DESIGN AND ANALYSIS OF MULTI-CHANNEL WIRELESS BODY AREA NETWORK

A THESIS
SUBMITTED IN PARTIAL FULLILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

MASTER OF ELECTRONICS & TELECOMMUNICATION ENGINEERING

BY

ARINDAM RAY

Registration Number: 140692 of 2017-2018

Examination Roll Number: M4ETC19009

UNDER THE GUIDANCE OF

PROF. ITI SAHA MISRA

DEPARTMENT OF ELECTRONICS AND TELECOMMUNICATION ENGINEERING

JADAVPUR UNIVERSITY

KOLKATA – 700032

MAY 2019

FACULTY OF ENGINEERING AND TECHNOLOGY

JADAVPUR UNIVERSITY

CERTIFICATE OF RECOMMENDATION

This is to certify that the dissertation entitled **"Design and Analysis of Multi-Channel Wireless Body Area Network"** has been carried out by **Arindam Ray (University Registration Number: 140692 of 2017-2018)** under my guidance and supervision and be accepted in partial fulfillment of the requirements for the degree of master of Technology in Electronics and Telecommunication Engineering. The research results presented in the thesis have not been included in any other paper submitted for any degree to any other university or institute.

(Prof. Iti Saha Misra)
Supervisor
Department of Electronics and
Telecommunication Engineering
Jadavpur University
Kolkata - 700032

COUNTERSIGNED

(Prof. Sheli Sinha Chaudhuri)
Head of the Department
Department of Electronics and
Telecommunication Engineering
Jadavpur University
Kolkata - 700032

(Prof. Chiranjib Bhattacharjee)
Dean
Faculty of Engineering and Technology
Jadavpur University
Kolkata - 700032

FACULTY OF ENGINEERING AND TECHNOLOGY

JADAVPUR UNIVERSITY

DEPARTMENT OF ELECTRONICS AND TELECOMMUNICATION ENGINEERING

CERTIFICATE OF APPROVAL*

The foregoing thesis is hereby approved as an accreditable study of an engineering subject, carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval, the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it has been submitted.

Committee on final examination
for the evaluation of the Thesis

Signature of the Examiner

Signature of the Supervisor

*Only in case the thesis is approved.

FACULTY OF ENGINEERING AND TECHNOLOGY

JADAVPUR UNIVERSITY

DECLARATION OF
ORIGINALITY AND COMPLAINCE OF ACADEMIC THESIS

I hereby declare that this thesis titled **"Design and Analysis of Multi-Channel Wireless Body Area Network"** contains literature survey and original research work by the undersigned candidate, as part of his Degree of Master of Technology in Electronics and Telecommunication Engineering.

All information has been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

Name: **ARINDAM RAY**

Examination Roll Number: **M4ETC19009**

Thesis Title: **Design and Analysis of Multi-Channel Wireless Body Area Network**

____

Signature of the candidate

ACKNOWLEDGEMENT

I would like to express my sincere thanks to Prof. Iti Saha Misra for her valuable guidance, advice and supervision that have served as a pillar of strength throughout my entire postgraduate years. I am privileged to witness her enthusiastic and dedicated interest towards research that motivates me and enriches my personal growth, both as a student and a researcher. I am indebted to her for her extensive support – the innovative ideas and extraordinary experiences that she has shared with me have helped me tackle numerous problems easily, and I am sure, will continue to do so for a very long time.

I would like to extend my appreciation to my friends and seniors without whose support and contribution, this thesis would not have been possible. I convey my earnest thanks to Tanumoy Manna, Arijit Ghosh, Tanmoy Kundu, Sudipta Dey and Sreya Ghosh, for there generous contributions towards the completion of this thesis.

I must acknowledge the academic resources that were offered to me from Jadavpur University. I would like to sincerely thank the administrative and technical staff members of the department who have been kind enough to advise and help in their respective roles.

Last but definitely not the least, I remain ever grateful to my family who have selflessly devoted their lives towards the fulfillment of my dreams. I dedicate this thesis to them.

Place: Kolkata

Date:

(Arindam Ray)

Department of Electronics and Telecommunication Engineering

Jadavpur University

ABSTRACT

A Wireless Body Area Network (WBAN) is a network that integrates a number of physical devices that are placed at various positions on a human body with the objective of recording and interpreting the physical conditions that the body is exposed to, as well as its reaction to those conditions. The rapid advancement in the technology behind the development of sensors to capture minute details of the functioning of the human body has led to more and more data being generated from each of these physical devices. Moreover, the data generated is not linear in nature, but quite random and possesses varying parameters. Under such a scenario, it becomes essential to develop a strong backbone network that can handle and efficiently process the data that is generated from all of these devices. The said network needs to be robust and capable of handling non-linear data, while maintaining a high threshold for performance.

The goal of this thesis is to design and analyze the performance of a multi-channel WBAN in terms of various network parameters like delay and packet error rates. Towards this objective, a model for the aforementioned multi-channel WBAN has been first proposed. Several parameters for the designed model have then been optimized using classical optimization techniques like KKT with the hope of obtaining better network performance; there are even provisions to tweak the network based on the use case. Simulations have been run based on those parameters and it has been seen in the end results that the proposed solution does work as expected.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction to Wireless Body Area Network

A Wireless Body Area Network (WBAN) connects independent devices or nodes (e.g. sensors and actuators) that are situated in the clothes, on the body or under the skin of a person. The network typically expands over the whole human body and the nodes are connected through a wireless communication media. However, each of these nodes are physically independent of each other, which means that they have their own power sources and transmitter and receiver systems.

A WBAN offers many promising new applications in the area of remote health monitoring, home/health care, medicine, multimedia, sports and many other, all of which make advantage of the unconstrained freedom of movement a WBAN offers. In the medical field, for example, a patient can be equipped with a wireless body area network consisting of sensors that constantly measure specific biological functions, such as temperature, blood pressure, heart rate, electrocardiogram (ECG), respiration, etc. The advantage is that the patient doesn't have to stay in bed, but can move freely across the room and even leave the hospital for a while. This improves the quality of life for the patient and reduces hospital costs. In addition, data collected over a longer period and in the natural environment of the patient, offers more useful information, allowing for a more accurate and

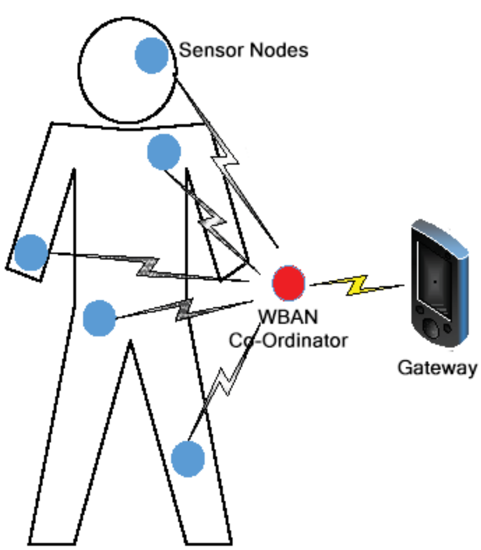

Figure 1.1 Conceptual view of WBAN

sometimes even faster diagnosis. WBAN is thus a particular area which could permit cheap and constant health monitoring of medical records through the Internet.

1.2 Motivation for the work

The concern of non-continuous monitoring of health becoming being a primary factor for the cause of a large number of diseases (chronic diabetes, cardiovascular, pulmonary, allergy etc.) has alarmed the medical community, in the past decade. In many instances it has been found that countless medical complications could have been avoided, if a regular watch could have been ensured on certain vital body parameters. This is because a lot of diseases have the characteristic that their symptoms accumulate over time, rather than come up suddenly. Every year, millions of people die from cancer, cardiovascular disease, Parkinson’s, asthma, obesity, diabetes and many more chronic or fatal diseases. The common problem with all current fatal diseases is that many people experience the symptoms and have the disease diagnosed when it is too late. The cost associated with diagnosis and treatment of such diseases, also increases almost exponentially with the delay caused in detection of the disease.

All of these highlighted problems demand the formation of an easy to use, low-cost and effective solution to uplift the dismal condition of the health sector globally. The demand for health solutions has been so extensive and far-reaching that the number of health professionals required to satisfy the needs of each and every individual has been inadequate, to say the least. The next best solution, would of course be to incorporate some sort of automation that would ensure that the vital health statistics of an individual is logged, analyzed and sent to a professional for examination and verification, should the need arise to do so. This would ensure that a professional need only go through the data that has already been accumulated, making the process faster, and would also rule out the possibility of a misdiagnosis; at least the ones that are caused by faulty reporting of the observed symptoms. The recent advancement of technology in the field of wearable devices have also given a huge impetus and the necessary boost to pull of this idea. But as the devices are physically independent of each other, the need arises to develop a strong backbone network that is highly efficient and fault tolerant; which is where the work done in this thesis comes in.

The hard work and effort made for this project would be duly rewarded if it can indeed improve the health of each and every citizen in this country and elsewhere, and improve the living standards of all.

1.3 Objective of the Thesis

The main objective of the thesis is to develop a low latency, fault tolerant multi-channel network for wearable devices. As an extension, the concepts used in this thesis can be extended to other sensor or small-scale networks, albeit with little or no modification. The main advantage offered by the proposed system is that it provides a number of parameters that can be tweaked according to the requirement or use case. A lot of factors come in that affect the working condition of the network, when the fact that the devices can be present anywhere on or inside the body come in. All of those facts have been considered and the most likely scenarios explained and detailed further in this work.

It has been observed that in certain cases, some of the desirable working conditions of the network contradict each other. In such a scenario, optimization has been done so as to select a set of parameters that provide an acceptable working condition while not making the network absolutely impossible to use. The optimization used in this case has been categorized as a classical optimization technique in literature.

It is to be remembered that no matter how much tweaking is done on the network level, the devices themselves have certain limitations as well. There must be an acceptable level of energy used by each of these devices as they are battery powered and thus energy constrained. Also, since they are close body devices, they must not emit power harmful enough to damage the body tissues. These facts have been checked and shown to be nominal for the designed network.

1.4 Outline of the Thesis

In this chapter, a very basic overview of a Wireless Body Area Network has been presented. The motivation and objective for this thesis has also been briefly discussed.

Chapter 2 describes the background information that acts a foundation for this research work.

In chapter 3, the research methodology adapted during the course of this work is described. The entire network model, including the multi-channel conditions have been detailed. This includes the channel access schemes, the packet structures, the path loss models and the underlying mechanism for the functioning of the entire network.

Chapter 4 deals with modifying the back-off time used in the CSMA/CA system to improve the data throughput. A comparative analysis has also been provided with existing methodologies in the same topic.

Chapter 5 deals with finding an optimal packet length for optimal performance of the network under a set of constraints. A thorough analysis has presented in this regard, by modifying the working parameters of the network and observing the changes.

In chapter 6, the entire work done has been summarized concisely and the exact parameters for the functioning of the network have been discussed. The future scope for this project has also been stated, along with the improvements that can be made for the existing setup.

CHAPTER 2

BACKGROUND STUDY

2.1 Wireless Communication

Wireless communication falls under that segment of the communication industry that has seen the fastest growth in recent years for its adaptability and high demand in the market. Many new applications that include, but are not limited to wireless sensor networks, automated devices, smart homes and Internet of Things and remote telemedicine are evolving from research ideas to concrete systems [1]. In this project, we are mainly going to focus on the design and development of a low latency, fault-tolerant Wireless Body Area Network to be used for wearable devices. The background information necessary for development of the said network has been discussed in this chapter.

2.2 Wireless Sensor Network

Wireless Sensor Networks consist of individual nodes that can interact with their environment by sensing or controlling physical parameters; these nodes have to work together to fulfill their tasks as usually, a single node is incapable of doing so, and they use wireless communication to enable this collaboration [2].

“A sensor network is a deployment of massive numbers of small, inexpensive, self-powered devices that can sense, compute, and communicate with other devices for the purpose of gathering local information to make global decisions about a physical environment”.

2.3 Wireless Body Area Network

Wireless Body Area Network (WBAN) has emerged as a vital technology that is capable of providing better methods to diagnose various hazardous diseases. This technology works in actual time to monitor the health issues cum physiological parameters of the patients. WBAN is a fast-developing technology; hence various issues need to be addressed till now. In WBAN either sensor network on a band or various sensors are worn by a patient or which are light in weight that monitor various physiological signals. They are able to transmit bio signals (vital signs) to the concerned System at a Healthcare Center. The monitoring healthcare specialist retrieves the patient data and processes it. WBAN comes up as a revolutionary technique from the past few years and it is easily acceptable as explained by [3].

WBAN devices may be embedded inside the body, implants, may be surface-mounted on the body in a fixed position Wearable technology or may be accompanied devices which humans can carry in different positions, in clothes pockets, by hand or in various bags. Whilst there is a trend towards the miniaturization of devices, in particular, networks consisting of several miniaturized body sensor nodes together with a single body central unit. Larger decimeter (tab and pad) sized smart devices, accompanied devices, still play an important role in terms of acting as a data hub, data gateway and providing a user interface to view and manage WBAN applications, in-place. The development of WBAN technology started around 1995 around the idea of using wireless personal area network technologies to implement communications on, near, and around the human body. About six years later, the term "WBAN" came to refer to systems where communication is entirely within, on, and in the immediate proximity of a human body. A WBAN system can use WPAN wireless technologies as gateways to reach longer ranges. Each node in a WBAN is an independent node which is able to search and find a suitable path for transmitting data at a remote location. The WBAN node can also connect to the internet for transmitting data. Using WPAN as a gateway, WBAN can be extended to a wider range and also the wearable devices on the human body can be connected to the internet.

2.4 WBAN in existing medical research

WBAN has multifarious applications exclusive to the medical field, and as such, a lot of work has been done in this domain. Body inertial-sensing network [4] is a project that uses a new method of gestures of body segments to estimate the knee joint angle and identify gait cycles. It was designed to provide data for real-time measuring of three degrees of freedom orientation. It contains four sensing components: a three-axis accelerometer, a three-axis magnetometer, a three-axis gyroscope, and the temperature sensor. Each node, part of a star topology, transmits data to the central base station (CBS), which is connected to a computer via wireless. For energy savings reasons, wireless transmission is not always active. Every node in the network sends a synchronization request packet to the CBS when it wants to send data. After this request, the connection between the CBS and the node is established.

Unobstructive Body Area Networks [5] are a system that collects and transmits data from sensor nodes to a control center capable of analyzing and processing the information. The system creates movement profiles based on the data sent by the nodes and detects any abnormal movement in real time, allowing for monitored rehabilitation of the user.

CodeBlue [6] is referred to as a prototype healthcare Wireless Sensor Network that defines the architecture for hardware and a framework for software. The framework provides protocols for device discovery, subscribing a routing layer and a simple query interface that allows for requesting data from groups of nodes. It provides protocols and services for node naming, discovery, any-to-any ad hoc routing, authentication, and encryption.

The MEDiSN architecture [7] includes a number of Physiological Monitors (PMs) to collect patient's physiological data. Relay Points (RP) aggregate and forward data from PMs. A gateway collects all the data from RPs using management command handling. PMs only send data and are not involved with data forwarding. RPs self-organize into a routing tree and use hop-by-hop bidirectional data traffic retransmissions, which are prone to packet collision and corruption. The backend server host stores patient data and supports multiple gateways. The connection between the backend server host and the gateways is made through existing network (i.e., intranet or Internet).

Low power Medical Ad hoc Sensor Networks (MASN) [8] consist of low-cost ECG sensors that are attached to the patients' bodies. They involve a cluster based, energy-aware ECG collection scheme whereby the ECG data are reliably relayed to the sink node in the form of aggregated data packets.

A Wireless Sensor Enabled by Wireless Power (WPWS) [9] presents an RFID system architecture. The nodes have no batteries and have two antennas: a power antenna that works at 915 MHz and induces energy to sensors on each node and a data communication antenna that works in a 433 MHz band. The power antenna was designed to gather power from a standard reader. A special physical data link layer was designed for this purpose. WPMS requires the definition of only three layers: the physical (PHY) layer, the media access control (MAC) layer, and the application (APP) layer.

WirelessHART [10] is the first open wireless communication standard specifically designed for process measurement and control applications. WirelessHART was officially released in September 2007 and implements a secure and Time Division Multiple Access (TDMA) based wireless mesh networking technology operating in the 2.4 GHz Industrial, Scientific and Medical (ISM) radio band. To support the mesh communication technology, each node is required to be able to forward packets on behalf of other devices. Both the MAC and network layer provide security services.

