]. This protocol continuously communicate with its components in a partial or completely damaged infrastructure condition. This routing protocol uses adhoc network to communicate continuously which draws our attention to use it in a BBN architecture. The routing protocol is evaluated using parameters like Packet Delivery Ratio (PDR) and Energy Consumption.

Parameter	Value
Area	200m X 200m
Number of WBANs	[40...100]
Mobility model	Random Waypoint
Transmission power	-15dBm
Initial energy	18720 Joules
Transmission rate	-89.3 dBm

Table 8.3: Simulation Parameters

Throughput of our system is calculated using Packet Delivery Ratio (PDR) parameter. This is calculated for each type of health data as categorized by different stages of system as shown by Equation 8.7 for contagious data.

$$PDR(\%) = \frac{\sum Received\ C(t)\ data\ packets}{\sum Sent\ \ C(t)\ datapackets} \tag{8.7}$$

Table 8.3 depicts simulation parameters used in our system.

8.5.2 Results

The results obtained are given as follows.

Figure 8.7 indicates the number of clusters formed and number of colours required. Both increases with increase in density in our enclosed 200m X 200m area. This is expected because of randomness of clustering algorithm, number of channels in each cell is restricted. Since adjacent channels do not get assigned same colours, inter-WBAN interference mitigates. The figure also depicts that used channel group did not change significantly with an increase in WBAN density. This justifies appropriate frequency band utilization by unsupervised coloring algorithm for spectrum allocation in multiple WBANs.

Figure 8.8 shows average interference due to spectrum allocation used in both the cases. The result shows that evenly distributed cooperating WBANs outperforms randomly placed ones in a confined area. Moreover, stability of the colouring algorithm used is justified as interference values do not vary much for both scenarios.

The graph in Figure 8.9 illustrates Throughput of our system. As given in 8.7 throughput is measured in terms of packet delivery ratio for different data types. The result obtained shows that data generated by contagious WBANs are delivered with highest PDR, followed by infectious WBAN data and data from Exposed stage WBANs. Results obtained are aligned with our health statues priorities of Equation 8.4. It is worth mentioning that beyond 40 WBANs, PDR of Exposed WBANs data $S(t)$ rapidly deteriorates as resources are occupied by higher priority traffic data. This signifies that precarious WBANs need to be quarantined on a priority basis to efficiently control spread of epidemic.

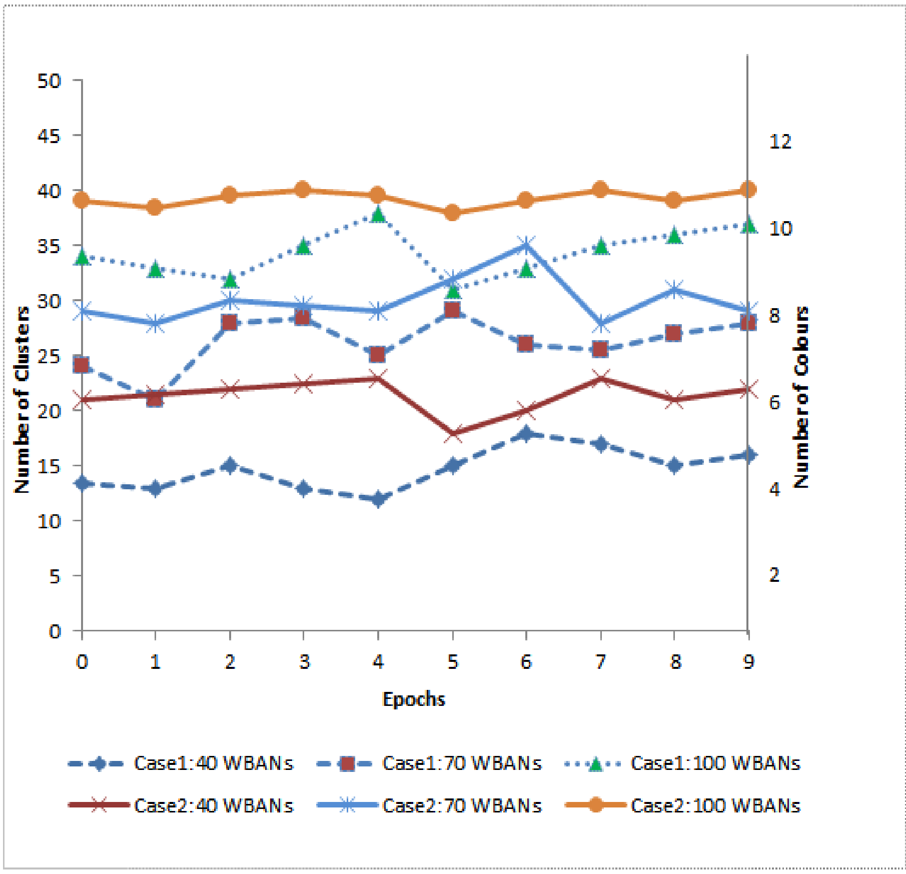

Figure 8.7: Number of colours used per cluster

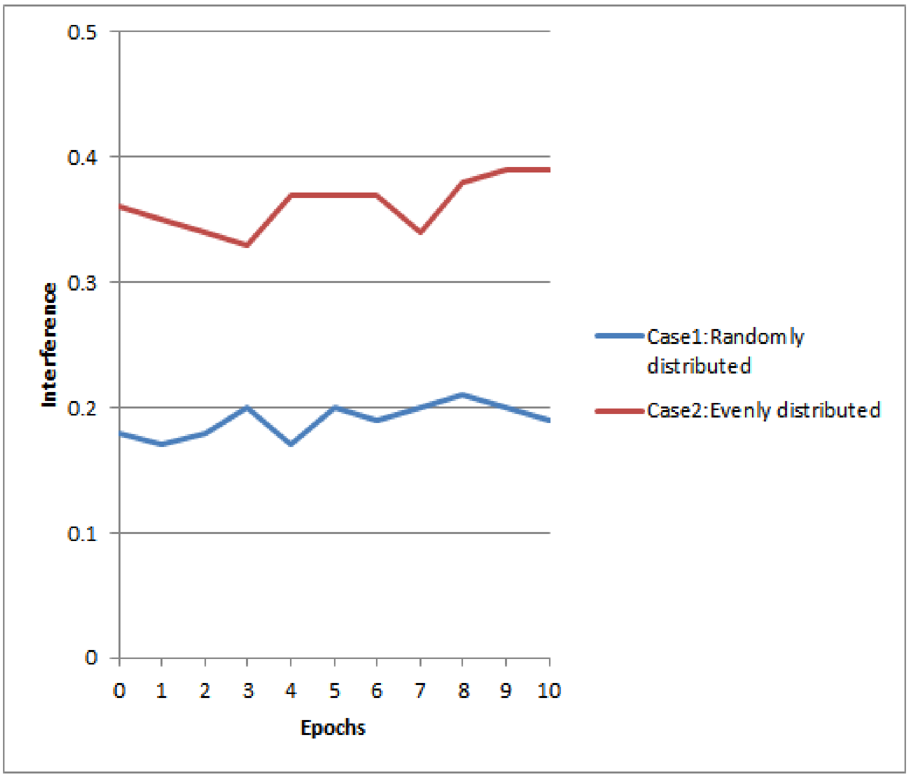

Figure 8.8: Interference value of spectrum allocation for different Usecases

Figure 8.10 shows that the energy consumption is directly proportional to the density of WBANs in the enclosed area. It is calculated by the Resource Manager of the simulator. For each WBAN, it is computed as the total of transmission, buffering, reception and idle energy used. As expected, the graph illustrates that WBANs with critical health status $C(t)$ consume maximum energy.