The details of all these works [48] have been summarized in Table 2.1.

WBAN Projects	Application/Transport layer	Network layer	Data Link layer	Physical layer
CodeBlue	MoteTrack	TinyADMR	IEEE 802.15.4 MAC	IEEE 802.15.4
MASN	ECG Software MoteTrack	LEACH RMCP	IEEE 802.15.4 MAC	IEEE 802.15.4
MEDISN	-	CTP	IEEE 802.15.4 MAC	IEEE 802.15.4
Unobstructibe BAN	-	-	IEEE 802.15.1 MAC	IEEE 802.15.1
WirelessHART	WirelesHART applications	Graph routing	WirelessHART DL Layer	IEEE 802.15.4
WPWS	Experimental ModBus applications	-	Modbus serial protocol	4333MHz (data) 915Mhz (power)

Table 2.1 WBAN in medical research

2.5 Existing work on performance improvement in WBAN

As WBAN sensors are placed in/on the body, the battery size is small. Battery life is proportional to battery size. In WBAN data is processed in power efficient manner. Power efficiency is the key feature while designing WBAN besides the use of high layered energy-efficient MAC protocols. One such protocol is proposed by [11] in which multi-hop architecture has been discussed. As the data handled by WBAN is of low power, he suggested a gossiping strategy based on TDMA based MAC protocol for data transmission between sensor and the gateway. Results show that power consumed is low in comparison to TDMA based Star network.

Another energy efficient model was proposed by [12] which are known as a wireless device driver for low duty peripherals. This device controls all the devices connected to it to make the system reliable. The device driver is not always connected with the peripherals and user can depart/rejoin it according to the requirement. These techniques save the latency time by making use of either Bluetooth or Zigbee.

Collision, overhead, packet overhead, etc. are the main reasons for energy wastage in the design of MAC protocol in WBAN [13-14]. In these two protocols proposed were CSMA/CA and TDMA. For research and implementation purpose, they used IEEE standard 802.15.4 (Bluetooth and Zigbee) as communication protocols. The Zigbee has low data rate and low bandwidth as compared to the Bluetooth. Zigbee is used with star topology whereas Bluetooth is widely used with master-slave configuration.

For super frame-structured WBAN MAC protocols [15] suggested user defined and easily understandable handling scheme for crisis times. Instead of Contention-Free Period (CFP), they proposed Mixed Period. Next, they also discussed another scheme for data transmission that is known as Extended Period (EP), which provides guaranteed time slot (GTS) to that slots that are not assigned time because of massive traffic and crisis. This scheme can be implemented to a general super frame-structured MAC protocol named ex. IEEE 802.15.4 and its next version. That also helps in random Contention-Free Period allotments.

According to design choices [16] gave a practical solution to the implementation problems. In the application model, sensors decode the data and send output periodically. Accordingly, a sensor may be added and removed in the network at any unit time. By making use of the offset-free scheduling model in which the processes are processed periodically, and schedule length is equal to the hyper period of the process. Because of limitation in resources, it may not be practically possible for a sensor node to keep a long global schedule covering the hyper-period.

[17] Proposed a novel MAC protocol for WBAN that uses an out-of-band wakeup radio. This special wake-up radio circuit attached with each node is used for triggering a node to

wake up from a sleep state. The implementation cost for the same device is very low, and design is very simple. It can save power, but it has a limitation of range up to 10-15 feet only.

By the use of new technology, Cooperative Network Coding (CNC), [18] have given a WBAN, which is highly reliable and provides increased throughput and removes single points of failure. CNC in WBAN gives a wonderful idea to mitigate the loss of packets; latency is reduced as data is sent again and again. It removes any point loss, and increases the percentage of successful recovery of the meaningful data at the receiver end in real time applications. Now a day's CNC is not only used in its original configuration (one-to-one) but also multiple-input-multiple-output (MIMO) systems.

For tackling the multi-channel problem, a few sparse solutions exist in literature. Slotted Seeded Channel Hopping (SSCH) is a distributed link-layer protocol that increases the capacity of an IEEE 802.11 network by utilizing frequency diversity. SSCH switches each radio across multiple channels so that multiple flows within interfering range of each other can simultaneously occur on orthogonal channels. SSCH is a distributed protocol and does not require synchronization. SSCH devices maintain the channel schedule. The channel schedule is the list of channels that the device plans to switch to in subsequent slots and the time at which it plans to make each switch. Each device maintains a list of the channel schedules for all other devices it is aware of. If the sender knows the receiver's hopping schedule, the sender will probably be able to send quickly to the receiver by changing its own schedule. In the uncommon case that the sender does not know the receiver's schedule, then the traffic incurs a latency penalty while the sender discovers the receiver' s new schedule [19].

Dynamic Channel Assignment (DCA) MAC protocol dynamically assigns channels to devices in an on-demand fashion and is a degree-independent protocol. Each device maintains two data structures. One is Channel Usage List (C~L), which records the channels being used by neighboring devices. This list is distributedly maintained. Other is Free Channel List (FCL), which is dynamically computed from CUL. The sender sends an RTS carrying its FCL. Then the receiver matches this FCL with its CUL to identify a data channel and replies a CTS. On receiving receiver's CTS, the sender sends a RES (reservation) packet to inhibit neighborhood from using the same channel. Similarly, the CTS inhibits receiver's neighborhood from using that channel. All these happen on the control channel. A data frame is transmitted on that data channel [20].

The Dynamic Open Spectrum Sharing (DOSS) MAC protocol allows nodes to adaptively select an arbitrary spectrum. Because DOSS devices are secondary spectrum users, they first detect the presence of primary users. Then DSSS devices set up three operational frequency bands/channels: a data band, a control channel, and a busy tone band. An initial control channel is set at the time the network is set up. This channel may migrate slowly over time to a better channel. The busy tone band is used to solve the hidden and exposed terminal problems and to assign data channels. DSSS protocol establishes a one-to-one mapping between the busy tones and data channels. With the spectrum mapping, a receiver converts the spectrum over which it is receiving to a busy tone and sends the busy tone in order to inform other neighbors not to send. The sender and the receiver negotiate on the dynamic channel for the data transmission. The sender sends its available channel information through a REQ packet. The receiver finds a common channel for both, responds to a REQ_ACK and turns on the mapping busy tone. The sender and the receiver communicate over the negotiated dynamic data channel [21].

For the dynamic backoff problem, many backoff schemes have been proposed and studied in the technical literature. Binary exponential backoff (BEB) is an algorithm being widely used in the MAC-layer protocols [22-24]. The simplicity and good performance of BEB contribute to its popularity. Unfortunately, the fairness of the BEB scheme is relatively poor in some scenarios [25], [26].

To address the problem of unfairness in the BEB scheme, the multiplicative increase linear decrease (MILD) algorithm was introduced in the MACAW protocol [25]. In the MILD scheme, a collided node increases its backoff interval by multiplying it by 1.5. A successful node decreases its backoff interval by one step, which is defined as the transmission time of the request packet [request-to-send (RTS)]. Since the MACAW protocol assumes that a successful node has a backoff interval that is somehow related to the contention level of the local area, the current backoff interval is included in each transmitted packet. A backoff interval copy mechanism is implemented in each node, to copy the backoff intervals of the overheard successful transmitters.

In [27], an exponential backoff scheme has been proposed to control the retransmission probability of each busy node on slotted random-access channels. At the beginning of each slot, a busy node “flips” a biased coin according to the retransmission probability, to decide whether or not to transmit in the slot. The operation of the proposed scheme is based on (0, 1, e) channel feedback, in which 0, 1 and e represent idle, successful, and collided channel status, respectively. Each node decreases the retransmission probability by multiplying it by a factor of q ($0<q<1$), when the channel feedback of the previous slot is e (collisions). When the channel feedback is 0 (idle), the retransmission probability is increased by multiplying it with $1/q$. The retransmission probability is unchanged when channel feedback is 1 (success).

In [28], a fair backoff control scheme for an IEEE 802.11-based wireless ad hoc network has been proposed. In the scheme, the contention window (backoff interval) is changed according to the received packets and the fair share of channel assigned to each node.

For the packet length optimization problem, it must be remembered that the effective throughput is affected by a number of parameters, including transmission rate, packet length and header size characteristics. The transmission parameters should be adapted according to channel conditions to improve link performance. The mechanism to select one of the multiple available transmission packet sizes falls under link adaptation. The current link adaptation schemes used in IEEE 802.15 wireless standard are proprietary (mostly based on received signal strength and packet error rates) and in many cases can lead to inefficient network utilization and unnecessary rate adaptation. An early investigation of the effect of packet size on throughput was conducted in [29]. Rate adaptation using a theoretical framework to evaluate the throughput has been investigated in [30]. A link adaptation strategy for the related IEEE 802.1lb was provided in [31].

It is seen that although there is existing literature that provides some rudimentary models of multi-channel networks, they are not fully equipped to tackle the nuances of having multiple nodes in the said networks. The thesis thus aims to provide a robust, fault-tolerant network that has the capability to operate on multiple adjoining channels in the WBAN framework, while maintaining optimal working conditions. The CSMA/CA scheme has been selected as the access technique that works on these multiple channels, keeping in mind the contention-based access any real time device should have; this is particularly important for wearable devices as they may contain time critical data. Expanding further into the CSMA/CA technique used, the backoff length is modified to obtain better throughput and energy efficiency than existing methodologies. The thesis explores the possibility of further bettering the network performance by performing a packet length optimization on the data that is to be delivered. It is seen that based on different use cases, the packet length can be optimized to offer different error rates and delay times. These results also vary with the number of channels selected in the multi-channel model. Overall, the work in this thesis thus enables a user to design a flexible network that can be configured as per demand.

CHAPTER 3

MULTI-CHANNEL WBAN MODEL AND ACCESS MECHANISM

3.1 Introduction

Before diving deep into the internal architecture and functioning of a multi-channel WBAN, it is essential to know some of the scenarios in which such a network will work and the necessary requirements for that. Based on application, WBAN can be categorized into the following types:

1. *Wearable WBAN:* Wearable medical applications of WBANs include Disability Assistance, Human Performance Management and Wearable Health Monitoring in general. These applications require WBAN nodes to be usually placed on the surface of the human body. No implants are necessary.
2. *Implant WBAN:* This class of applications is relative to nodes implanted in the human body either underneath the skin or in the blood stream. The applications include cardiovascular diseases, cancer detection and diabetes control.
3. *Remote Control of Medical Devices:* The ubiquitous Internet connectivity of WBANs allows for networking of the devices and services in home care known as Ambient Assisted Living (AAL), where each WBAN wirelessly communicates with a back-end medical network [32]. These are mainly used for patient monitoring and telemedicine applications.
4. *Non-medical uses:* These are sparse in nature and include entertainment, emotion detection and certain biometric applications.

It is necessary to know the potential applications before designing the network, because the use cases affect the performance of the same, as can be seen later. For example, the path loss characteristics will be different for in body nodes (implants) and out/on body nodes (surface nodes) and thus will produce different results. The typical medical application scenarios along with their data rates [32] have been tabulated in Table 3.1.

Application Type	Sensor Node	Data Rate
In-body medical application	Pacemaker	Low, few Kbps
	Endoscope Capsule	High, 2 Mbps
	Glucose sensor	Low, few Kbps
On-body medical application	Blood pressure	Very low, few bps
	SpO2	Low, around 30 Kbps
	ECG	Low, few Kbps

Table 3.1. Data rates of in/on-body applications

3.2 History of the IEEE 802.15.6 standard

Early developments in Wireless Personal Area Networks (WPANs) were first made in the 90s by different groups working at MIT (Massachusetts Institute of Technology). Their initial aim was to interconnect information devices attached to the human body. They also intended to use electric field sensing to determine body positioning, through which the capability of modulating the electric field for data transmission throughout the body was realized.

Recent developments in wireless technologies has a major focus on increasing network throughput which shifts the focus of WPANs to short range, low power and low-cost technologies. Network lifetime has a greater importance in WBANs as devices are expected to perform over longer periods of time. Also, WPANs do not satisfy the medical communication requirements because of close proximity to the human body tissue. Thus, a standard model was required for the successful implementation of Body Area Networks addressing both its consumer electronics and medical applications.

The IEEE 802 working group had a number of success stories in the realization of the international standardization for WBANs. A standing committee, Wireless Next Generation (WNG), was established in January 2006, within WG15 (Working Group) aiming for the examination of new topics and direction. In May 2006, an interest group of WBAN, namely, (IG-WBAN) was initially established. The call for WBAN applications by TG6 was later closed in May 2008 and compiled all submitted application into a single document. The IEEE 802.15.6 working group established the first draft of the communication standard of WBANs in April 2010, optimized for low-power on-body/in-body nodes for various medical and non-medical applications. The approved version of the IEEE 802.15.6 standard was ratified in February 2012 [33] and describes its aim as follows: "To develop a communication standard for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics, personal entertainment and other."

3.3 Requirements of WBAN in IEEE 802.15.6

The main requirements (ideal) of IEEE 802.15.6 standard are listed below [34-35]:

- WBAN links should support bit rates in the range of 10 Kb/s to 10 Mb/s.
- Packet Error Rate (PER) should be less than 10% for a 256-octet payload for a majority (95%) of the best performing links based on PER.
- Nodes should be capable of being removed and added to the network in less than 3 seconds.
- Each WBAN has to be capable of supporting 256 nodes, although the actual number of nodes is way less.

- Nodes should be capable of reliable communication even when the person is on the move. Although it is acceptable for network capacity to be reduced, data should not be lost due to unstable channel conditions. The considered applications include postural body movements relative to sitting, walking, twisting, turning, running, waving arms and dancing among others which result in the shadowing effect and channel fading. Nodes in a WBAN may move individually with respect to each other, however the WBAN itself may move location resulting in interference.
- Jitter, latency and reliability should be supported for WBAN applications that require them. Latency should be less than 125 ms in medical applications and less than 250 ms in non-medical applications whilst jitter should be less than 50 ms.
- On-body and in-body WBANs should be capable of coexisting within range.
- Up to 10 randomly distributed, co-located WBANs should be supported by the physical layer in a 6 cu.m. cube.
- All devices should be capable of transmitting at 0.1 mW (-10 dBm) and the maximum radiated transmission power should be less than 1 mW (0 dBm). This complies with the Specific Absorption Rate (SAR) of the Federal Communications Commission's 1.6 W/Kg in 1gm of body tissue.
- WBANs should be capable of operating in a heterogenous environment where networks of different standards cooperate amongst each other to receive information.
- A WBAN can incorporate UWB technology with a narrow-band transmission to cover different environments and support high data rates. For instance, some medical application such as ECG monitoring might require a UWB-based WBAN to support higher data rates.
- WBANs must incorporate QoS management features to be self-healing and secure as well as allowing priority services.
- Power saving mechanisms should be incorporated to allow WBANs to operate in a power constrained environment.

3.4 Types of Nodes in a WBAN

A node in a WBAN is defined as an independent device with communication capability. Nodes can be classified into two different groups based on their functionality, implementation and role in the network. The classification of nodes in WBANs based on functionality is as follows:

i. *Body Network Co-Ordinator (BNC)* - This device is in charge of collecting all the information received from sensors and actuators and handles interaction with other users. The PD then informs the user through an external gateway, a display/LEDs on the device or an actuator. This device may also be called Body Control Unit (BCU), body gateway, sink, or Personal Device (PD) in some application.

ii. *Sensor (Node)* - Sensors in WBANs measure certain parameters in one's body either internally or externally. These nodes gather and respond to data on physical stimuli, process necessary data and provide wireless response to information. These sensors are either physiological sensors, ambient sensors or biokinetics. Some existing types of these sensors could be used in one's wrist watch, mobile, or earphone and consequently, allow wireless monitoring of a person anywhere, anytime and with anybody. A list of different types of commercially available sensors used in WBANs are as follows: EMG, EEG, ECG, Temperature, Humidity, Blood pressure, Blood glucose, Pulse Oximetry (SpO2), CO2 Gas sensor, Thermistor, Spirometer, Plethysmogram, DNA Sensor, Magnetic Biosensor, Transmission Plasmon Biosensor, Motion (Gyroscope/Accelerometer/Tri-Axial Accelerometer), etc.