8.6 Conclusion

In this work, a BBN architecture with cooperating WBANs is shown to be able to control an epidemic spread. We have considered a confined area with two different distribution scenarios. We have also proposed quarantined strategies by minimizing contact between different staged WBANs. An unsupervised learning algorithm is used to efficiently divide the area into non-overlapping clusters. This ensures effective utilisation of bandwidth as spectrum is allocated minimizing inter-WBAN interference. Performance analysis of our system guarantee a low epidemic spread of the disease in an enclosed area by enhancing throughput and minimising interference of our stable system.

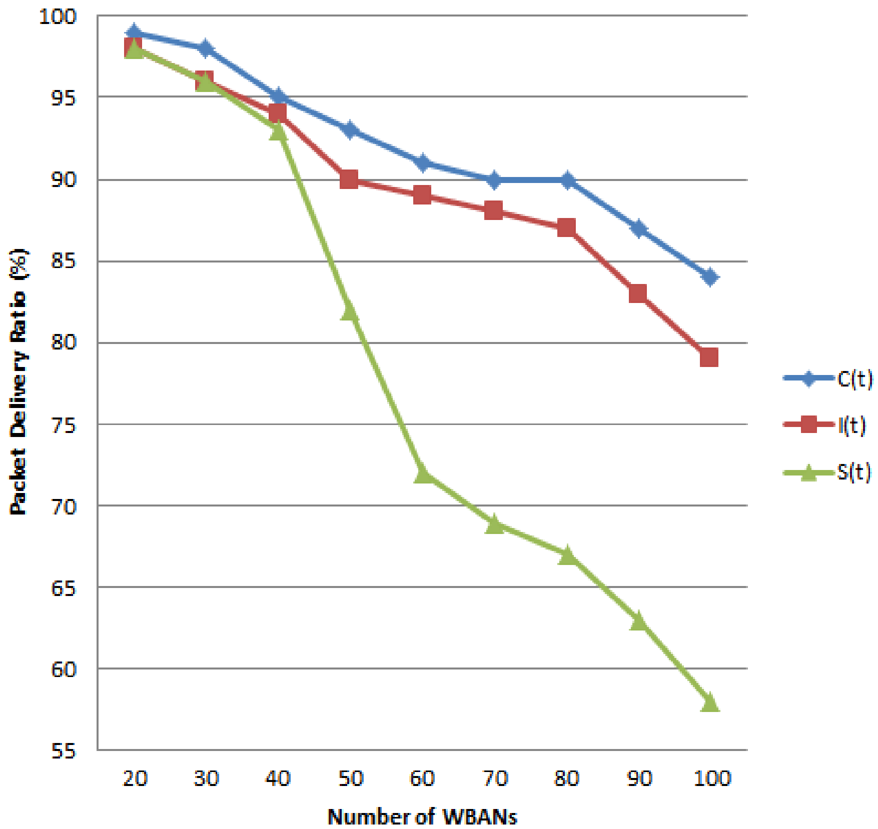

Figure 8.9: Throughput of Epidemic data

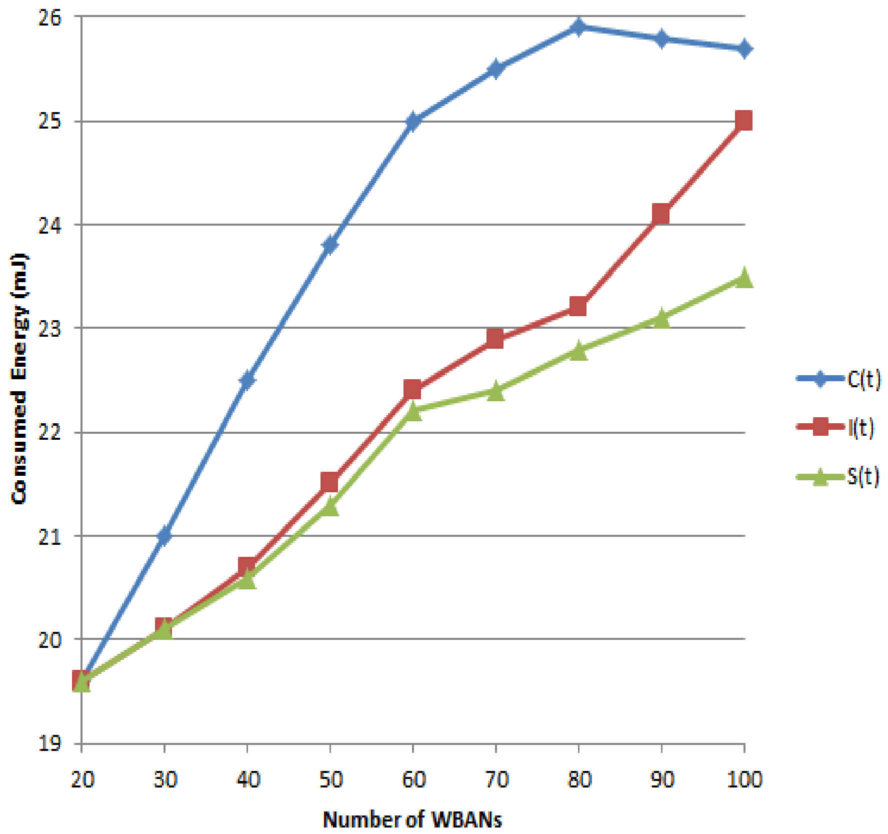

Figure 8.10: Energy Consumed wrt System Density

Chapter 9

Conclusion and Future Work

9.1 Introduction: Broad Aims

Major outcomes of this thesis are several algorithms for efficient routing, many of which are based on analytical foundation, that can effectively transfer the data in one or more WBAN systems without compromising a number of QoS parameters. The efficiency and effectiveness of these algorithms or protocols are evaluated through extensive simulation which measure several parameters such as energy consumption, transmission power, stability of a network, delay, throughput (PDR) , lifetime of a network, SAR etc.

Considering the stringent QoS requirement for a WBAN it has been observed that the current state of the art, though provides numerous solutions, but none of them jointly optimize these parameters. So, there is always a trade off between between one and another. The Healthcare sector based on WBAN deals with critical health data. Classifying the data into proper categories and routing them accordingly is one of the major task in this thesis. We have also identified that SAR is an important parameter that cannot be ignored at any point while dealing with sensors which are on the human body. Many of our proposed protocols attempt to overcome these shortcomings and prove to be much better than a naive algorithm implementing the WBAN IEEE 802.15.6 based CSMA/CA technology.

9.2 Research Contributions

As discussed in Chapter 1, the general objective of this thesis was to develop efficient routing algorithms that seek to ensure effective and reliable communication within and between multiple WBANs.

In chapter 3, fixed nodes are introduced as forwarder nodes and a proper subset of relay and sensor nodes are selected based on a cost function that leads to a thermal aware multi-hop routing protocol. This protocol is efficient in terms of transmitting power, delivery ratio and network lifetime.

In chapter 4, the objective is to reduce interference among multiple WBANs located closely by optimising the power needed to transmit. This also helps in increasing throughput. The method is to assign available bandwidth.

In chapter 5, Anycast algorithm has been modified to introduce a WBAN topology architecture by using two coordinators on the human body. Double coordinators ensure that any sender is near to anyone of the coordinators in one hop. Thus, introducing a second coordinator in a strategic position ensures a star topology. This decreases the end to end delay and enhances stability period, packet delivery ratio and remaining energy of the network.