IEEE 802.15.6 has proposed another classification for nodes in a WBAN based on the way they are implemented within the body, which is provided as follows:

i. *Implant Node* – This type of node is planted in the human body, either immediately underneath the skin or inside the body tissue.

ii. *Body Surface Node* – This type of node is either placed on the surface of the human body or 2 centimeters away from it.

iii. *External Node* – This type of node is not in contact with the human body and rather a few centimeters to 5 meters away from the human body.

The classification of nodes in WBANs based on their role in the network is as follows:

i. *Coordinator* – The coordinator node is like a gateway to the outside world, another WBAN, a trust center or an access coordinator. The coordinator of a WBAN is the PD, through which all other nodes communicate.

ii. *End Nodes* – The end nodes in WBANs are limited to performing their embedded application. However, they are not capable of relaying messages from other nodes.

iii. *Relay* – The intermediate nodes are called relays. They have a parent node, possess a child node and relay messages. In essence if a node is at an extremity, any data sent is required to be relayed by other nodes before reaching the PDA. The relay nodes may also be capable of sensing data.

3.5 Topology of WBAN

The IEEE 802.15.6 working group has considered WBANs to operate in either a one-hop or two-hop star topology with the node in the center of the star being placed on a location like the waist. The one-hop technology is more common and provides a number of advantages over the two-hop technology. Two feasible types of data transmission exist in the one-hop star topology: *transmission from the device to the coordinator* and *transmission from the coordinator to the device*.

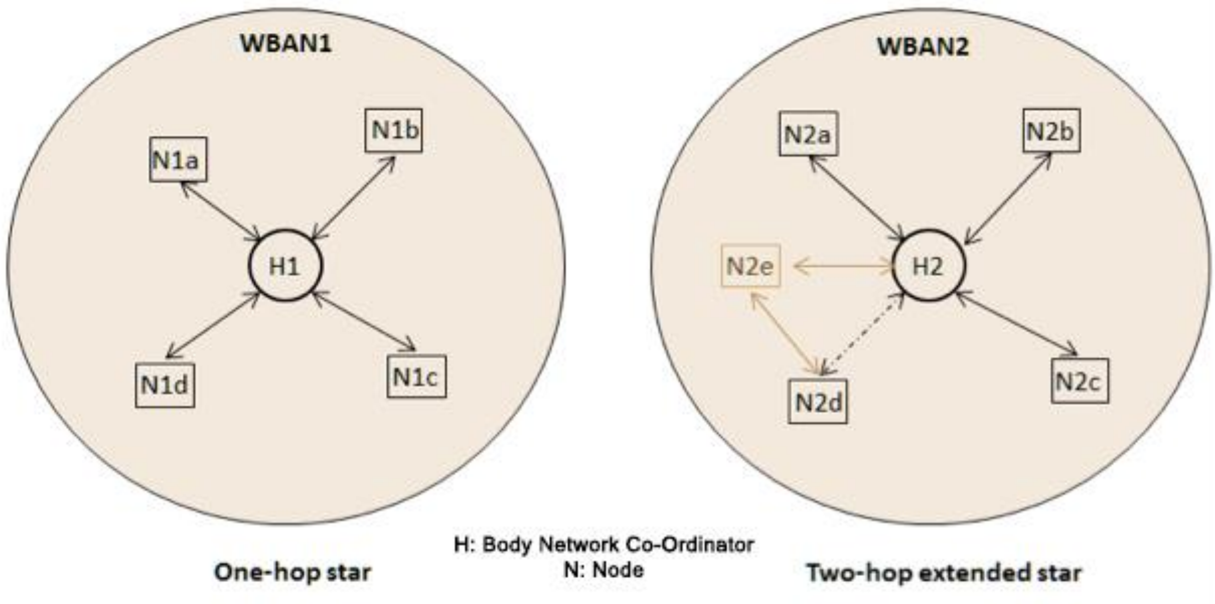

Figure 3.1 WBAN Network Architecture

The communication methods that exist in the star topology are *beacon mode* and *non-beacon mode*. In the *beacon mode*, the network coordinator, which is the node in the center of the star topology controls the communication. It transmits periodic beacons to define the beginning and the end of a superframe to enable network association control and device synchronization. The duty cycle of the system, which is the length of the beacon period, can be specified by the user and based on WBAN's standard. In the *non-beacon mode*, a node in the network is capable of sending data to the coordinator and can use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) when required. The nodes need to power up and poll the coordinator to receive data.

However, the coordinator cannot communicate with the nodes at all times as the nodes must wait till they are invited to participate in a communication. Since both one-hop and two-hop star topologies exist in WBANs, careful considerations need to be taken into account upon the choice of the one-hop or the two-hop topology. When all nodes in the network are directly connected to the sink, the network is considered to have a one-hop star topology. In a WBAN, the coordinator is known as the sink node to which all nodes talk. However, in a multi-hop architecture, nodes are connected to access points via other nodes. Table 3.2 provides a comparison between a multi-hop network and a one-hop star topology.

Criteria	**Star Network**	**Multi-Hop Networks**
Energy Consumption	For nodes in close proximity to the PDA, the power used to transmit to the PDA will be low. The nodes further away, however, will consistently require more power to be able to transmit information.	The nodes that are closest to the PDA consume more energy as they will have to forward not only their own information but also information from other nodes.
Delay in Transmission	The star network presents the least possible delay present in transmission from any sensor to the PDA, as there is only a single hop.	Dependent on how the network is configured. In terms of delay, the nodes closest to the PDA can get their information through quickly, without any intermediate relay.
Interference	Sensors that are farther away from the PDA require transmission with higher power, increasing the amount of interference.	Since each node is only transmitting to its neighbor nodes, the energy of transmission is kept low and hence mitigates the effects of interference.
Node Failure and Mobility	Only the failed node will be affected and the rest of the network can perform as needed.	The part of the network that involves the failed node has to be reconfigured. Overheads are involved.

Table 3.2 Comparison between star and multi-hop network in WBAN

This table shows that multihop transmission has a higher delay and lower transmission power compared to the one-hop star topology. The multihop configuration involves overheads along with its network operation; as increasing the number of hops could lead to a high complexity. More specifically, using relays in WBANs assists in reducing the concentration of the transmission power from the source to its destination. Thus, the further apart the source and destination are in distance, the higher transmission power is required. Through the use of relays, the transmission heat will be distributed and a convenient heat will be obtained for the surrounding area of the transmitting sensor. As per the latest version of the IEEE standard proposed for WBANs, only two hops are supported in IEEE WBAN standards compliant communication. Proprietary systems could use more than two hops, but then inter-operability would be a problem, as they would not be standard-compliant.

3.6 Communication architecture of WBAN

The communication architecture of WBANs can be separated into two different tiers as follows:

- Tier-1: Intra-WBAN communication
- Tier-2: Inter-WBAN communication

Fig. 3.2 illustrates these communication tiers in an efficient, component-based system for WBANs. In Fig. 3.2, the devices are scattered all over the body in a centralized network architecture where the exact location of a device is application specific. However, as the body may be in motion (e.g. running, walking) the ideal body location of sensor nodes is not always the same; hence, WBANs are not regarded as being static.

Tier-1: Intra-WBAN communication: Tier-1 depicts the network interaction of nodes and their respective transmission ranges (~ 2 meters) in and around the human body. Fig. 3.2

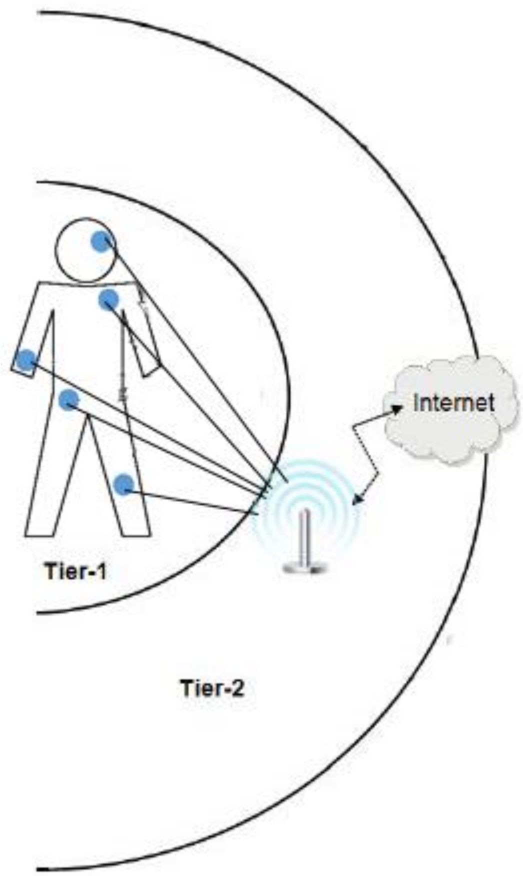

Figure 3.2 Communication Tiers in a Wireless Body Area Network

illustrates WBAN communication within a WBAN and between the WBAN and its multiple tiers. In Tier-1, variable sensors are used to forward body signals to a Personal Server (PS), located in Tier-1. The processed physiological data is then transmitted to an access point in Tier-2.

Tier-2: Inter-WBAN communication: This communication tier is between the PS and one or more access points (APs). The APs can be considered as part of the infrastructure, or even be placed strategically in a dynamic environment to handle emergency situations. Tier-2 communication aims to interconnect WBANs with various networks, which can easily be accessed in daily life as well as cellular networks and the Internet. The more the technologies supported by a WBAN, the easier it is for them to be integrated within applications. The paradigms of inter-WBAN communication are divided into two subcategories as follows:

Infrastructure based architecture – The architecture shown in Fig. 3.3 is used in most WBAN applications as it facilitates dynamic deployment in a limited space such as a hospital as well as providing centralized management and security control. The AP can act as a database server related to its application.

Ad-hoc based architecture – In this architecture, multiple APs transmit information inside medical centers as shown in Fig. 3.4. The APs in this architecture form a mesh construction that enables flexible and fast deployment, allowing for the network to easily expand, provide larger radio coverage due to multi-hop dissemination and support patient mobility.

The coverage range of this configuration is much larger compared to the infrastructure-based architecture, and therefore facilitates movement around larger areas. In fact, this interconnection extends the coverage area of WBANs from 2 meters to 50 meters, which is suitable for both short and long-term setups.

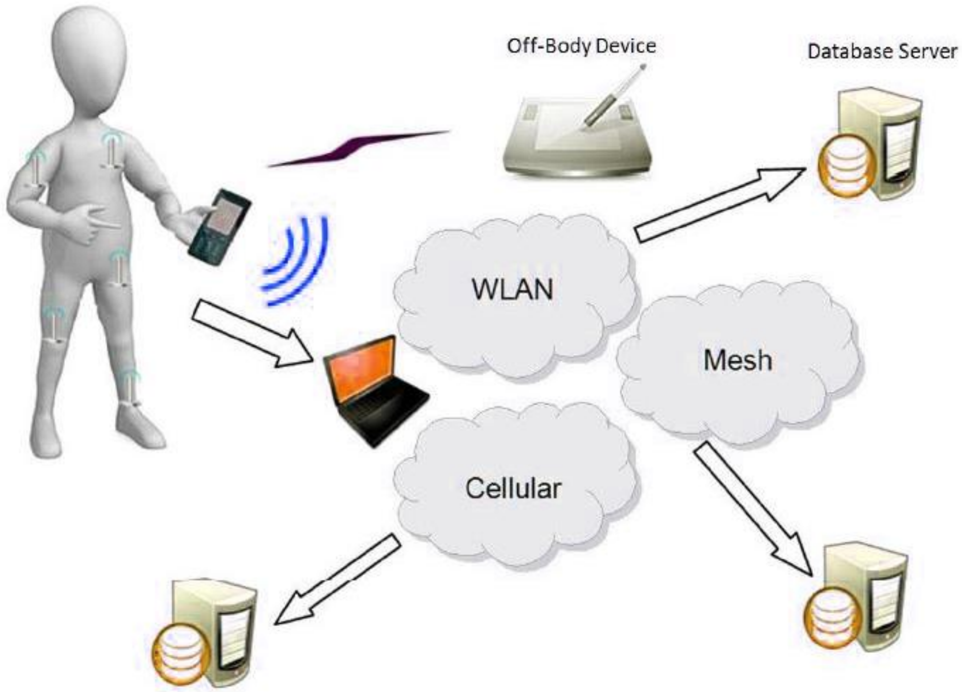

Figure 3.3 Inter-WBAN Communication: Infrastructure-based mode

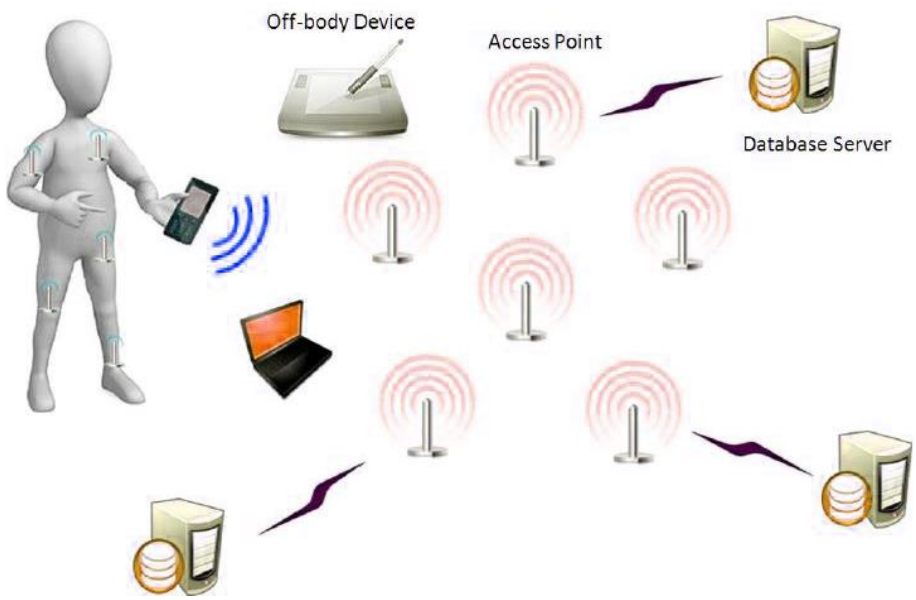

Figure 3.4 Inter-WBAN Communication: Ad-Hoc based mode

The work considered in this thesis is mostly concerned with Tier 1, single hop communication from the on-body nodes to the BNC.

3.7 Layers in WBAN

Generally, all approved standards of 802.15 propose PHY and MAC layers. They do not supply any network, transport or application layer and therefore call for other parties to develop them. The IEEE 802.15.6 (WBAN) working group has defined new Physical (PHY) and Medium Access Control (MAC) layers for WBANs that provide low complexity, low cost, high reliability, ultra-low power and short-range wireless communication in or around the human body. The standard has also mentioned that "There may be a logical node management entity (NME) or hub management entity (HME) that exchanges network management information with the PHY and MAC as well as with other layers".

3.7.1 Physical Layer

The PHY layer of IEEE 802.15.6 is responsible for the following tasks: activation and deactivation of the radio transceiver, Clear channel assessment (CCA) within the current channel and data transmission and reception. The choice of the physical layer depends on the target application: medical/non-medical, in and on-body. The PHY layer provides a procedure for transforming a physical layer service data unit (PSDU) into a physical layer protocol data unit (PPDU). IEEE 802.15.6 has specified two different physical layers: Narrow Band (NB) and Human Body Communication (HBC).

NB PHY is responsible for data transmission/reception, activation or deactivation of the radio transceiver and Clear Channel Assessment (CCA) in the current channel. Based on the NB specifications, in order to construct PPDU, the PSDU has to be pre-appended with a Physical Layer Preamble (PLCP) and a physical layer header (PSDU) shown in Fig.

3.5. The PCLP preamble aids the receiver in carrier-offset recovery, packet detection and timing synchronization. The PCLP header is sent after the PCLP preamble via the data rates given in its operating frequency band. It transfers the necessary information required for successfully decoding a packet to its receiver. The PSDU, which is the last component of PPDU contains a MAC header, a MAC frame body and a Frame Check Sequence (FCS). NB PHY uses Binary Phase Shift keying (BPSK), Differential Binary Phase Shift Keying (DBPSK) and Quadrature Phase Shift Keying (QPSK) modulation techniques except at 420- 450 MHz where it can use the Gaussian Minimum Shift Keying (GMSK) modulation technique.

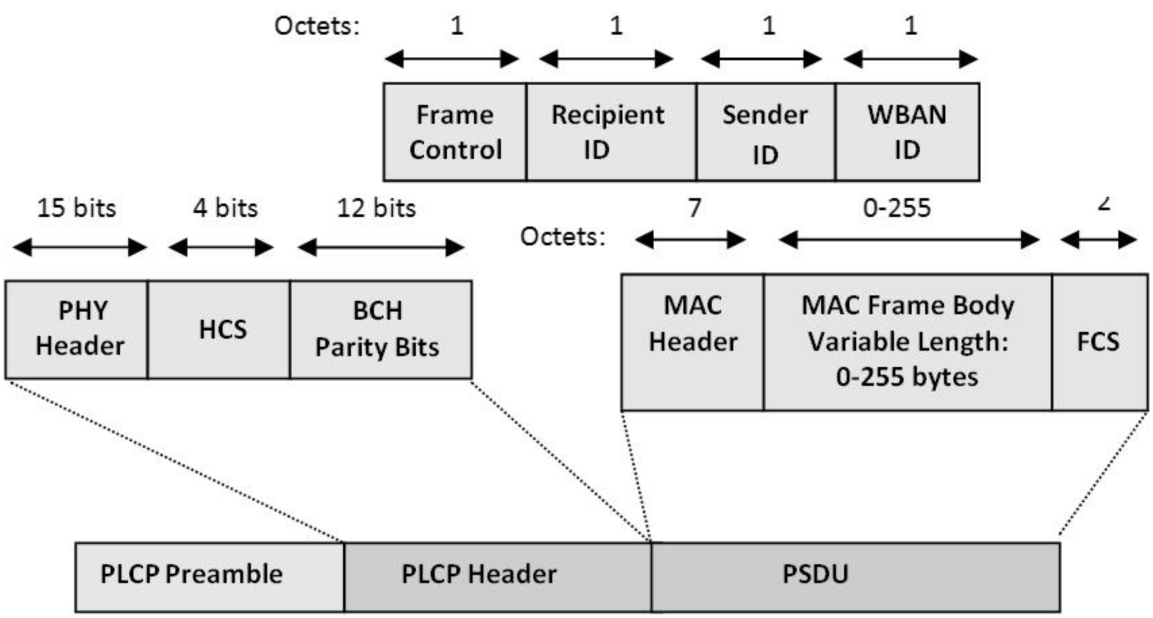

Figure 3.5 NB PPDU Structure of WBAN

HBC PHY provides the Electrostatic Field Communication (EFC) requirements that covers modulation, preamble/Start Frame Delimiter (SFD) and packet structure. The structure of the Physical Protocol Data Unit (PPDU) is composed of the PLCP preamble, Start Frame Delimiter (SFD), PLCP Header, and PHY Payload (PSDU) as shown in Fig. 3.6. The SFD and preamble are specified data patterns. They are pre-generated and sent before the payload and packet header. The SFD sequence is only transmitted once, whereas

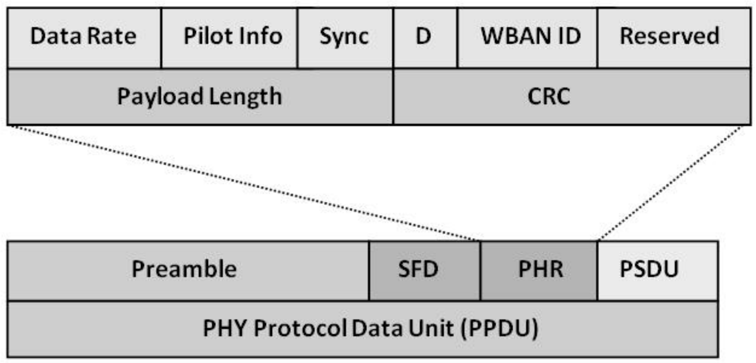

Figure 3.6 HBC PPDU Structure of WBAN

the preamble sequence is sent four times to assure packet synchronization. The initial PLCP preamble is created as a 64-bit gold code sequence which is repeated four times and is spread using a Frequency Shift Code (FSC). The SFD sequence is also created by using a 64-bit gold code generator that is spread using an FSC. Once the receiver has received the packet, it uses the preamble sequence to detect the beginning of the packet. It then detects the start of the frame using the SFD. The PHY header consists of the following fields: data rate, pilot information, synchronization, WBAN ID, payload length and a CRC calculated over the PHY header.

The NB PHY uses seven different frequency bands as shown in Table. 3.3. It offers various bit rates, channels and modulation schemes. The first licensed band in NB PHY is the Medical Implant Communication Service (MICS) utilized for implant communication with a range of 402-405 MHz in most countries. The next licensed band in NB PHY is the Wireless Medical Telemetry Services (WMTS) utilized in medical

Frequency	Bandwidth
402-405 MHz	300 kHz
420-450 MHz	300 kHz
863-870 MHz	400 kHz
902-928 MHz	500 kHz
956-956 MHz	400kHz
2360-2400 MHz	1 MHz
2400-2438.5 MHz	1 MHz

Table 3.3 Frequency Band and Bandwidth of PHY Layer of WBAN

telemetry systems. Neither MICS nor WMTS support high data rate applications. The Industrial, Scientific and Medical (ISM) band is available worldwide and supports high data rate applications. But, since various wireless devices such as IEEE 802.15.4 and IEEE 802.15.1 use the ISM band, there is a high probability for interference. The sixth band (2360- 2400 MHz) of NB PHY is assigned for medical device use. The seventh band (2400-2483.5 MHz) is a license-free ISM band that has been used most commonly. Importantly the 2360-2400 band is not an ISM band; hence, interference is significantly reduced compared to the 2400+ ISM band.

Nodes in WBANs are scattered in and over the whole body, which creates multiple transmission channels between the nodes based on their location in/on the body. In scenarios where a hundred sensors are attached to a person's body, the system becomes quite bulky to be carried around. Thus, the USA Federal Communications Commission (FCC) and communication authorities of other countries have allocated the MICS band at 402-405 MHz with 300KHz channels to enable wireless communication with implanted medical devices. This leads to better penetration through the human tissue compared to higher frequencies, high level of mobility, comfort and better patient care in implant to implant, implant to body surface and implant to external scenarios. Additionally, the 402-405 MHz frequencies have conducive propagation characteristics for the transmission of radio signals in the human body and do not cause severe interference for other radio operations in the same band. In fact, the MICs band is an unlicensed, ultra-low power, mobile radio service for transmitting data to support therapeutic or diagnostic operation related to implant medical devices and is internationally available. It is specifically chosen to provide low-power, small size, fast data transfer as well as a long communication range. The frequency range of the MICS band allows high-level integration with the radio frequency IC (RFIC) technology, which leads to miniaturization and low power consumption.

For this thesis, the NB PPDU structure of PHY is used to work in the 300 kHz band in the frequency range of 402-405 MHz, as mostly Human Body Communication devices with low bit rates are used.

3.7.2 MAC Layer

The IEEE 802.15.6 working group defines a MAC layer on top of the PHY layer in order to control channel access. The hub (or coordinator) divides the entire channel (or time axis) into a chain of superframes for time referenced resource allocations. The hub also chooses beacon periods of equal length to bound the superframes. The offsets of the beacon periods can also be shifted by the hub. The beacons are normally sent in each beacon period unless prohibited by regulations in the MICS band or inactive superframes. The coordinator is responsible for channel access coordination through one of the following three access modes:

1) *Beacon Mode with Beacon Period Superframe Boundaries:* In this channel access mode, the hub sends beacons in each beacon period unless prohibited by restrictions in the MICS band or inactive superframes. The hubs manage the communication of the superframe structure using Timed frames (T-poll) or beacon frames. The superframe structure of IEEE 802.15.6 is shown in Fig. 3.7. It consists of an Exclusive Access Phase 1 (EAP1), a Random-Access Phase 1 (RAP1), a Type I/II phase, an Exclusive Access Phase 2 (EAP 2), a Random-Access Phase 2 (RAP 2), a Type I/II phase, and a Contention Access Phase (CAP). In CAPs, RAPs and EAPs, nodes strive for resource allocation via either the slotted Aloha access procedure or more commonly, through CSMA/CA. EAP1 and EAP2 are utilized for high priority traffic such as reporting emergency events; while CAP, RAP1 and RAP2 are only used for regular traffic. Type I/II phases are utilized for bi-link allocation intervals, downlink allocation intervals, uplink allocation intervals, and delay bi-link allocation intervals. Polling is used in type I/II phases for resource allocation. Based on the application requirements, any of these

periods can be disabled by setting the duration length to zero. This channel access mode is most considered by researchers and developers. Thus, this mode has been considered in this thesis.

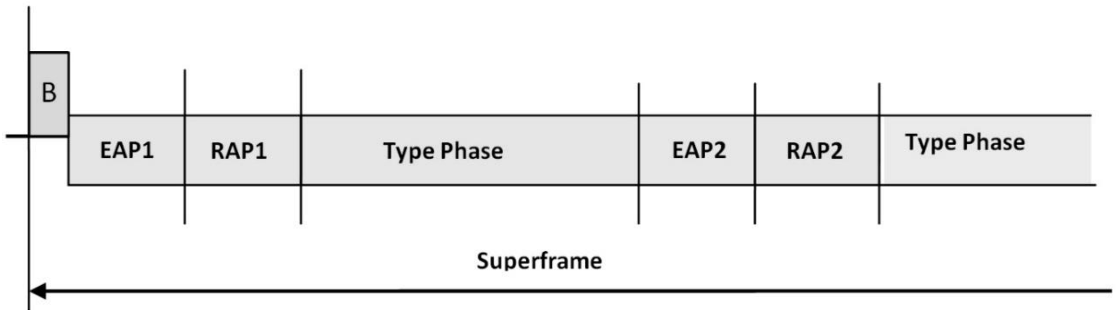

Figure 3.7 Superframe Structure of WBAN [36]

2) *Non-beacon mode with superframe boundaries:* This access mode is not capable of transmitting beacons and is forced to use the Timed frames (T-poll) of the superframe structure. The whole superframe is either covered by one Type I or one Type II access phase, but not both.

3) *Non-beacon mode without superframe boundaries:* In this access mode, only unscheduled Type II polled allocation is provided by the coordinator, meaning each node has to establish its own time schedule independently. Three categories of access mechanisms exist in each period of the superframe, which are as follows:

(a) *Scheduled access and variants (connection-oriented contention-free access)* – This access mechanism schedules slot allocation in one or multiple upcoming superframes also named after 1-periodic or m-periodic allocations.

(b) *Unscheduled and improvised access (connectionless contention-free access)* – This access mechanism utilizes posting or polling for resource allocation.

(c) *Random access mechanism* – In this access mechanism either the slotted Aloha procedure or CSMA/CA are used for resource allocation.

3.8 Channel Model of WBAN

Based on the IEEE WBAN 802.15.6 standard, three communication channels are considered. These channel models are described as in-body, on-body, and off-body channels. Similar to free space wireless channels, signals in WBAN experience absorption, reflection, and shadowing, which are caused by propagation in body tissue. Depending on the location of the transmitter and the receiver, both large-scale and small-scale fadings may affect the propagating signal. Similar to the classical wireless communication channels, the path-loss in WBAN is not only distance dependent, but also has a frequency-dependent nature.

The path-loss model between the receiver and the transmitter as a function of the distance *d* is described, which is based on the Friis formula for the free-space path-loss. It is

given by:

$$PL(d) = PL_0 + 10nlog_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

where n, d_0, PL_0, and X_σ represent the path-loss exponent, the reference distance, the path-loss at the reference distance, and the shadowing component, respectively. n tends to vary from 2.3 to 3.8 for WBAN applications.

Based on the existing experimental measurements for indoor environments, statistical distributions such as Rayleigh, Gaussian, log-normal, Ricean, and Nakagami-*m* have been studied for modeling of WBAN fading channel [37-38]. Unlike free-space small-scale fading, Rayleigh distribution is not an appropriate model for WBAN communication channels. On the other hand, it is shown in [39] that small-scale fading in UWB and narrowband channels is properly modeled by log-normal distribution.

According to the IEEE WBAN 802.15.6 standard and the specific absorption rate value regulated by the Federal Communications Commission, the maximum radiated power of the transmitter, denoted by P_{max}, should be 0 dBm. The communication channel and the channel parameters depend on the location of the transmitter and the receiver. Depending on the sensor location, the working frequency could be different from point to point. Generally, in-body and on-body communication channels work in the range of 402-405 MHz.

The received signal in the i^{th} time slot is given by $y_i = h_i x_i + n_i$, where h_i, x_i, and n_i are the channel gain of the link between the transmitter and the receiver, the transmitted signal, and the additive white Gaussian noise (AWGN) with zero-mean and variance N_0, respectively. As described earlier, statistical distribution of the fading channel is assumed to be log-normal.

3.9 CSMA/CA in WBAN

As mentioned previously, in the beacon access mode of the WBAN MAC, there exists multiple Exclusive Access Phases (EAP), Random-Access Phases (RAP) and a single Contention Access Phases (CAP) where nodes strive for resource allocation via either the slotted Aloha access procedure or more commonly, through the CSMA/CA access scheme.

Carrier-sense multiple access with collision avoidance (CSMA/CA) is a network multiple access method in which carrier sensing is used, but nodes attempt to avoid collisions by beginning transmission only after the channel is sensed to be "idle”. When they do transmit, nodes transmit their packet data in its entirety. It is particularly important for wireless networks, where the collision detection of the alternative CSMA/CD is not possible due to wireless transmitters desensing their receivers during packet transmission.

In CSMA/CA, the moment a node receives a packet intended for sending, the first thing it does is to listen to the broadcast channel for a pre-specified time frame to determine if another node is broadcasting on the channel inside the wireless range. If the broadcast channel is detected as "idle," the node can then start transmitting the data packet.

If the broadcast channel is detected as "busy," the node holds the transmission, waits for a random time frame and then checks all over again to find out whether the channel is free. This time frame is referred to as the backoff factor. The backoff factor is counted down using a backoff counter.

If the channel is free when the backoff counter gets to zero, the node sends the data packet. If the channel is not clear even when the backoff counter reaches zero, the backoff factor is scheduled yet again (usually doubled from its previous value, up to a certain maximum), and the entire scenario is repeated. This is repeated until the channel becomes available. As soon as the channel becomes available, the data packet is transmitted. Once the data is received by the receiving node, it sends back an acknowledgment packet (ACK) after a short while. If the ACK is not received, it is assumed that the packet is lost and then a retransmission is set up.

Hidden Node Problem: In wireless networking, the hidden node problem or hidden terminal problem occurs when a node can communicate with a wireless access point (AP), but cannot directly communicate with other nodes that are communicating with that AP. This leads to difficulties in medium access control sublayer since multiple nodes can send data packets to the AP simultaneously, which creates interference at the AP resulting in neither packet getting through. For example, in Fig 3.8, node A can communicate with node B. Node C can also communicate with Access Point node B. However, nodes A and C cannot communicate with each other as they are out of range of each other. Thus, nodes A and C may send data simultaneously to node B, resulting in a collision. Collision

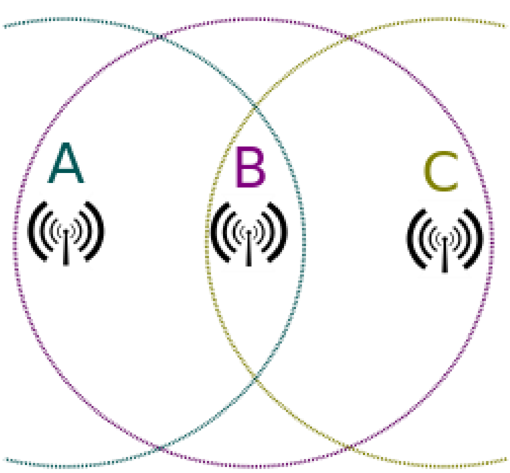

Figure 3.8 Hidden node problem in CSMA/CA

avoidance schemes involving Request to Send/Clear to Send (RTS/CTS) packets may be used to mitigate this problem.