Chapter 6 tries to consider important QoS issues like adverse effect of heating of the implanted sensors on human tissues along with energy constraint and interference issues jointly by designing a topology which has an optimised number of relay nodes. In this method multicasting has been used to reduce transmission of unnecessary packets. This design also leads to minimum hop count from body sensor to coordinator node.

Chapter 7 addresses the problem of the optimal location of the relay node in a WBAN in terms of energy consumption and lifetime. We have examined the energy consumed per successful transmission of a bit for different payload values, along with the energy efficiency of a relay-assisted WBAN compared to different distances between the source and destination, different modulation schemes, and different payloads. We have considered relay placement for 2-D and 3-D WBAN. From the experiments, we may conclude that the optimal position of the relay is not at the center of the source and destination nodes. If the relay is placed at the optimal location, the lifetime of the WBAN is greatly enhanced.

In Chapter 8, we present a novel application of WBAN technology with an objective of controlling spread of an epidemic like COVID 19. It is achieved by using multiple cooperating WBANs which lead to a network called body to body network. Our proposed quarantine strategies minimizes contact between WBANs having different stages based on their health status. Unsupervised learning algorithm is used to efficiently divide the area into non overlapping classes in order to minimise inter-WBAN interference.

9.3 Research Limitation

Like any other research work, this research has many limitations and poses more problems than it solves.

We have evaluated our system based on simulation. Implementation of our system in a test bed would give us clarity of our system as the performance of our system in a test bed would get tested in presence of different environmental factors like physical objects, electronic devices and various weather conditions.

Security issues have not been considered in this research work though they are an important design factor as we are dealing with health data which are private and personal.

Different other fine tuning of several parameters like modulation parameters, network codings etc may better analyse our proposed system.

We have also restricted ourselves to some regular human postures. The effect of complicated postures on our algorithm is yet to be determined.

9.4 Future Research

Following research works may be taken up in future on Wireless Body Area Network (WBAN).

- Different healthcare applications require different sets of QoS parameters. Identifying appropriate algorthms and protocols to deal with such diverse multi criteria requirements is an interesting research domain.
- Results of our research are mostly drawn from simulation studies. We all know that in real world, many of the assumptions implicitly present in simulation environment do not hold good, Thus, it is very important to carry out the experimental setup and validate the performance in a real test bed.
- Our research area is mostly confined within Tier 1 communication of WBAN architecture. This proposal can be further extended and analysed for the entire WBAN orientation.
- Incorporating security in the Healthcare sector to ensure the privacy of a patient is an important open research area with respect to this work. of MAC and routing protocols which could address this diverse
- Fault detection and their prevention should become an integral parts of WBAN algorithms. Incorporating these features with limited energy resource in WBAN topology is still a challenge and fascinating future research.

Bibliography

[1] A Fatih Demir et al. "Numerical characterization of in vivo wireless communication channels". In: *2014 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-Bio2014)*. IEEE. 2014, pp. 1–3.

[2] Ali Fatih Demir et al. "Anatomical region-specific in vivo wireless communication channel characterization". In: *IEEE journal of biomedical and health informatics* 21.5 (2016), pp. 1254–1262.

[3] *understanding healthcare access in india*. 2013. URL: http://docshare04.docshare.tips/files/25555/255552955.pdf.

[4] *Nejm Group*. URL: https://catalyst.nejm.org/about/journal.

[5] Sriyanjana Adhikary, Sankhayan Choudhury, and Samiran Chattopadhyay. "A new routing protocol for WBAN to enhance energy consumption and network lifetime". In: *Proceedings of the 17th international conference on distributed computing and networking*. 2016, pp. 1–6.

[6] Sriyanjana Adhikary, Biswajit Ghosh, and Sankhayan Choudhury. "QoS Enhancement in WBAN with Twin Coordinators". In: *Advanced Computing and Systems for Security*. Springer, 2021, pp. 85–97.

[7] Sriyanjana Adhikary, Samiran Chattopadhyay, and Sankhayan Choudhury. "A Novel bio-inspired algorithm for increasing throughput in wireless body area network (WBAN) by mitigating inter-wban interference". In: *Advanced Computing and Systems for Security*. Springer, 2018, pp. 21–37.

[8] Sriyanjana Adhikary et al. "Reliable routing in Wireless Body Area Network using optimum number of relay nodes for enhancing network lifetime". In: *Journal of Ambient Intelligence and Smart Environments* Preprint (2022), pp. 1–19.

[9] Sriyanjana Adhikary and Sankhayan Choudhury. "Mitigate Inter-WBAN Interference in Body-to-Body Network to Restrain Epidemic Spread". In: *SN Computer Science* 4.1 (2023), pp. 1–11.

[10] Sana Ullah et al. "A comprehensive survey of wireless body area networks". In: *Journal of medical systems* 36.3 (2012), pp. 1065–1094.

[11] David Arney et al. "Biomedical devices and systems security". In: *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*. IEEE. 2011, pp. 2376–2379.

[12] Hadda Ben Elhadj, Lamia Chaari, and Lotfi Kamoun. "A survey of routing protocols in wireless body area networks for healthcare applications". In: *International Journal of E-Health and Medical Communications (IJEHMC)* 3.2 (2012), pp. 1–18.

[13] Fei Jiang et al. “Artificial intelligence in healthcare: past, present and future”. In: *Stroke and vascular neurology* 2.4 (2017).

[14] Samaneh Movassaghi, Mehran Abolhasan, and Justin Lipman. “A review of routing protocols in wireless body area networks”. In: *Journal of Networks* (2013).

[15] Nawel Yessad et al. “QoS-based routing in Wireless Body Area Networks: A survey and taxonomy”. In: *Computing* 100.3 (2018), pp. 245–275.

[16] Javed Iqbal Bangash et al. “A survey of routing protocols in wireless body sensor networks”. In: *Sensors* 14.1 (2014), pp. 1322–1357.

[17] Christian Henry Wijaya Oey and Sangman Moh. “A survey on temperature-aware routing protocols in wireless body sensor networks”. In: *Sensors* 13.8 (2013), pp. 9860–9877.

[18] Faisal Jamil et al. “Adaptive thermal-aware routing protocol for wireless body area network”. In: *Electronics* 8.1 (2019), p. 47.

[19] Cheng Guo, R Venkatesha Prasad, and Martin Jacobsson. “Packet forwarding with minimum energy consumption in body area sensor networks”. In: *2010 7th IEEE Consumer Communications and Networking Conference*. IEEE. 2010, pp. 1–6.

[20] Mohamed Maalej, Sofiane Cherif, and Hichem Besbes. “QoS and energy aware cooperative routing protocol for wildfire monitoring wireless sensor networks”. In: *The Scientific World Journal* 2013 (2013).

[21] Amal Sammoud et al. “A new biometrics-based key establishment protocol in WBAN: Energy efficiency and security robustness analysis”. In: *Computers & Security* 96 (2020), p. 101838.

[22] Indrajit Pandey, Himadri Sekhar Dutta, and Jyoti Sekhar Banerjee. “WBAN: a smart approach to next generation e-healthcare system”. In: *2019 3rd International Conference on Computing Methodologies and Communication (ICCMC)*. IEEE. 2019, pp. 344–349.

[23] Mubarak Umar, Zhenqiang Wu, and Xuening Liao. “Mutual authentication in body area networks using signal propagation characteristics”. In: *IEEE Access* 8 (2020), pp. 66411–66422.

[24] Mohammad Abdur Razzaque, Muta Tah Hira, and Mukta Dira. “QoS in body area networks: A survey”. In: *ACM Transactions on Sensor Networks (TOSN)* 13.3 (2017), pp. 1–46.