Collision Avoidance: If another node was heard during sensing of the channel, the system waits for a period of time (usually random) for the node to stop transmitting before listening again for a free communications channel. Request to Send/Clear to Send (RTS/CTS) may optionally be used at this point to mediate access to the shared medium. This goes some way to alleviating the problem of hidden nodes because, for instance, in a wireless network, the Access Point only issues a Clear to Send to one node at a time. However, wireless implementations do not typically implement RTS/CTS for all transmissions; they may turn it off completely, or at least not use it for small packets. If the medium was identified as being clear or the node received a CTS to explicitly indicate it can send, it sends the frame in its entirety. The node awaits receipt of an acknowledgement packet from the AP to indicate the packet was received and check summed correctly. A very simplified working of the standard CSMA/CA is shown in Fig. 3.9.

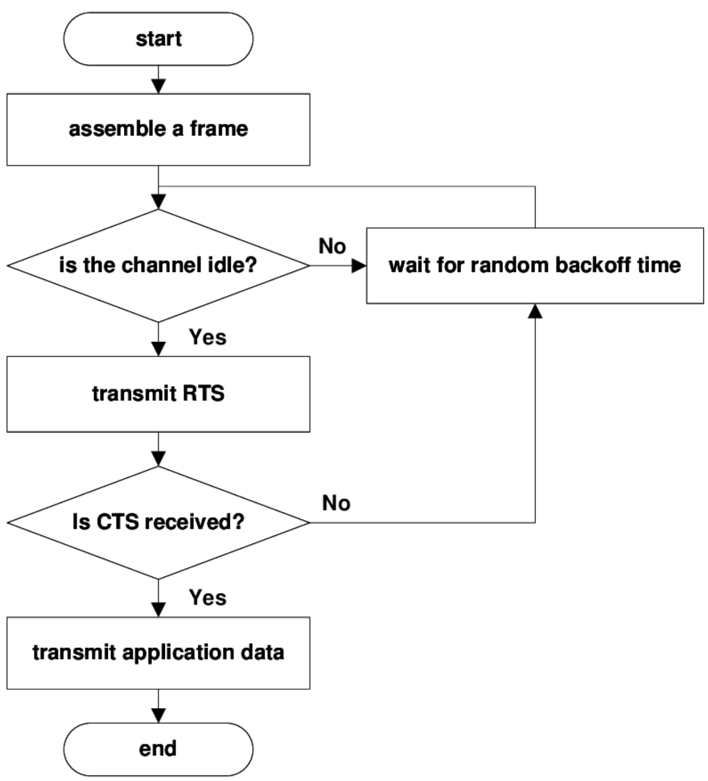

Figure 3.9 The CSMA/CA working principle

3.10 The multi-channel scenario

3.10.1 Motivation

The single channel condition present in the existing WBAN systems might create a bottleneck for real-time transmission of data from the nodes to the BNC. This is because a number of on-body nodes might want to send data simultaneously to the BNC, or do so in time intervals that are extremely close to each other. This becomes more apparent as the number of nodes increases, since there are more contenders for a single channel at any given point in time. It may so happen that the data from a given set of nodes are pushed so far in the waiting queue that they are processed at a time when they are no longer relevant, thereby rendering them completely useless. The data rate for most applications, however lies in the low kilobits per second range, and thus the bandwidth required to transmit them is also quite low (for BPSK, DBPSK, QPSK, DQPSK modulation techniques). The 402-405 MHz range that is primarily used in WBAN is excessive for such low bitrate applications. It makes sense, therefore to split up the available bandwidth into smaller channels, so that multiple channels are available for communication at any given time, thereby reducing the delay for data transmission from a node. Under such a scheme, the entire 300 kHz channel may be split up into multiple (say 4) channels each of smaller bandwidth (say 75 kHz). Each of the nodes in the system can then transmit on any of the said channels, following a certain set of rules or access technique.

3.10.2 The Multi-channel model

As specified before, for the multi-channel model, the entire available bandwidth is split up into smaller channels. If B be the available bandwidth for transmission and we create N equally wide channels, each small channel would have a bandwidth b given by

$$b_i = \frac{B-(N-1)b_s}{N} \qquad (3.1)$$

where the subscript i stands for the i^{th} channel such that $\sum_{i=1}^{N} b_i = B$ and b_s is the channel spacing between two adjacent channels. In our case, B has a value of 300kHz, so the choice of N and b_s would dictate the width of each channel. As an example, considering $N = 4$ and $b_s = 2$ kHz gives a width of 73.5 kHz to each channel. For BPSK modulation that considers only the width of the main lobe of the pulse, this would translate to a maximum bit rate of 36.75 Kbps at passband, which is more than sufficient for most WBAN applications. For QPSK at passband, this rate goes up to 73.5 Kbps. Fig 3.10 gives an idea of the proposed channel segregation. It can be seen that one amongst the 4 created channels have been assigned as the control channel, while the remaining channels have been treated as data channels. These categories are necessary as at least one control channel needs to be present to co-ordinate between the BNC and nodes correctly.

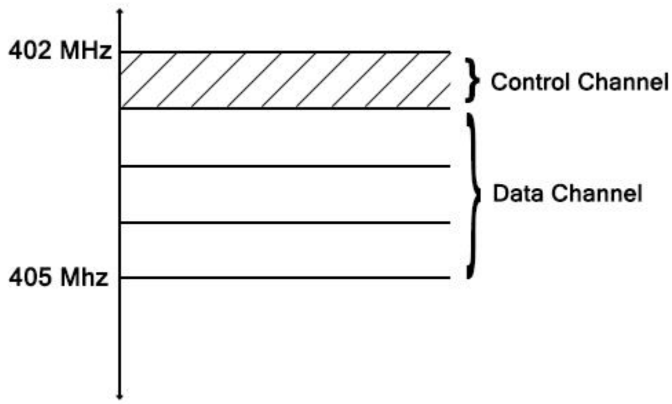

Figure 3.10 Multi-channel scenario in WBAN

3.10.3 The channel access technique

The access technique for different nodes to gain access to the requisite channels in system is of pivotal importance. In order to define the access mechanism, a few certain inherent assumptions have been made. These include:

- There are M nodes in a single coverage area, i.e. the human body, that are identical to each other except for the rate at which their data may be generated.
- Overlapping transmissions at any of the N channels causes loss of all colliding packets at that channel.

- It is assumed that the capture effect is minimal, i.e., every receiving node gets its radio signal attenuated almost similarly.
- A busy channel will not process new packets until it successfully transmits the current packet. Packet preemption is not allowed.

Fig. 3.11 shows the topological view of the proposed WBAN system.

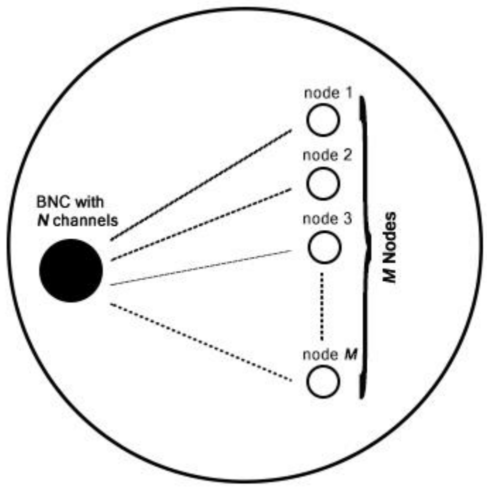

Figure 3.11 Topological view of proposed WBAN

The channel access mechanism can be described in the following way:

- During the initial setup phase, the BNC decides the channel number that each of the nodes must transmit in. It does so by allocating channels in a cyclic manner. As an example, if there are 7 nodes and 3 data channels, nodes 1,4 and 7 get channel 1, nodes 2 and 5 get channel 2, and nodes 3 and 6 get channel 3 as their allocated channels. In order for this to happen successfully, the BNC must know the number of nodes beforehand, which can be easily programmed into it at setup time.
- The nodes all listen on the control channel initially to get their allocated channels. The BNC transmits a beacon frame over the control channel during a beacon superframe. A beacon superframe consists of beacon slots, with each beacon slot mapping to each data channel. If the beacon frame is sending in the first beacon duration, it means that the first channel is reserved. The absence of a beacon frame

during any beacon slot means that the relative data channel is not reserved. By listening to the control channel, nodes know which channel is reserved for communication between a node and the BNC. For example, if node 1 listens and finds that the beacon frame during beacon slot 1 is inactive, it means that channel 1 is free and can be safely occupied. When channel 1 is occupied the beacon slot 1 is no longer inactive and thus node 2 cannot occupy it. It thus listens to beacon slot 2, finds it empty and occupies channel 2. Channel 3 is similarly occupied by node 3. After all the data channels have been occupied once and the same communicated to the nodes, all the beacon slots are again cleared up. Thus, node 4 checks beacon slot 1 and finds it empty. Thus, it gets allocated to channel 1. Node 5,6 and 7 are similarly allocated to channels 2,3 and 1. Thus the channel allocation proceeds in a cyclic fashion. Then the node that has been allocated a channel sends a data packet over the negotiated data channel to the BNC. Fig. 3.12 shows an example scenario in the described process. The transition from the state where node 2 has been allocated a channel to the state where node 3 has been allocated a channel has been shown. The same transition happens between nodes 5 and 6 being allocated channels.

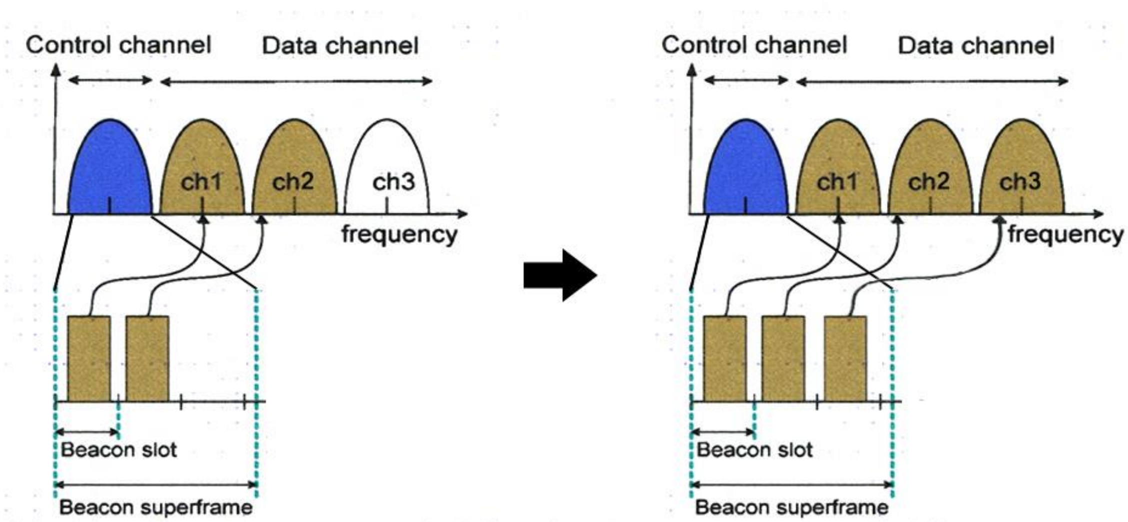

Figure 3.12 Channel allocation procedure

- Since multiple nodes have thus been mapped to every channel, the possibility of collisions arises on every channel. When a new packet arrives at a non-idle channel (i.e. a channel that is already occupied by another node), the packet will be put into a queue for that channel. The queue is infinite size, i.e. overflows do not occur.
- Before the transmission of a packet, a node generates a random back off waiting time according to the uniform distribution between 0 and T_{BACK}, the length of its back off interval. All nodes have the same value of T_{BACK} and this value does not change. It is assumed that delayed first transmission (DFT) occurs, in which new packet arrivals are subject to the random delay. It is also considered that immediate first transmission (IFT) occurs, i.e. the first packet on an idle channel is not subjected to the said back off.
- At the end of the random back off waiting time, the packet is sent.
- If the packet transmission is unsuccessful, a new random back off waiting time is generated and applied to the packet for retransmission. If the maximum number of retries has however been reached, the packet is dropped. Thus, for each channel we have a CSMA/CA technique being applied.

The unsuccessful packets back off and are sent again after a random period of time in this case, thus the channel throughput is equal to the input traffic load until the channel is saturated by the arriving packets at the network capacity.

3.10.4 Channel Aggregation

If a certain node in the network demands a higher bandwidth for high rate transmissions, then the narrow channels provided would be of limited use. Under such a scenario, a modified version of basic channel aggregation techniques can be used. The node that demands a high transmission rate must make multiple requests for channel allocation, i.e. it must make requests for channel allocation even after being allocated one channel. Thus, it must keep listening for beacons even after it is allocated one channel.

3.10.5 Summary

The multi-channel model takes advantage of the fact that the entire existing channel (402-405MHz) is not required for low rate communications, as demanded by WBAN devices. It gives scope to a larger number of devices to communicate simultaneously with the BNC, thereby reducing the network latency and increasing the throughput. In case a larger bandwidth is required for high bit rate applications, the policy of channel aggregation can be used to reserve the requisite number of channels for transmission. The only drawback of the multi-channel model is that is requires more hardware and processing at the BNC, which should not be a problem given the advanced processing capabilities of today’s systems. As an example, if a human body has 6 on-body nodes that communicate with the BNC, the single channel configuration would mean that 6 devices are simultaneously contending for access over a single channel. However, in the multi-channel scenario, assuming 3 data channels are available, it would imply that 2 nodes contend for access over each channel, thus drastically reducing the contention by a factor of almost 3. This would immensely help in scenarios where the data is time-critical in nature, which it usually is for medical applications.

3.10.6 Analysis of the proposed model

The multi-channel access technique provides a number of advantages to the designed system. The first and most obvious advantage is having a reduced latency or delay. This is because each external node, on an average has to wait for a lesser amount of time to gain access to a channel. The normalized delay D in normal CSMA/CA can be modified from what is present in [40] to have:

$$D = \left(\frac{p_{k^*} \left\lceil \frac{M}{N} \right\rceil}{R_b} - 1 \right) R + 1 + a \quad (3.2)$$

Here p_k is the payload length, M is the number of nodes in the WBAN network, N is the number of data channels, R_b is the bit rate and a is the normalized propagation time. The normalization is done with respect to the time taken to transmit a packet of data. R is the average delay between two consecutive transmissions (i.e., a retransmission) of a given packet. We have,

$$R = 1 + 2a + \alpha + \delta \quad (3.3)$$

where α is the normalized transmission time of the acknowledgement packet, and δ is the normalized average retransmission delay. Packets are retransmitted when transmissions are unsuccessful due to primarily two reasons - the “BNC busy” situation, and due to “collisions”. A multiuser receiver is unavailable only when it is currently transmitting or receiving on the same channel on which the new incoming packet is transmitted. δ thus forms an important criterion for the delay constraint and can be said to be the normalized back off delay. The ceiling function is used to correctly give an estimate of the network traffic per channel, as each channel is assigned to more than one node. For our scenario it is assumed that a is negligibly small and is excluded from our calculations. Also, for simplicity it is assumed that the acknowledgement packets are much smaller than the data packets and that they are sent over an ideal channel with negligible delay. Hence, $\alpha = 0$ and we use $R = 1 + \delta$.

Fig. 3.13 shows the concepts discussed previously in a graphical manner. The following parameters have been incorporated while generating this graph. It has been assumed that the bit rate R_b is 35 Kbps, the packet length p_k is 2 Kb, and the number of nodes M is 8.