[25] Kyung Sup Kwak, Sana Ullah, and Niamat Ullah. “An overview of IEEE 802.15. 6 standard”. In: *2010 3rd international symposium on applied sciences in biomedical and communication technologies (ISABEL 2010)*. IEEE. 2010, pp. 1–6.

[26] Arthur W Astrin, Huan-Bang Li, and Ryuji Kohno. “Standardization for body area networks”. In: *IEICE transactions on communications* 92.2 (2009), pp. 366–372.

[27] Miaoxin Li and Mingjie Zhuang. "An overview of physical layers on wireless body area network". In: *Anti-counterfeiting, Security, and Identification* (2012), pp. 1–5.

[28] Sana Ullah et al. "A study of MAC protocols for WBANs". In: *Sensors* 10.1 (2009), pp. 128–145.

[29] Fasee Ullah et al. "Medium access control (MAC) for wireless body area network (WBAN): superframe structure, multiple access technique, taxonomy, and challenges". In: *Human-centric Computing and Information Sciences* 7.1 (2017), pp. 1–39.

[30] Khaled A Ali, Jahangir H Sarker, and Hussein T Mouftah. "Urgency-based MAC protocol for wireless sensor body area networks". In: *2010 IEEE international conference on communications workshops*. IEEE. 2010, pp. 1–6.

[31] Hadda Ben Elhadj, Saadi Boudjit, and Lamia Chaari Fourati. "A cross-layer based data dissemination algorithm for IEEE 802.15. 6 WBANs". In: *2013 International Conference on Smart Communications in Network Technologies (SaCoNeT)*. Vol. 1. IEEE. 2013, pp. 1–6.

[32] Begonya Otal, Luis Alonso, and Christos Verikoukis. "Highly reliable energy-saving MAC for wireless body sensor networks in healthcare systems". In: *IEEE Journal on Selected Areas in Communications* 27.4 (2009), pp. 553–565.

[33] Jing Liu et al. "A novel energy efficient MAC protocol for wireless body area network". In: *China Communications* 12.2 (2015), pp. 11–20.

[34] ZA Khan et al. "Effect of packet inter-arrival time on the energy consumption of beacon enabled MAC protocol for body area networks". In: *Procedia Computer Science* 32 (2014), pp. 579–586.

[35] Sara Zafar Jafarzadeh and Mohammad Hossein Yaghmaee Moghaddam. "Design of energy-aware QoS routing algorithm in wireless sensor networks using reinforcement learning". In: *2014 4th International Conference on Computer and Knowledge Engineering (ICCKE)*. IEEE. 2014, pp. 722–727.

[36] Djamel Djenouri and Ilangko Balasingham. "LOCALMOR: Localized multi-objective routing for wireless sensor networks". In: *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*. IEEE. 2009, pp. 1188–1192.

[37] Md Abdur Razzaque, Choong Seon Hong, and Sungwon Lee. "Data-centric multi-objective QoS-aware routing protocol for body sensor networks". In: *Sensors* 11.1 (2011), pp. 917–937.

[38] Zahoor A Khan et al. "QPrd: QoS-aware peering routing protocol for delay-sensitive data in hospital body area network". In: *Mobile Information Systems* 2015 (2015).

[39] Zahoor Khan et al. "Energy-aware peering routing protocol for indoor hospital body area network communication". In: *Procedia Computer Science* 10 (2012), pp. 188–196.

[40] O Rehman et al. "A survey on indoor localization techniques in wireless body area sensor networks". In: *J. Basic. Appl. Sci. Res* 3.6 (2013), pp. 14–23.

[41] Sana Ullah et al. “A study of MAC protocols for WBANs”. In: *Sensors* 10.1 (2010), pp. 128–145.

[42] Nick F Timmons and William G Scanlon. “An adaptive energy efficient MAC protocol for the medical body area network”. In: *2009 1st international conference on wireless communication, vehicular technology, information theory and aerospace & electronic systems technology*. IEEE. 2009, pp. 587–593.

[43] Okundu Omeni et al. “Energy efficient medium access protocol for wireless medical body area sensor networks”. In: *IEEE Transactions on biomedical circuits and systems* 2.4 (2008), pp. 251–259.

[44] Stevan Jovica Marinkovic et al. “Energy-efficient low duty cycle MAC protocol for wireless body area networks”. In: *IEEE Transactions on Information Technology in Biomedicine* 13.6 (2009), pp. 915–925.

[45] Gengfa Fang and Eryk Dutkiewicz. “BodyMAC: Energy efficient TDMA-based MAC protocol for wireless body area networks”. In: *2009 9th international symposium on communications and information technology*. IEEE. 2009, pp. 1455–1459.

[46] Gill R Tsouri, Adrian Sapio, and Jeff Wilczewski. “An investigation into relaying of creeping waves for reliable low-power body sensor networking”. In: *IEEE transactions on biomedical circuits and systems* 5.4 (2011), pp. 307–319.

[47] Adrian Sapio and Gill R Tsouri. “Low-power body sensor network for wireless ecg based on relaying of creeping waves at 2.4 ghz”. In: *2010 International Conference on Body Sensor Networks*. IEEE. 2010, pp. 167–173.

[48] Muhannad Quwaider and Subir Biswas. “Probabilistic routing in on-body sensor networks with postural disconnections”. In: *Proceedings of the 7th ACM international symposium on Mobility management and wireless access*. 2009, pp. 149–158.

[49] Dr.K.Suriyakrishnaan and D. Sridharan. “A REVIEW OF RELIABLE AND SECURE COMMUNICATION IN WIRELESS BODY AREA NETWORKS”. In: 2014.

[50] Anirban Bag and Mostafa A Bassiouni. “Biocomm–A cross-layer medium access control (MAC) and routing protocol co-design for biomedical sensor networks”. In: *International Journal of Parallel, Emergent and Distributed Systems* 24.1 (2009), pp. 85–103.

[51] Benoit Latre et al. “A low-delay protocol for multishop wireless body area networks”. In: *Mobile and Ubiquitous Systems: Fourth Annual International Conference on Networking & Services 2007, Philadelphia, Pennsylvania, USA*. 2007, pp. 479–486.

[52] Bart Braem et al. “The wireless autonomous spanning tree protocol for multihop wireless body area networks”. In: *2006 Third Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services*. IEEE. 2006, pp. 1–8.

[53] Turki Ali Alghamdi. “Cluster based energy efficient routing protocol for wireless body area networks”. In: *Trends in Applied Sciences Research* 11.1 (2016), p. 12.

[54] Thomas Watteyne et al. "AnyBody: a self-organization protocol for body area networks." In: *BODYNETS*. 2007, p. 6.

[55] Zahid Ullah et al. "Robust and efficient energy harvested-aware routing protocol with clustering approach in body area networks". In: *IEEE Access* 7 (2019), pp. 33906–33921.

[56] Muhammad Anwar et al. "Green communication for wireless body area networks: energy aware link efficient routing approach". In: *Sensors* 18.10 (2018), p. 3237.

[57] S Ahmed et al. "Co-LAEEBA: Cooperative link aware and energy efficient protocol for wireless body area networks". In: *Computers in Human Behavior* 51 (2015), pp. 1205–1215.

[58] Aarti Sangwan and Partha Pratim Bhattacharya. "Revised EECBSR for Energy Efficient and Reliable Routing in WBAN." In: *Majlesi Journal of Telecommunication Devices* 7.2 (2018).

[59] Gengfa Fang et al. "Distributed inter-network interference coordination for wireless body area networks". In: *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE*. IEEE. 2010, pp. 1–5.

[60] Ramtin Kazemi, Rein Vesilo, and Eryk Dutkiewicz. "A novel genetic-fuzzy power controller with feedback for interference mitigation in wireless body area networks". In: *2011 IEEE 73rd vehicular technology conference (VTC Spring)*. IEEE. 2011, pp. 1–5.

[61] Ramtin Kazemi et al. "Reinforcement learning in power control games for internetwork interference mitigation in Wireless Body Area Networks". In: *Communications and Information Technologies (ISCIT), 2012 International Symposium on*. IEEE. 2012, pp. 256–262.

[62] Huankai Chen et al. "User-priority guided Min-Min scheduling algorithm for load balancing in cloud computing". In: *2013 National Conference on Parallel computing technologies (PARCOMPTECH)*. IEEE. 2013, pp. 1–8.

[63] Lei Zou et al. "Bayesian game based power control scheme for inter-WBAN interference mitigation". In: *2014 IEEE global communications conference*. IEEE. 2014, pp. 240–245.

[64] Ramtin Kazemi et al. "Inter-network interference mitigation in wireless body area networks using power control games". In: *Communications and Information Technologies (ISCIT), 2010 International Symposium on*. IEEE. 2010, pp. 81–86.

[65] Amira Meharouech et al. "A game theoretical approach for interference mitigation in body-to-body networks". In: *2015 IEEE international conference on communication workshop (ICCW)*. IEEE. 2015, pp. 259–264.

[66] Amira Meharouech, Jocelyne Elias, and Ahmed Mehaoua. "A two-stage game theoretical approach for interference mitigation in Body-to-Body Networks". In: *Computer Networks* 95 (2016), pp. 15–34.

[67] Hyosun Hwang and Nak Myeong Kim. "An enhanced frame transmission method for medical devices with ultra low power operation". In: *IEEE Transactions on Consumer Electronics* 58.1 (2012), pp. 154–160.

[68] Guan-Tsang Chen, Wen-Tsuen Chen, and Shan-Hsiang Shen. "2L-MAC: A MAC protocol with two-layer interference mitigation in wireless body area networks for medical applications". In: *2014 IEEE international conference on communications (ICC)*. IEEE. 2014, pp. 3523–3528.

[69] Jiangshuai Huang et al. "Adaptive finite-time consensus control of a group of uncertain nonlinear mechanical systems". In: *Automatica* 51 (2015), pp. 292–301.

[70] Anagha Jamthe, Amitabh Mishra, and Dharma P Agrawal. "Scheduling schemes for interference suppression in healthcare sensor networks". In: *2014 IEEE international conference on communications (ICC)*. IEEE. 2014, pp. 391–396.

[71] Seungku Kim and Byung Kwon Song. "A prioritized resource allocation algorithm for multiple wireless body area networks". In: *Wireless Networks* 23.3 (2017), pp. 727–735.

[72] Judhistir Mahapatro et al. "Interference mitigation between WBAN equipped patients". In: *2012 Ninth International Conference on Wireless and Optical Communications Networks (WOCN)*. IEEE. 2012, pp. 1–5.

[73] Samaneh Movassaghi et al. "Aim: Adaptive internetwork interference mitigation amongst co-existing wireless body area networks". In: *2014 IEEE global communications conference*. IEEE. 2014, pp. 2460–2465.

[74] Samaneh Movassaghi, Mehran Abolhasan, and David Smith. "Smart spectrum allocation for interference mitigation in wireless body area networks". In: *2014 IEEE international conference on communications (ICC)*. IEEE. 2014, pp. 5688–5693.

[75] Mohammad N Deylami and Emil Jovanov. "A distributed scheme to manage the dynamic coexistence of IEEE 802.15. 4-based health-monitoring WBANs". In: *IEEE journal of biomedical and health informatics* 18.1 (2013), pp. 327–334.

[76] Zilong Jin et al. "A prediction algorithm for coexistence problem in Multiple-WBAN environment". In: *International Journal of Distributed Sensor Networks* 2015 (2015), p. 7.

[77] Ming Li et al. "Throughput optimization with fairness consideration for coexisting WBANs". In: *2015 IEEE international conference on communications (ICC)*. IEEE. 2015, pp. 6418–6423.

[78] BeomSeok Kim and Seokhoon Kim. "An AHP-based interface and channel selection for multi-channel MAC protocol in IoT ecosystem". In: *Wireless Personal Communications* 93.1 (2017), pp. 97–118.

[79] Changle Li et al. "MC-MAC: a multi-channel based MAC scheme for interference mitigation in WBANs". In: *Wireless Networks* 24.3 (2018), pp. 719–733.

[80] Roy C Park, Hoill Jung, and Sun-Moon Jo. "ABS scheduling technique for interference mitigation of M2M based medical WBAN service". In: *Wireless personal communications* 79.4 (2014), pp. 2685–2700.

[81] Junchao Han et al. "HCVP: A hybrid cognitive validation platform for WBAN". In: *2012 International Conference on Wireless Communications and Signal Processing (WCSP)*. IEEE. 2012, pp. 1–6.

[82] Qiang Shen et al. "Adaptive cognitive enhanced platform for WBAN". In: *2013 IEEE/-CIC International Conference on Communications in China (ICCC)*. IEEE. 2013, pp. 739–744.

[83] Dramane Ouattara et al. "Mitigating the hospital area communication's interference using Cognitive Radio Networks". In: *2013 IEEE 15th international conference on e-Health networking, applications and services (Healthcom 2013)*. IEEE. 2013, pp. 324–328.

[84] Stevan J Marinkovic and Emanuel M Popovici. "Nano-power wireless wake-up receiver with serial peripheral interface". In: *IEEE Journal on selected areas in communications* 29.8 (2011), pp. 1641–1647.

[85] Nhat-Quang Nhan, Matthieu Gautier, and Olivier Berder. "Asynchronous MAC protocol for spectrum agility in wireless body area sensor networks". In: *2014 9th International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*. IEEE. 2014, pp. 203–208.

[86] Ian F Akyildiz et al. "A survey on sensor networks". In: *Communications magazine, IEEE* 40.8 (2002), pp. 102–114.

[87] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan. "Energy-efficient communication protocol for wireless microsensor networks". In: *System sciences, 2000. Proceedings of the 33rd annual Hawaii international conference on.* IEEE. 2000, 10–pp.

[88] Sebastian Ramirez Denault. "Evaluation of smart-fabric approach to biomechanical energy harvesting". PhD thesis. Massachusetts Institute of Technology, 2014.

[89] Ashraf Darwish and Aboul Ella Hassanien. "Wearable and implantable wireless sensor network solutions for healthcare monitoring". In: *Sensors* 11.6 (2011), pp. 5561–5595.

[90] Selva Ganesh Elangovan. "Verification and Performance Analysis of Time Base Coded Data Protocol". PhD thesis. Concordia University, 2012.

[91] IEEE 802.16 Working Group et al. "IEEE standard for local and metropolitan area networks-Part 16: Air interface for fixed broad-band wireless access systems". In: *IEEE Std. 802.16-2004* (2004).

[92] Nadeem Javaid et al. "M-ATTEMPT: A new energy-efficient routing protocol for wireless body area sensor networks". In: *Procedia Computer Science* 19 (2013), pp. 224–231.

[93] Fazl e Hadi and Abid Ali Minhas. “EAA: ENERGY AWARE ANYCAST ROUTING IN WIRELESS SENSOR NETWORKS”. In: *JOURNAL OF ENGINEERING AND APPLIED SCIENCES* 30.1 (2011).

[94] S Yousaf et al. “Incremental relay-based co-cestat protocol for wireless body area networks”. In: *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2014 Ninth International Conference on.* IEEE. 2014, pp. 113–119.