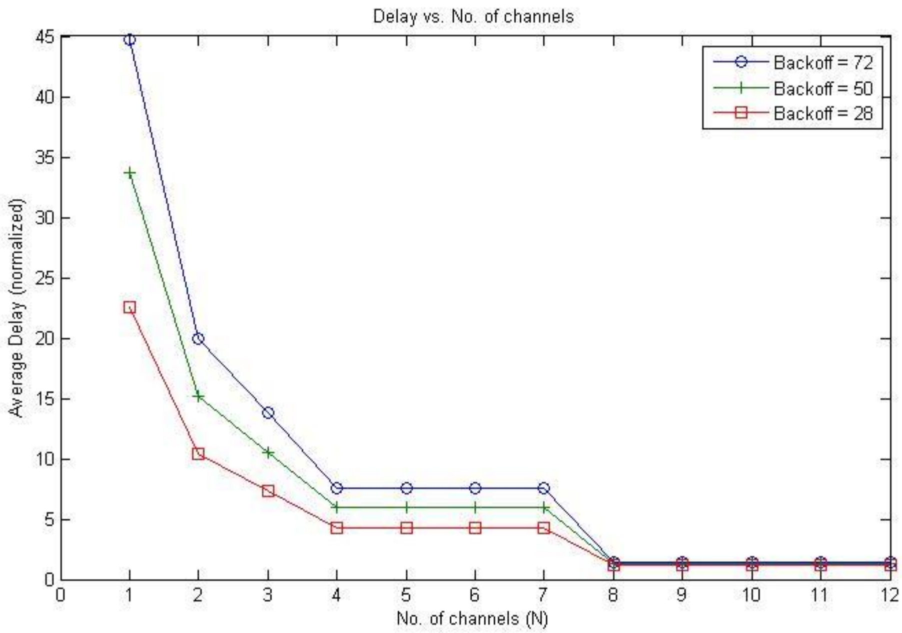

Figure 3.13 Average delay vs. No. of channels for different backoffs

It is seen that the delay increases with increasing backoff, which does prove to be quite intuitive as well. If the backoff time increases, the delay for a packet to be delivered also increases simultaneously. It is interesting to observe that the delay drops to a negligible value (only the time required to transmit a packet) once the number of channels equals or surpasses the number of nodes (8 in this case). In that case, each and every node has exclusive access to a separate channel and can carry out undelayed transmission of data, as it does not have to wait for other nodes to complete sending their data.

3.11 Conclusion

It is seen that the multi-channel design proves to be superior to the single-channel condition in terms of providing lower latency and thus better throughput. The more the number of channels, the better is the situation. However, the maximum number of channels that can be created is limited by the required bandwidth of operation of a single node. It has also been seen that the backoff time plays an important role in the design of the system. In the next chapter, this backoff interval has been modified to suit the working conditions of the network and it has been seen that a better throughput has been obtained when compared to the current techniques available.

CHAPTER 4

A PROPOSED MODIFIED BACKOFF SCHEME FOR WBAN

4.1 Introduction

As has been observed in the previous chapter, the backoff interval chosen plays an important role in determining the network performance, among other factors. In this chapter, a modified backoff scheme is described that builds upon existing techniques to provide better network performance. The scheme is described at first, and the observed results discussed at the end of the chapter.

4.2 Existing work: pros and cons

In every multi-node network, where more than one node transmits on a given channel, there is a probability of collisions. This occurs when each of the given nodes need to transmit data that does is not generated at a predefined point in time. The data being accumulated at every channel in the controller (BNC in this case) is thus random in nature with respect to the time in which it arrives at the BNC. This leads to collisions. A core functionality of a MAC layer is to provide a solution to mitigate the effects of these collisions, or design principles that reduce the possibility of one. ALOHA, for example allows data packets to be sent as soon as they are generated. A lot of other schemes also employ the ALOHA principle to reserve channels for packet transmissions, like the packet-reservation multiple access (PRMA) scheme [41].

A lot of existing MAC schemes use a feedback to ensure that data packets were received correctly, and thus mitigate the effects of collisions. Radio environments, however prove to be a much trickier challenge, as packet collisions cannot be easily detected at all. For radio environments, thus, most schemes use the principle of random back off. The node that is sending out data waits for a random period of time before retrying to send its data again. (The node understands that the data has not been received when it does not receive an acknowledgement packet.) This random period of time is what is referred to as the back off time, or in certain existing literature, as the retransmission delay. Algorithms have been developed that dynamically change the back off delay to address varying network conditions and improve its performance. Back off algorithms usually select the back off time randomly from a range of zero to a maximum time delay, referred to as the back off interval (T_{BACK}). Selecting proper values of T_{BACK} is essential, as too small a value can cause repeated collisions, while a large value would introduce unwanted latency into the system. Thus, high throughput, as well as low delay are complementary characteristics in the context of back off intervals, and algorithms that can improve the conditions of both are in demand. Fairness amongst competing nodes should also be kept in mind while designing algorithms. In a multi-channel multi-node case, each of the nodes must have a proper T_{BACK}.

The existing BEB (Binary Exponential Backoff) algorithm is widely used in several MAC schemes. Here, every node doubles its backoff interval (up to a maximum value T_{BACK}) after a collision takes place; and decreases the interval to a minimum value T_{BACK_MIN} after a successful transmission. BEB can be summarized by the following set of equations:

$$t_B \leftarrow \min(2t_B, T_{BACK}) , \quad \text{upon collision}$$

$$t_B \leftarrow T_{BACK\_MIN} , \quad \text{upon successful transmission}$$

where t_B is the backoff interval value. The values of T_{BACK_MIN} and T_{BACK} are selected based on the number of active nodes and the traffic load of the network. The simplicity of the BEB scheme makes it popular; but its fairness is relatively poor [42]. For example, when two nodes compete for channel access where one node has higher probability of data transmission and is successful in a transmission, it keeps on occupying the channel because it decreases its backoff with each successful transmission. The second node, on the other hand, keeps on increasing its back off. Thus, the first node effectively plays a monopolistic role in capturing the channel.

The MILD (Multiplicative Increase Linear Decrease) algorithm addresses this problem of fairness of channel occupancy to a certain extent. In MILD, a collided node changes its backoff interval by multiplying its existing backoff interval by 1.5. A successful node changes its backoff interval by decreasing it by one (in terms of transmission time of the RTS packet) from the existing value. A backoff interval copy mechanism used to copy the backoff intervals of overheard successful transmitters mitigates the problem of channel unfair channel occupancy. The following set of equations can be used to describe this scheme:

$t_B \leftarrow \min(1.5t_B, , T_{BACK})$, upon collision

$t_B \leftarrow t_{B\_PACK}$, upon overhearing success

$t_B \leftarrow \max(t_B - 1, T_{BACK\_MIN})$, upon successful transmission

where t_{B_PACK} is the back off interval included in the overheard packet. The MILD scheme also maintains a backoff interval for each channel instead of for every node to further improve the fairness. One drawback of this scheme is that the packet overhead is increased due to the included backoff interval in the same. Also, there is the effect of migration of backoff intervals in this case. If several areas exist with varying traffic loads in a connected network, the backoff intervals of one area will migrate to other areas. The network performance of those areas would be affected adversely, as those backoff intervals do not correctly represent the actual channel contention levels in those said areas.

4.3 The SBA scheme

The SBA (Sensing Backoff Algorithm) scheme was designed [43] to remove the adverse effects of the previous schemes and has been quite popular since its inception in the wireless sensor category of networks as well. In its design, the SBA scheme considers how fast the change of backoff intervals should be in a collided transmitter and how other nodes should respond to those changes. The BEB scheme tends to favor the last perceived successful transmitter, while the remaining nodes do not change their backoff intervals. The MILD scheme changes the backoff interval more cautiously, while allowing the remaining nodes to copy the backoff interval value from the successful packet.

The SBA scheme is so designed that the nodes sensing successful packet transmissions decrease their backoff intervals. Compared with the BEB scheme, this sensing approach improves the fairness aspect of the problem immensely. The backoff interval migration problem is also avoided, as the copy mechanism is not used. The operation of the SBA scheme also does not require precise information about the number of active nodes in a network.

In the SBA scheme, each node that experiences a packet collision increases its backoff by multiplying itself with a positive factor α, which is greater than 1. The node which has a successful transmission decreases its backoff interval by multiplying the existing backoff interval by a factor θ, which is less than 1. All active nodes sensing a successful transmission decrease their backoff intervals by β steps, each step being defined as the transmission time of a packet (t_{PACK}). The SBA operation can be described by the following set of equations:

$t_B \leftarrow \min(\alpha t_B, T_{BACK})$, upon collision

$t_B \leftarrow \max(t_B - \beta t_{PACK},\ T_{BACK\_MIN})$, upon successful packet sensing

$t_B \leftarrow \max(\theta t_B, T_{BACK\_MIN})$, upon successful transmission

The optimal backoff interval in a given area, given that the number of active nodes N_A is known, and the time required to transmit one packet is t_{PACK}, is given by $T_{BACK\_OPT} = 4N_A\, t_{PACK}$, as mentioned in [43]. On one hand, a smaller T_{BACK_OPT} leads to lower channel throughput, because of the larger probability of repeated collisions. On the other hand, a larger T_{BACK_OPT} drives nodes into a defer state too often with the channel being idle in a larger fraction of time, lowering the channel throughput as well, and increasing the latency. The SBA algorithm aims to increase the throughput of the network, by optimizing the values of the parameters α, β and θ. Based on the assumptions made in [43], the equations deciding the values of the said parameters are:

$$\alpha = 1.2$$

$$1.72(\alpha - 1) = 2(1 - \theta) + \frac{\beta}{4}$$

$$1.52(\alpha - 1) = 2(1 - \theta) + \frac{8\beta}{40}$$

The solution set for the above equations are (α = 1.2, β = 0.8, θ = 0.93).

4.4 The modified SBA scheme

Although the SBA scheme proposed in [43] does increase the network performance in terms of its throughput, an even better performance can be achieved by modifying certain parameters. The packet sensing part, in particular, forms the crux of the entire SBA scheme, and can be fine-tuned. It is seen that the backoff time is changed in the other nodes when one node sends its packets by sensing. This change in other nodes, is however in the form of a constant decrease by a value β, and does not take into consideration the existing backoff time as is done during successful transmission by a node or during collision (by the parameters θ and α respectively). The modified SBA algorithm does exactly this, and improves the network throughput over the SBA scheme. The SBA operation can be described by the following set of equations:

$$t_B \leftarrow \min(at_B, T_{BACK}) \,, \quad \text{upon collision} \quad (4.1a)$$

$$t_B \leftarrow \max(t_B - \frac{bt_{PACK}}{t_B},\ T_{BACK\_MIN}) \,, \quad \text{upon successful packet sensing} \quad (4.1b)$$

$$t_B \leftarrow \max(ct_B, T_{BACK\_MIN}) \,, \quad \text{upon successful transmission} \quad (4.1c)$$

Here, the parameter a is greater than 1 and c is less than 1. By taking into account the existing backoff interval value while updating it during sensing, the modified SBA scheme provides a better control over its adaptivity. The values of the parameters a, b and c can be obtained in the manner described next.

The change in the backoff intervals of all nodes in the network should approach zero asymptotically, when the system would be in equilibrium. The change in this backoff interval is given by ΔT_{BACK}. We have,

$$\Delta T_{BACK}(t) = \Delta T_{BACK}^{S}(t) + \Delta T_{BACK}^{C}(t) \quad (4.2)$$

where $\Delta T_{BACK}^{S}(t)$ and $\Delta T_{BACK}^{C}(t)$ are the net change of T_{BACK} due to the successful transmissions and the collided transmissions, respectively, in the period of time t. In the calculation of these two parameters, it is assumed that the successful and collided transmissions are sent by nodes that have a backoff interval of T_{B_AVG}, which is the average of the backoff intervals over a time t. The objective is to find optimal values of the parameters a, b, c to maintain T_{B_AVG} as close as possible to $T_{BACK\_OPT} = 4N_A\, t_{PACK}$, so that network throughput is maximized.

Every node changes its backoff interval from T_{B_AVG} to cT_{B_AVG} with a net change of $(c\text{-}1)T_{B\_AVG}$, after a successful transmission. All other nodes change their backoff intervals by b/T_{B_AVG}, thus resulting in a net change in T_{BACK} of $(-b/T_{B\_AVG})(t_{PACK})(N_A\text{-}1)$. So, $\Delta T_{BACK}^{S}(t)$ can be written as

$$\Delta T_{BACK}^{S}(t) = \rho^{s}(t)\left[(c-1)T_{BAVG} - \frac{bt_{PACK}}{T_{BAVG}}(N_A - 1)\right] \quad (4.3)$$

where $\rho^{s}(t)$ is the total number of successful transmissions in a time t.

The nodes multiply their backoff interval by a after each collided transmission, with a net change in T_{BACK} of $(a-1)T_{B\_AVG}$. So, we have $\Delta T^{C}_{BACK}(t)$ as

$$\Delta T^{C}_{BACK}(t) = \rho^{c}(t)[(a-1)T_{BAVG}] \tag{4.4}$$

where $\rho^{c}(t)$ is the total number of collided packets in a time t.

The net change of T_{BACK} should tend to zero. Thus $\lim_{t\to\infty} \frac{\Delta T_{BACK}(t)}{t} \approx 0$, or we have

$$\lim_{t\to\infty} \frac{\rho^{s}(t)\left[(c-1)T_{BAVG} - \frac{bt_{PACK}}{T_{BAVG}}(N_A - 1)\right] + \rho^{c}(t)[(a-1)T_{BAVG}]}{t}$$

should equal to zero, which can be rearranged as:

$$\lim_{t\to\infty} \frac{\rho^{s}(t)T_{BAVG}}{t}\left\{\left[(c-1) - \frac{bt_{PACK}}{T^{2}_{BAVG}}(N_A - 1)\right] + \frac{\rho^{c}(t)}{\rho^{s}(t)}[(a-1)]\right\}$$

Now, since $\lim_{t\to\infty} \frac{\rho^{S}(t)T_{BAVG}}{t}$ cannot be equal to zero, we have the master equation as

$$\lim_{t\to\infty} \frac{\rho^{c}(t)}{\rho^{s}(t)}(a-1) = (1-c) + \frac{bt_{PACK}}{T^{2}_{BAVG}}(N_A - 1) \tag{4.5}$$

To evaluate $\lim_{t\to\infty} \frac{\rho^{c}(t)}{\rho^{s}(t)}$, we assume that the number of busy periods [43] in a time t is $n(t)$. The total number of successful packets is then given by:

$$\rho^{s}(t) = n(t).P_s$$

where P_S is the probability that no other nodes transmit in the duration t_{PACK} and is given by [43] as

$$P_S = \left(1 - \frac{2t_{PACK}}{T_{BACK}}\right)^{N_A - 1} \tag{4.6}$$

The total number of collided packets is given by

$$\rho^c(t) = n(t)(1 - P_S)(L + 1) \qquad (4.7)$$

where it is assumed that there are $L + 1$ packets in each failed busy period. L is given by [43] as

$$L = \left(\frac{T_{BACK}}{T_{BACK} - 2t_{PACK}}\right)^{N_A} \qquad (4.8)$$

Thus,

$$\lim_{t\to\infty} \frac{\rho^c(t)}{\rho^s(t)} = \frac{(1 - P_S)(L + 1)}{P_S}$$

which on simplification, yields

$$\lim_{t\to\infty} \frac{\rho^c(t)}{\rho^s(t)} = \left(\frac{T_{BACK}}{T_{BACK} - 2t_{PACK}}\right)^{2N_A - 2} - 1 \qquad (4.9)$$

Putting this value back in the master equation, and utilizing $T_{BACK} = 4N_A\, t_{PACK}$ for the optimal case, we get

$$\left(\left[\frac{4N_A\, t_{PACK}}{4N_A\, t_{PACK} - 2t_{PACK}}\right]^{2N_A - 2} - 1\right)(a - 1) = (1 - c) + \frac{b}{16{N_A}^2\, t_{PACK}}(N_A - 1)$$

which on simplification, yields

$$\left(\left[\frac{2N_A}{2N_A - 1}\right]^{2N_A - 2} - 1\right)(a - 1) = (1 - c) + \frac{b}{16{N_A}^2\, t_{PACK}}(N_A - 1) \qquad (4.10)$$

The parameter *a* can be chosen as per requirement, as discussed later (a value of 1.02 can be chosen for optimal performance). By setting N_A to values of infinity (this is because choosing infinity nodes can asymptotically guarantee the best throughput), and a nominal value of eleven, we obtain equations that allow us to get values of parameters *b* and *c*. These are given below.

$$a = 1.02 \quad (4.11a)$$

$$1.52(a-1) = (1-c) \quad (4.11b)$$

$$1.535(a-1) = (1-c) + \frac{b}{1936\, t_{PACK}} \quad (4.11c)$$

A set of solutions, assuming the packet time to be 50ms, which is applicable to WBAN systems, gives the following set of values (*a* = 1.02, *b* = 0.0075, *c* = 0.97).

4.5 Throughput and Energy considerations

The channel throughput *S* of a channel [44] can be given as

$$S \cong \frac{P_S.\overline{U}}{P_S.\overline{T_S} + (1-P_S).\overline{T_f} + \overline{I}} \quad (4.12)$$

where P_S is the probability of successful packet transmissions, $\overline{U}$, $\overline{T_S}$, $\overline{T_f}$ and $\overline{I}$ are the average duration of the utilization period, the duration of the successful busy period, the duration of the failed busy period, and the duration of the idle period, respectively. This equation is an approximation, although a viable one, because each random variable has been replaced with its average value.

The energy efficiency ρ_{energy} is given as [45]

$$\rho_{energy} = \frac{E[Energy_{succ}]}{E[Energy_{transmission}] + E[Energy_{idle}]} \quad (4.13)$$

where $E[Energy_{succ}]$ is the average energy consumed by a successful transmission, $E[Energy_{transmission}]$ is the average energy spent during transmission and $E[Energy_{idle}]$ is the average energy consumed during idle time which simplifies to [45]

$$\rho_{energy} = \frac{t_{PACK}\left(1-\frac{2t_{PACK}}{T_{BACK}}\right)^{N_A-1}}{t_{PACK}\left[2-\left(1-\frac{2t_{PACK}}{T_{BACK}}\right)^{N_A-1}\right] + \frac{T_{BACK}}{2N_A}} \quad (4.14)$$

4.6 Performance Analysis

A plot of the throughput versus the total number of active nodes has been provided in Fig. 4.1 following our improved SBA scheme. It is seen that the choice of the parameter '*a*' dictates the throughput performance of the network. A value of a = 0.6 provides the best performance. The throughput naturally falls as the number of contenders on the network increase. Also, it is seen that a value less than one of '*a*' severely affects the throughput performance, although the severity decreases with the increasing number of active nodes. The output curves for a = 1.06 and a = 1.02 show that the throughput is indeed improved over the existing SBA scheme.

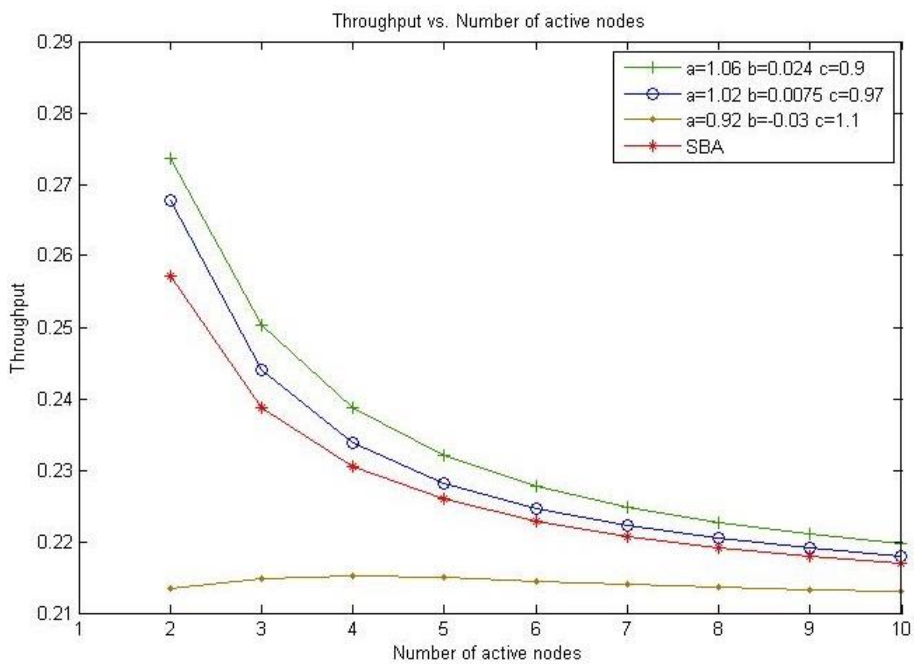

Figure 4.1 Throughput vs. Number of active nodes

Fig. 4.2 highlights the variation of the throughput with varying values of '*a*'. It is seen that the curves peak at specific values of '*a*' depending on the number of nodes active in the channel. Also, the peaks get lowered with increasing values of N_A. These curves may be used to choose appropriate values of '*a*' depending on the values of N_A. This also sets the precedence for using an adaptive algorithm to change the values of '*a*' depending on the network conditions, as will be discussed later.

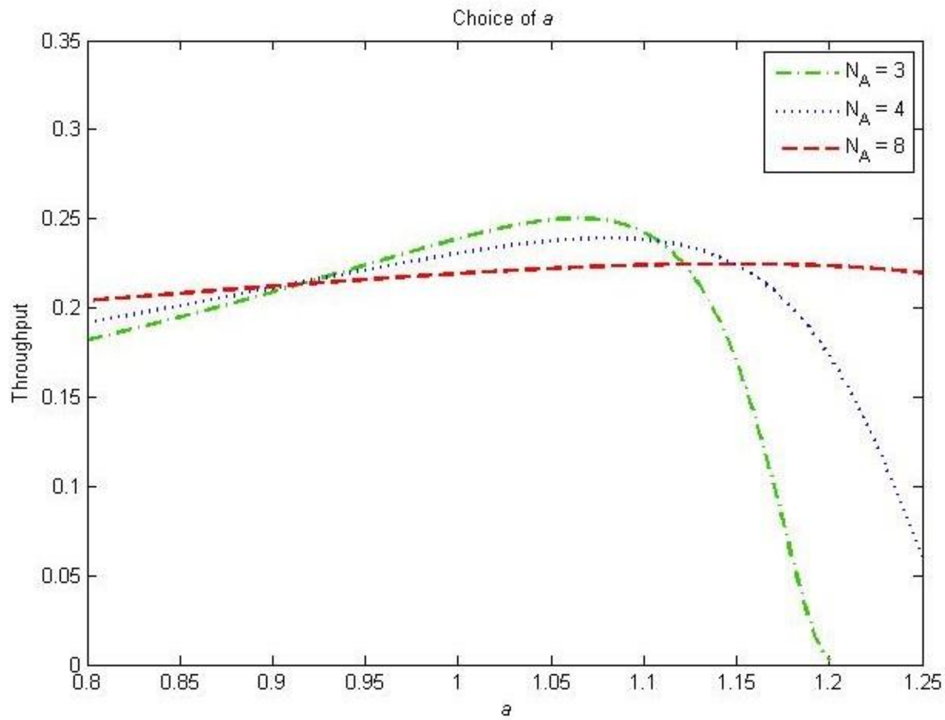

Figure 4.2 Choice of the parameter *a* for throughput

For the energy consideration, we see in Fig. 4.3 that the modified SBA scheme does improve over the SBA scheme, but to a lesser extent than that of the network throughput improvement. The energy efficiency also falls off as the number of active nodes increase, and is dependent on the choice of '*a*'.

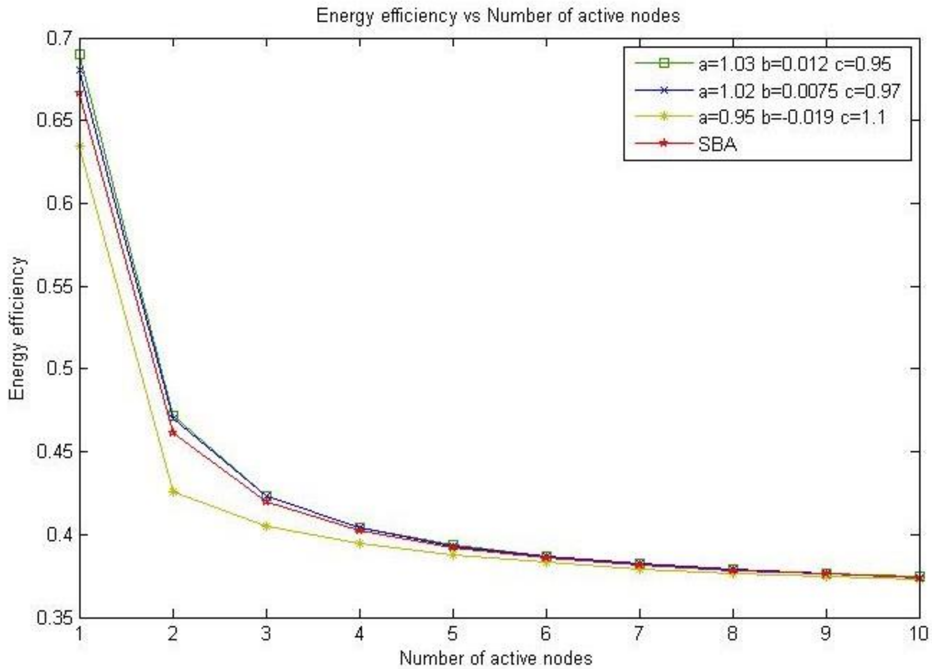

Figure 4.3 Energy efficiency vs. Number of active nodes

Fig. 4.4 highlights the variation of the energy efficiency with changing values of '*a*'. As

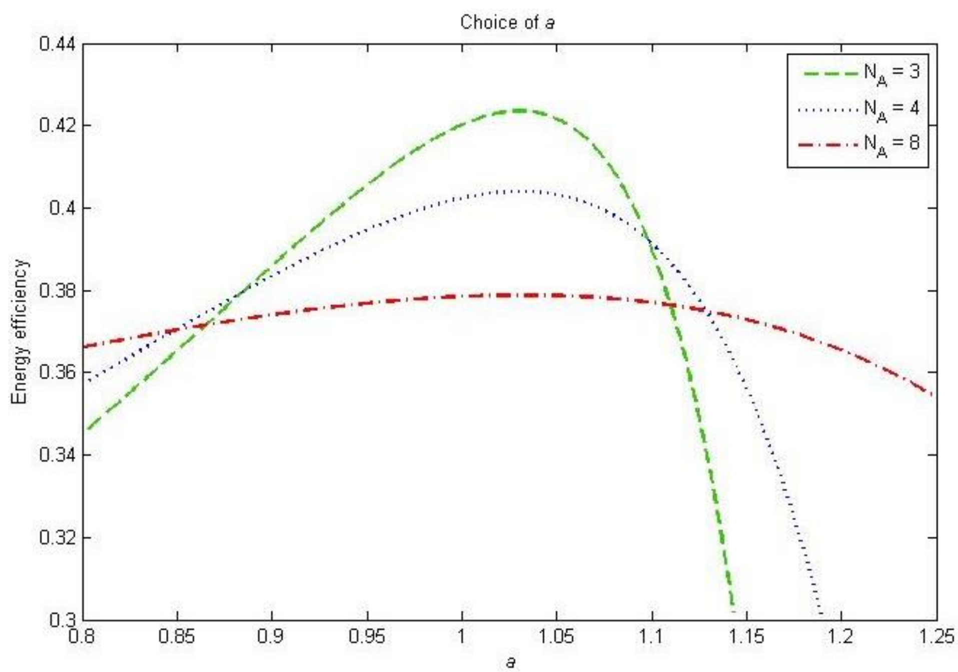

Figure 4.4 Choice of the parameter *a* for energy efficiency

seen in the case of throughput, the curves peak at a certain value of '*a*', the peaks being higher at lower values of N_A. As discussed before, the value of '*a*' can thus be adaptively selected to provide a better energy efficiency if the number of active nodes in the network can be estimated.

Fig. 4.5 provides an insight into the overall choice of '*a*' and compares it with the performance of the SBA scheme for $\alpha = 1.2$ for the condition where the number of active nodes is 4. It is seen that within the modified SBA scheme itself, the choice of '*a*' would determine if the user wants to give priority to the throughput or the energy efficiency, as the said curves peak at different points, albeit very close ones. The regions where the modified scheme works better than the SBA scheme can also be seen clearly (for $a>1$ as discussed previously). It can be seen that to have good throughput characteristics as well as good energy efficiency, values from 1.03 to 1.06 can be assigned to '*a*'.

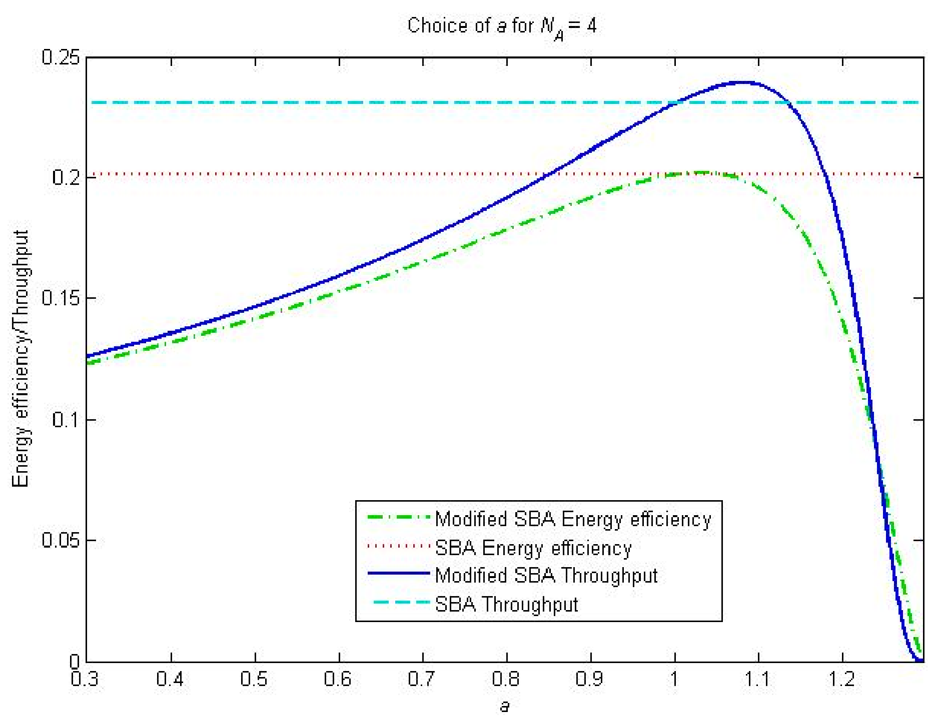

Figure 4.5 Choice of *a* for the modified SBA scheme

4.7 Conclusion

The proposed modified SBA scheme does increase the throughput of the network, while providing good energy efficiency as compared to the SBA scheme. However, the fact that the optimum '*a*' changes with changing values of N_A can be used to construct an adaptive algorithm that uses the estimates of N_A to dynamically change the value of '*a*'. Such an algorithm would increase the efficiency of the system even further, while placing a larger burden on the computational complexity of the devices. WBAN being an immensely power constrained network, the possibility of such a scheme has not been explored further. Some sparse work has been done on the said adaptive scheme though, as can be seen in [45].

The next chapter deals with further optimizing the network, this time with respect to the payload or packet size used for transmission of data in the said WBAN network. It has been seen that characteristics of the network like delay/latency and bit error rate can be improved in this way.

CHAPTER 5

PACKET LENGTH OPTIMIZATION IN WBAN

5.1 Introduction

As discussed in the previous chapter, several parameters of a multi-channel WBAN network can be optimized and improved to provide better network performance. Towards that end, this chapter aims to find an optimal working condition for the network, that has acceptable delay and bit error rate characteristics. The parameter that has been optimized is the payload or packet length that the nodes transmit to the BNC. A classical constrained optimization technique, called the Karush–Kuhn–Tucker (KKT) optimization technique has been performed to find the optimal packet length. It has also been observed that based on certain requirements, the optimal solution can be changed. Thus, this provides a flexible network configuration that can changed as per requirement.

5.2 Optimization techniques

WBAN devices possess a small form factor and are power constrained in nature. Thus, dynamic and evolutionary optimization techniques cannot be applied in their case, as they would require larger processing power and would consume more energy. Classical optimization techniques provide an easier solution, as they do not require to be updated on every iteration, thus consuming lesser energy and processing power. However, since wireless networks can themselves be dynamic in nature, classical optimization techniques that only have the capability to produce a global optima can be inappropriate to serve the required needs. Constrained optimization, on the other hand provides the opportunity to bind in the restrictions of the system into the optimization and thus offer more flexible and robust solutions. Broadly speaking, optimization can be categorized into the following types:

- *Continuous Optimization vs. Discrete Optimization*

  Some models only make sense if the variables take on values from a discrete set, often a subset of integers, whereas other models contain variables that can take on any real value. Models with discrete variables are discrete optimization problems; models with continuous variables are continuous optimization problems.