[95] Anum Tauqir et al. “Distance aware relaying energy-efficient: Dare to monitor patients in multi-hop body area sensor networks”. In: *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2013 Eighth International Conference on.* IEEE. 2013, pp. 206–213.

[96] Q Nadeem et al. “Simple: Stable increased-throughput multi-hop protocol for link efficiency in wireless body area networks”. In: *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2013 Eighth International Conference on.* IEEE. 2013, pp. 221–226.

[97] S Akram et al. “The-fame: Threshold based energy-efficient fatigue measurement for wireless body area sensor networks using multiple sinks”. In: *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2013 Eighth International Conference on.* IEEE. 2013, pp. 214–220.

[98] Muhammad Rahim Baig et al. “Anycasting in dual sink approach (acids) for wbasns”. In: *International Journal of Advanced Computer Science and Applications* 8.3 (2017).

[99] Elisabeth Reusens et al. “Characterization of on-body communication channel and energy efficient topology design for wireless body area networks”. In: *IEEE Transactions on Information Technology in Biomedicine* 13.6 (2009), pp. 933–945.

[100] Jocelyne Elias and Ahmed Mehaoua. “Energy-aware topology design for wireless body area networks”. In: *Communications (ICC), 2012 IEEE International Conference on.* IEEE. 2012, pp. 3409–3410.

[101] Jocelyne Elias et al. “A reliable design of wireless body area networks”. In: *Global Communications Conference (GLOBECOM), 2013 IEEE.* IEEE. 2013, pp. 2742–2748.

[102] Anirudh Natarajan et al. “To hop or not to hop: Network architecture for body sensor networks”. In: *Sensor, Mesh and Ad Hoc Communications and Networks, 2009. SECON’09. 6th Annual IEEE Communications Society Conference on.* IEEE. 2009, pp. 1–9.

[103] Anirudh Natarajan et al. “Link layer behavior of body area networks at 2.4 GHz”. In: *Proceedings of the 15th annual international conference on Mobile computing and networking.* ACM. 2009, pp. 241–252.

[104] Raffaele D’Errico, Ramona Rosini, and Mickael Maman. “A performance evaluation of cooperative schemes for on-body area networks based on measured time-variant channels”. In: *Communications (ICC), 2011 IEEE International Conference on.* IEEE. 2011, pp. 1–5.

[105] Elyes Ben Hamida, Raffaele D'Errico, and Benoit Denis. "Topology dynamics and network architecture performance in wireless body sensor networks". In: *New Technologies, Mobility and Security (NTMS), 2011 4th IFIP International Conference on*. IEEE. 2011, pp. 1–6.

[106] Humaid S Alshamsi, Hessa S Al-Shamisi, and Hongying Mengi. "Traffic Modeling of Wireless Body Area Network". In: ().

[107] Anil K Jacob and Lillykutty Jacob. "Energy efficient MAC for QoS traffic in wireless body area network". In: *International Journal of Distributed Sensor Networks* 11.2 (2015), p. 404182.

[108] Yang Zhou et al. "Topology design and cross-layer optimization for wireless body sensor networks". In: *Ad Hoc Networks* 59 (2017), pp. 48–62.

[109] *Castalia*. `https://omnetpp.org/download-items/Castalia.html`. Accessed: 2006.

[110] Wen-Bin Yang and Kamran Sayrafian-Pour. "Interference mitigation for body area networks". In: *2011 IEEE 22nd international symposium on personal, indoor and mobile radio communications*. IEEE. 2011, pp. 2193–2197.

[111] Shih Heng Cheng and Ching Yao Huang. "Coloring-based inter-WBAN scheduling for mobile wireless body area networks". In: *IEEE Transactions on parallel and distributed systems* 24.2 (2012), pp. 250–259.

[112] Ruben de Francisco, Li Huang, and Guido Dolmans. "Coexistence of WBAN and WLAN in medical environments". In: *2009 IEEE 70th vehicular technology conference fall*. IEEE. 2009, pp. 1–5.

[113] Xuan Wang and Lin Cai. "Interference analysis of co-existing wireless body area networks". In: *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*. IEEE. 2011, pp. 1–5.

[114] Andrew Zhang et al. "Performance of piconet co-existence schemes in wireless body area networks". In: *2010 IEEE Wireless Communication and Networking Conference*. IEEE. 2010, pp. 1–6.

[115] Lukasz Januszkiewicz. "Simplified human body models for interference analysis in the cognitive radio for medical body area networks". In: *2014 8th International Symposium on Medical Information and Communication Technology (ISMICT)*. IEEE. 2014, pp. 1–5.

[116] Omer Aziz et al. *Body sensor network*. 2011.

[117] Zhaoyang Zhang et al. "Interference mitigation for cyber-physical wireless body area network system using social networks". In: *Emerging Topics in Computing, IEEE Transactions on* 1.1 (2013), pp. 121–132.

[118] Emmanouil G Spanakis et al. "Cross layer interference management in wireless biomedical networks". In: *Entropy* 16.4 (2014), pp. 2085–2104.

[119] Eui-Jik Kim et al. "Asynchronous inter-network interference avoidance for wireless body area networks". In: *The Journal of Supercomputing* 65.2 (2013), pp. 562–579.

[120] Tomohiro Fukuya and Ryuji Kohno. "QoS-aware superframe management scheme based on IEEE 802.15. 6". In: *2016 10th International Symposium on Medical Information and Communication Technology (ISMICT)*. IEEE. 2016, pp. 1–4.

[121] Zhijun Xie et al. "A clique-based WBAN scheduling for mobile wireless body area networks". In: *Procedia computer science* 31 (2014), pp. 1092–1101.

[122] Loren Schwiebert, Sandeep KS Gupta, and Jennifer Weinmann. "Research challenges in wireless networks of biomedical sensors". In: *Proceedings of the 7th annual international conference on Mobile computing and networking*. ACM. 2001, pp. 151–165.

[123] Loren Schwiebert et al. "A biomedical smart sensor for the visually impaired". In: *Sensors, 2002. Proceedings of IEEE*. Vol. 1. IEEE. 2002, pp. 693–698.

[124] Cynthia Furse et al. "An implantable antenna for communication with implantable medical devices". In: *Proceedings of the IEEE Antennas and Propagation/URSI International Symposium*. 1999.

[125] Cynthia Furse et al. "A biocompatible antenna for communication with implantable medical devices". In: *Proceedings of the IEEE International Symposium on Antennas and Propagation*. 2002.

[126] Riccardo Cavallari et al. "A survey on wireless body area networks: Technologies and design challenges". In: *IEEE Communications Surveys & Tutorials* 16.3 (2014), pp. 1635–1657.

[127] Ian F Akyildiz, Tommaso Melodia, and Kaushik R Chowdhury. "A survey on wireless multimedia sensor networks". In: *Computer networks* 51.4 (2007), pp. 921–960.

[128] Khaled A Ali and Hussein T Mouftah. "Wireless personal area networks architecture and protocols for multimedia applications". In: *Ad Hoc Networks* 9.4 (2011), pp. 675–686.

[129] Min Chen et al. "Body area networks: A survey". In: *Mobile networks and applications* 16.2 (2011), pp. 171–193.

[130] Huasong Cao et al. "Enabling technologies for wireless body area networks: A survey and outlook". In: *IEEE Communications Magazine* 47.12 (2009), pp. 84–93.

[131] Tin-Yu Wu and Cheng-Han Lin. "Low-SAR Path Discovery by Particle Swarm Optimization Algorithm in Wireless Body Area Networks". In: *Sensors Journal, IEEE* 15.2 (2015), pp. 928–936.

[132] Yating Qu et al. "An Energy-Efficient Routing Protocol for Reliable Data Transmission in Wireless Body Area Networks". In: *Sensors* 19.19 (2019), p. 4238.

[133] Hassine Moungla et al. "Cost-effective reliability-and energy-based intra-wban interference mitigation". In: *Global Communications Conference (GLOBECOM), 2014 IEEE*. IEEE. 2014, pp. 2399–2404.

[134] Ali Raza Bhangwar et al. "Trust and Thermal Aware Routing Protocol (TTRP) for Wireless Body Area Networks". In: *Wireless Personal Communications* 97.1 (2017), pp. 349–364.

[135] `https://en.wikipedia.org/wiki/mixed-integer-programming/`.

[136] Deepak Ganesan et al. "Highly-resilient, energy-efficient multipath routing in wireless sensor networks". In: *ACM SIGMOBILE Mobile Computing and Communications Review* 5.4 (2001), pp. 11–25.

[137] Matthew Ettus. "System capacity, latency, and power consumption in multihop-routed SS-CDMA wireless networks". In: *Radio and Wireless Conference, 1998. RAWCON 98. 1998 IEEE*. IEEE. 1998, pp. 55–58.

[138] X Lin and I Stojmenovic. "Power-aware routing in ad hoc wireless networks". In: *SITE, University of Ottawa, TR-98* 11 (1998).

[139] Jocelyne Elias. "Optimal design of energy-efficient and cost-effective wireless body area networks". In: *Ad Hoc Networks* 13 (2014), pp. 560–574.

[140] Ansar Munir Shah et al. "ehealth wban: Energy-efficient and priority-based enhanced ieee802. 15.6 csma/ca mac protocol". In: *International Journal Of Advanced Computer Science and Applications* 9.4 (2018).

[141] M Geetha and R Ganesan. "CEPRAN-Cooperative Energy Efficient and Priority Based Reliable Routing Protocol with Network Coding for WBAN". In: *Wireless Personal Communications* (2020), pp. 1–19.

[142] Dion Paul, Hongmei Chi, and Clement Allen. "GPU-based simulation of wireless body area network". In: *Proceedings of the 8th International Conference on Body Area Networks*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering). 2013, pp. 244–247.

[143] Qinghui Tang et al. "TARA: thermal-aware routing algorithm for implanted sensor networks". In: *International conference on distributed computing in sensor systems*. Springer. 2005, pp. 206–217.

[144] Anirban Bag and Mostafa A Bassiouni. "Energy efficient thermal aware routing algorithms for embedded biomedical sensor networks". In: *Mobile Adhoc and Sensor Systems (MASS), 2006 IEEE International Conference on*. IEEE. 2006, pp. 604–609.

[145] Sana Ullah et al. "Numerical analysis of CSMA/CA for pattern-based WBAN system". In: *Biomedical Engineering and Informatics, 2009. BMEI'09. 2nd International Conference on*. IEEE. 2009, pp. 1–3.

[146] Bin Zhen, Huan-Bang Li, and Ryuji Kohno. "IEEE body area networks and medical implant communications". In: *Proceedings of the ICST 3rd international conference on Body area networks*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering). 2008, p. 26.

[147] B Banuselvasaraswathy and Vimalathithan Rathinasabapathy. “Self-heat controlling energy efficient OPOT routing protocol for WBAN”. In: *Wireless Networks* (2020), pp. 1–12.

[148] Muhannad Quwaider, Jayanthi Rao, and Subir Biswas. “Transmission power assignment with postural position inference for on-body wireless communication links”. In: *ACM Transactions on Embedded Computing Systems (TECS)* 10.1 (2010), p. 14.

[149] Paolo Barsocchi. “Position recognition to support bedsores prevention”. In: *IEEE journal of biomedical and health informatics* 17.1 (2012), pp. 53–59.

[150] Ghufran Ahmed, Danish Mahmood, and Saiful Islam. “Thermal and energy aware routing in wireless body area networks”. In: *International Journal of Distributed Sensor Networks* 15.6 (2019), p. 1550147719854974.

[151] Philippe Jacquet and Laurent Viennot. “Overhead in mobile ad-hoc network protocols”. In: (2000).

[152] K.S. Deepak and A.V. Babu. “Packet size optimization for energy efficient cooperative Wireless Body Area Networks”. In: *Annual IEEE India Conference (INDICON), 2012 IEEE*. IEEE. 2012, pp. 1–6.

[153] KS Deepak and AV Babu. “Packet size optimization for energy efficient cooperative wireless body area networks”. In: *India Conference (INDICON), 2012 Annual IEEE*. IEEE. 2012, pp. 736–741.

[154] Kamya Yekeh Yazdandoost. “Channel model for body area network (BAN)”. In: *IEEE802. 15-07-0943-00-0ban* (2007).

[155] KS Deepak and Anchare V Babu. “Enhancing reliability of IEEE 802.15. 6 wireless body area networks in scheduled access mode and error prone channels”. In: *Wireless Personal Communications* 89.1 (2016), pp. 93–118.

[156] Xigang Huang, Hangguan Shan, and Xuemin Shen. “On energy efficiency of cooperative communications in wireless body area network”. In: *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*. IEEE. 2011, pp. 1097–1101.

[157] Anis Koubaa, Mário Alves, and Eduardo Tovar. “A comprehensive simulation study of slotted CSMA/CA for IEEE 802.15. 4 wireless sensor networks”. In: *Factory Communication Systems, 2006 IEEE International Workshop on*. IEEE. 2006, pp. 183–192.

[158] Jianliang Zheng and Myung J Lee. “A comprehensive performance study of IEEE 802.15. 4”. In: *Sensor network operations* 4 (2006), pp. 218–237.

[159] Vladimir M Vishnevsky et al. “Study of beaconing in multihop wireless PAN with distributed control”. In: *IEEE Transactions on Mobile Computing* 7.1 (2008), pp. 113–126.

[160] Tallat Jabeen, Humaira Ashraf, and Ata Ullah. “A survey on healthcare data security in wireless body area networks”. In: *Journal of ambient intelligence and humanized computing* 12.10 (2021), pp. 9841–9854.

[161] Qingling Liu et al. "A simple cross-layer mechanism for congestion control and performance enhancement in a localized multiple wireless body area networks". In: *Journal of Ambient Intelligence and Humanized Computing* (2021), pp. 1–18.

[162] Naveen Bilandi, Harsh K Verma, and Renu Dhir. "An intelligent and energy-efficient wireless body area network to control coronavirus outbreak". In: *Arabian Journal for Science and Engineering* 46.9 (2021), pp. 8203–8222.

[163] Raffaele Di Bari, Akram Alomainy, and Yang Hao. "Cooperative and low-power wireless sensor network for efficient body-centric communications in healthcare applications". In: *International Conference on Wireless Mobile Communication and Healthcare*. Springer. 2012, pp. 351–360.

[164] Dongjin Son, Bhaskar Krishnamachari, and John Heidemann. "Experimental study of the effects of transmission power control and blacklisting in wireless sensor networks". In: *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*. IEEE. 2004, pp. 289–298.

[165] Shan Lin et al. "ATPC: adaptive transmission power control for wireless sensor networks". In: *ACM Transactions on Sensor Networks (TOSN)* 12.1 (2016), p. 6.

[166] Shuo Xiao et al. "Transmission power control in body area sensor networks for healthcare monitoring". In: *IEEE Journal on Selected Areas in Communications* 27.1 (2009), pp. 37–48.

[167] Aida Ehyaie, Massoud Hashemi, and Pejman Khadivi. "Using relay network to increase life time in wireless body area sensor networks". In: *World of Wireless, Mobile and Multimedia Networks & Workshops, 2009. WoWMoM 2009. IEEE International Symposium on a*. IEEE. 2009, pp. 1–6.

[168] Xiaohui Liang et al. "Exploiting prediction to enable secure and reliable routing in wireless body area networks". In: *INFOCOM, 2012 Proceedings IEEE*. IEEE. 2012, pp. 388–396.

[169] Qi Zhang et al. "Reactive virtual coordinate routing protocol for body sensor networks". In: *Communications (ICC), 2012 IEEE International Conference on*. IEEE. 2012, pp. 3388–3393.

[170] Liheng Wang et al. "Wireless information and power transfer to maximize information throughput in WBAN". In: *IEEE Internet of Things Journal* 4.5 (2017), pp. 1663–1670.

[171] W Suwansin et al. "Analysis of heat transfer and specific absorption rate of electromagnetic field in human body at 915 MHz and 2.45 GHz with 3D finite element method". In: *The 5th 2012 Biomedical Engineering International Conference*. IEEE. 2012, pp. 1–4.

[172] Tommi Tuovinen et al. “On the evaluation of biological effects of wearable antennas on contact with dispersive medium in terms of SAR and bio-heat by using FIT technique”. In: *2013 7th International Symposium on Medical Information and Communication Technology (ISMICT)*. IEEE. 2013, pp. 149–153.

[173] Ghufran Ahmed et al. “Rigorous analysis and evaluation of specific absorption rate (SAR) for mobile multimedia healthcare”. In: *IEEE Access* 6 (2018), pp. 29602–29610.

[174] A Muthulakshmi and K Shyamala. “Efficient patient care through wireless body area networks—enhanced technique for handling emergency situations with better quality of service”. In: *Wireless Personal Communications* 95.4 (2017), pp. 3755–3769.

[175] Yuta Machida, Takahiko Yamamoto, and Kohji Koshiji. “A study on transmission characteristics and specific absorption rate using impedance-matched electrodes for various human body communication”. In: *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE. 2013, pp. 1883–1886.

[176] K Shashi Prabh et al. “BANMAC: an opportunistic MAC protocol for reliable communications in body area networks”. In: *2012 IEEE 8th International Conference on Distributed Computing in Sensor Systems*. IEEE. 2012, pp. 166–175.

[177] Jamshid Abouei et al. “Energy efficiency and reliability in wireless biomedical implant systems”. In: *IEEE Transactions on Information Technology in Biomedicine* 15.3 (2011), pp. 456–466.

[178] Chenfu Yi, Lili Wang, and Ye Li. “Energy efficient transmission approach for WBAN based on threshold distance”. In: *IEEE sensors journal* 15.9 (2015), pp. 5133–5141.

[179] Shuguang Cui, Andrea J Goldsmith, and Ahmad Bahai. “Energy-constrained modulation optimization”. In: *IEEE transactions on wireless communications* 4.5 (2005), pp. 2349–2360.

[180] C. Chakrabarti Y. Li B. Bakkaloglu. “A system level energy model and energy-quality evaluation for integrated transceiver front-ends”. In: *IEEE Trans. Very Large Scale Integr. (VLSI) Syst* 15.1 (2007), pp. 90–103.

[181] Working Group for Wireless Personal Area Networks (WPANs). *Channel Model for Body Area Network (BAN), IEEE P802.15*. IEEE Standard P802.15-08-0780-09-0006, 2009.

[182] A. Goldsmith. *Wireless Communications*. Cambridge, 2005.

[183] L.Jacob A.K.Jacob G.M.Kishore. “Lifetime and latency analysis of IEEE 802.15.6 WBAN with interrupted sleep mechanism”. In: *Sadhana – Academy Proceedings in Engineering Sciences* 42.6 (2017), pp. 865–878.

[184] Samiya M Shimly, David B Smith, and Samaneh Movassaghi. “Cross-layer designs for body-to-body networks: Adaptive CSMA/CA with distributed routing”. In: *2018 IEEE International Conference on Communications (ICC)*. IEEE. 2018, pp. 1–6.

[185] Zhaoyang Zhang et al. "Epidemic control based on fused body sensed and social network information". In: *2012 32nd International Conference on Distributed Computing Systems Workshops*. IEEE. 2012, pp. 285–290.

[186] Zhijun Xie et al. "An Optimal Backoff Time-Based Internetwork Interference Mitigation Method in Wireless Body Area Network". In: *Journal of Sensors* 2020 (2020).

[187] Zhaoyang Zhang et al. "Effective epidemic control and source tracing through mobile social sensing over WBANs". In: *2013 Proceedings IEEE INFOCOM*. IEEE. 2013, pp. 300–304.

[188] Aftab Ali and Farrukh Aslam Khan. "Energy-efficient cluster-based security mechanism for intra-WBAN and inter-WBAN communications for healthcare applications". In: *EURASIP Journal on Wireless Communications and Networking* 2013.1 (2013), pp. 1–19.

[189] Tigang Jiang, Honggang Wang, and Shaoen Wu. "Interference mitigation for wireless body area networks with fast convergent game". In: *GLOBECOM 2017-2017 IEEE Global Communications Conference*. IEEE. 2017, pp. 1–6.

[190] Bing Zhang and Yu Zhang. "An individual differentiated coexisting mechanism for multiple wireless body area networks based on game theory". In: *IEEE Access* 6 (2018), pp. 54564–54581.

[191] Emy Mariam George and Lillykutty Jacob. "Interference mitigation for coexisting wireless body area networks: Distributed learning solutions". In: *IEEE Access* 8 (2020), pp. 24209–24218.

[192] Shashidhar Gandham, Milind Dawande, and Ravi Prakash. "Link scheduling in wireless sensor networks: Distributed edge-coloring revisited". In: *Journal of Parallel and Distributed Computing* 68.8 (2008), pp. 1122–1134.

[193] Benedito JB Fonseca Jr. "An augmented graph-based coloring scheme to derive upper bounds for the performance of distributed schedulers in CSMA-based mbile ad hoc networks". In: *Proceedings of the 2006 international conference on Wireless communications and mobile computing*. 2006, pp. 761–766.

[194] Subramanian Ramanathan. "A unified framework and algorithm for channel assignment in wireless networks". In: *Wireless Networks* 5.2 (1999), pp. 81–94.

[195] Arwinder Dhillon and Ashima Singh. "Machine learning in healthcare data analysis: a survey". In: *Journal of Biology and Today's World* 8.6 (2019), pp. 1–10.

[196] Athanassios Boulis et al. "Castalia: A simulator for wireless sensor networks and body area networks". In: *NICTA: National ICT Australia* 83 (2011), p. 7.

[197] Varun G Menon, Joe Prathap Pathrose, and Jogi Priya. "Ensuring reliable communication in disaster recovery operations with reliable routing technique". In: *Mobile Information Systems* 2016 (2016).

[198] Brad Karp and Hsiang-Tsung Kung. "GPSR: Greedy perimeter stateless routing for wireless networks". In: *Proceedings of the 6th annual international conference on Mobile computing and networking*. 2000, pp. 243–254.

Sriyanjana Adhikary.

Samiran Chattopadhyay

PROFESSOR
Deptt. of Information Technology
JADAVPUR UNIVERSITY
Block - LB, Plot - 8, Sector - 3
Salt Lake, Kolkata - 700098, India

Sankhayan Choudhury

Professor
Department of Computer Science & Engineering
University of Calcutta