- *Unconstrained Optimization vs. Constrained Optimization*

  Another important distinction is between problems in which there are no constraints on the variables and problems in which there are constraints on the variables. Unconstrained optimization problems arise directly in many practical applications. Constrained optimization problems arise from applications in which there are explicit constraints on the variables. The constraints on the variables can vary widely from simple bounds to systems of equalities and inequalities that model complex relationships among the variables.

- *None, One or Many Objectives*

  Most optimization problems have a single objective function, however, there are interesting cases when optimization problems have no objective function or multiple objective functions. Feasibility problems are problems in which the goal is to find values for the variables that satisfy the constraints of a model with no particular objective to optimize

- *Deterministic Optimization vs. Stochastic Optimization*

  In deterministic optimization, it is assumed that the data for the given problem are known accurately. In optimization under uncertainty, or stochastic optimization, the uncertainty is incorporated into the model. Robust optimization techniques can be used when the parameters are known only within certain bounds; the goal is to find a solution that is feasible for all data and optimal in some sense.

Most optimization problems employ the use of an objective function that takes into consideration the parameters to be optimized, along with enforced constraints (if any). It then tries to find an extremum for the objective function within a region. The extremum for the function is usually found by considering gradients and the point(s) at which it is zero.

In this work, the KKT optimization technique has been used to optimize the packet length based on some constraints for other parameters of the WBAN network. The reason for choosing such parameters, and the KKT technique in general, is discussed in the later sections.

5.3 Parameters for optimization

To optimize the packet length of data packets sent out by the nodes, a set of characteristics or parameters of the network that are directly or indirectly affected by the said packet length have to be chosen. The delay incurred in a network, is an example of such a characteristic. When the packet length is increased, and a certain node is transferring its data to the BNC, the other nodes using the same channel have to wait for a longer period of time to send out its packets of data, thereby increasing the delay for the data for those other nodes. Another example of such a characteristic is the packet error probability or the packet error ratio. For a fixed bit error ratio, the packet error rate decreases as the number of bits in the packet (i.e. the packet length) increases. These two parameters are vital for the functioning of any network and are thus considered. In the context of a WBAN, these parameters are even more critical. If the delay of the packet transmission increases and goes beyond a certain specified limit, the communication will no longer be real time and will thus be useless. On the other hand, if the packet error ratio is not appreciably low as well, a lot of erroneous data will be transmitted and will again prove to be useless.

5.3.1 Delay

The relation between delay *D* and the packet length p_k has already been provided in chapter 3 and is reproduced here for convenience.

$$D = \left(\frac{p_k * \left\lceil \frac{M}{N} \right\rceil}{R_b} - 1 \right) R + 1 + a$$

Here p_k is the payload length, *M* is the number of nodes in the WBAN network, *N* is the number of data channels, R_b is the bit rate and *a* is the normalized propagation time. The normalization is done with respect to the time taken to transmit a packet of data. *R* is the average delay between two consecutive transmissions (i.e., a retransmission) of a given packet. We have,

$$R = 1 + 2a + \alpha + \delta$$

where α is the normalized transmission time of the acknowledgement packet, and δ is the normalized back off delay. Packets are retransmitted when transmissions are unsuccessful due to primarily two reasons - the “BNC busy” situation, and due to “collisions”. The ceiling function is used to correctly give an estimate of the network traffic per channel, as each channel is assigned to more than one node. For our scenario it is assumed that *a* is negligibly small and is excluded from our calculations. Also, for simplicity it is assumed that the acknowledgement packets are much smaller than the data packets and that they are sent over an ideal channel with negligible delay. Hence, $\alpha = 0$ and we use $R = 1 + \delta$. So, the final expression for the delay is given as

$$D = \left(\frac{p_{k^*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right)(1 + \delta) + 1 \quad (5.1)$$

The value of δ can be obtained from calculations made in the previous chapter, if the active number of contenders in each channel can be properly estimated [45]. It can also be chosen based on the application, as specified in [46]. Based on the assumption made in [46], we have δ as

$$\delta = \frac{CW_{min}}{2} * T_S \quad (5.2)$$

Where CW_{min} represents the minimum width of the contention window during the RAP period, and T_S is the slot time. CW_{min} can be chosen based on the application considered and the user priority defined as shown in Table 5.1 [46].

User priority	**Traffic designation**	**CW_{min}**
0 (Lowest)	Background	16
1	Best effort	16
2	Excellent effort	8
3	Video	8
4	Voice	4
5	Medical data or network control	4
6	High-priority medical data or network control	2
7 (Highest)	Emergency or medical implant event report	1

Table 5.1 User priority mapping and contention window bounds [46]

Fig 5.1 shows a plot of the average normalized delay D against the packet length p_k. It can be seen that as the number of channels increase, the delay decreases as previously explained.

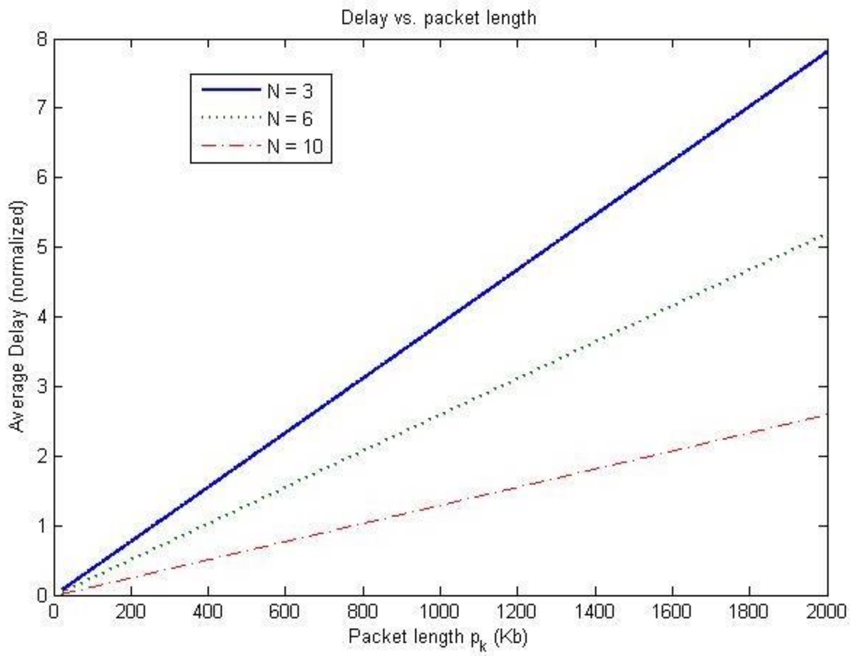

Figure 5.1 Delay vs. packet length

Also, as the packet length increases, the delay increases linearly as can be observed from the equation itself. The speed has been considered to be 30Kbps and the number of nodes *M* has been considered to be 8 as before.

5.3.2 Packet error ratio

The packet error ratio (PER) is a measure of the correctness of the received data packets. It thus serves as a measure to determine if the received packet contains data that was originally sent or has been hampered due to any reason whatsoever. Calculation of the packet error ratio, however requires knowledge of the bit error ratio (BER). The bit error ratio can be considered as an approximate estimate of the bit error probability. If the BER is denoted by its initials, then the probability that a received bit is correct is given by *(1 –*

BER). The probability that all such p_k bits in a packet is correct (i.e. the packet does not contain any errors) is thus $(1 - BER)^{pk}$. Thus, the PER is

$$PER = 1 - (1 - BER)^{p_k} \quad (5.3)$$

The BER, in turn depends on the modulation technique that is used during transmission. As WBAN primarily uses BPSK and QPSK modulation techniques, these have been focused on.

5.3.2.1 BPSK modulation

Binary Phase Shift Keying (BPSK) is a two-phase modulation scheme, where the 0's and 1's in a binary message are represented by two different phase states in the carrier signal. The constellation diagram for BPSK as shown in Fig. 5.2 has two constellation points, lying entirely on the x axis (in phase). It has no projection on the y axis (quadrature). This means that the BPSK modulated signal will have an in-phase component but no quadrature component. This is because it has only one basis function. The carrier phases are 180∘ apart and it has a constant envelope. The carrier's phase contains all the information that is being transmitted.

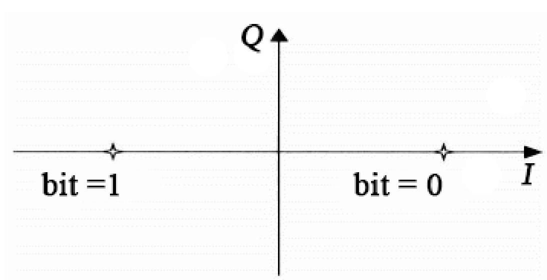

Figure 5.2 BPSK constellation diagram

The BER in BPSK is given by

$$BER_{BPSK} = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (5.4)$$

where E_b is the energy per bit used and N_0 is the noise density, and *erfc* denotes the complementary error function. E_b/N_0 (the energy per bit to noise power spectral density ratio) is an important parameter in any digital communication system. It is a normalized signal-to-noise ratio (SNR) measure, also known as the "SNR per bit".

The PER, when BPSK is used is thus given by

$$PER_{BPSK} = 1 - \left[1 - \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)\right]^{p_k} \tag{5.5}$$

5.3.2.2 QPSK modulation

Quadrature Phase Shift Keying (QPSK) is a form of phase modulation technique, in which two information bits (combined as one symbol) are modulated at once, selecting one of the four possible carrier phase shift states. The constellation diagram for QPSK as shown in Fig. 5.3 has four constellation points. A QPSK modulated signal will have an in-phase component as well as a quadrature component. This is because it has only two basis functions. The carrier phases are 90∘ apart and it has a constant envelope. The carrier's phase contains all the information that is being transmitted.

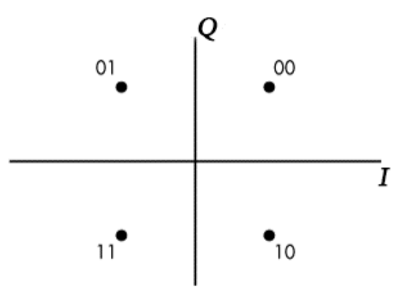

Figure 5.3 QPSK constellation diagram

The BER in QPSK is given by

$$BER_{QPSK} \leq erfc\left(\sqrt{\frac{E_b}{2N_0}}\right) + \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$$

which can be approximated by using a tighter bound [1] as

$$BER_{QPSK} \approx erfc\left(\sqrt{\frac{E_b}{2N_0}}\right)$$

The PER, when QPSK is used is thus given by

$$PER_{QPSK} = 1 - \left[1 - erfc\left(\sqrt{\frac{E_b}{2N_0}}\right)\right]^{p_k} \tag{5.6}$$

The PER vs. packet length characteristic is shown in Fig. 5.4.

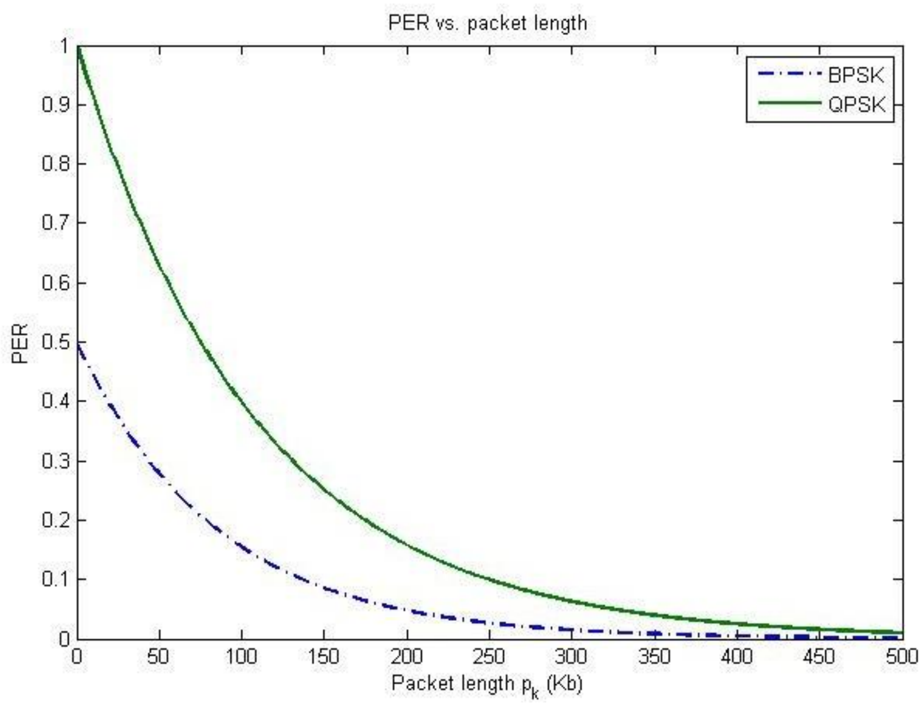

Figure 5.4 PER vs. packet length

The SNR considered is 10dB. The variation in PER between BPSK and QPSK modulation can be seen. Also, it is seen that the packet error ratio falls off as the packet length increases, as is expected.

5.4 Karush–Kuhn–Tucker (KKT) conditions for optimization

The Karush–Kuhn–Tucker (KKT) conditions are first derivative tests necessary conditions for a solution in nonlinear programming to be optimal, provided that some regularity conditions are satisfied. The KKT approach to nonlinear optimization generalizes the method of Lagrange multipliers, which allows only equality constraints, by allowing inequality constraints. The Kuhn-Tucker conditions are both necessary and sufficient if the objective function is concave and each constraint is linear or each constraint function is concave, i.e. the problems belong to a class called the convex programming problems. The KKT conditions have been described below.

The general mathematical programming problem is considered

$$minimize\ f(x), x \in R^n$$

$$subject\ to\ g_i(x) \leq 0, \quad i = 1, \ldots.., p$$

$$h_j(x) = 0, \quad j = 1, \ldots.., q$$

where $f, g_i . h_j$ are all continuously differentiable functions and form the Lagrangian function

$$L(x, \lambda, \mu) = f(x) + \sum_{i=1}^{p} \lambda_i g_i(x) + \sum_{j=1}^{q} \mu_j h_j(x) \quad (5.7)$$

The KKT optimality conditions are then

$$\frac{\partial}{\partial x_k} L(x, \lambda, \mu) = 0, \;\; k = 1, \ldots.., n \quad (5.7a)$$

$$\lambda_i \geq 0, \;\; i = 1, \ldots., p \quad (5.7b)$$

$$\lambda_i g_i(x) = 0, \;\; i = 1, \ldots., p \quad (5.7c)$$

$$g_i(x) \leq 0, \;\; i = 1, \ldots., p \quad (5.7d)$$

$$h_j(x) = 0, \; j = 1, \ldots., q \quad (5.7e)$$

Here, *n* is the number of variables on which the optimization has been done. The *g(x)*'s specify the inequality constraints and the *h(x)*'s specify the equality constraints. Either one or both of these constraints can be present in the system being modelled. Correspondingly, the λ's and the μ's are the Lagrangian multipliers for these constraints. There are *p* inequality constraints and *q* equality constraints.

5.5 Problem formulation

One of the primary reasons for choosing KKT as a method of optimization in the context is its ability to incorporate inequality constraints into itself. Also, since the PER is a non-linear function, a non-linear optimization method has to be used. The main objective of the proposed WBAN system is to reduce the PER while keeping the delay below a certain recommended value. The objective function thus has been formulated in the following way. Since the variable to be optimized is the packet length, the objective function is designed to be a function of the packet length p_k. We have,

$$f(p_k) = \left(\frac{p_{k*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right).(1 + \delta) + 1 + 1 - \left[1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]^{p_k} \quad (5.8)$$

or,

$$f(p_k) = \left(\frac{p_{k*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right).(1 + \delta) - \left[1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]^{p_k} + 2 \quad (5.9)$$

where y = (1/2) and z = 1 for BPSK modulation, and y = 1 and z = 2 for QPSK modulation.

The inequality constraint can be given as

$$g(p_k) = \left(\frac{p_{k*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right).(1 + \delta) + 1 \leq D_{max} \quad (5.10)$$

where D_{MAX} is the maximum allowable delay that can be incorporated into the system and would depend on the application of the WBAN system.

Thus, the Lagrangian function can be written as

$$L(p_k) = \left(\frac{p_{k^*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right).(1+\delta) - \left[1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]^{p_k} + 2 + \lambda\left\{\left(\frac{p_{k^*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right).(1+\delta) + 1 - D_{max}\right\} \quad (5.11)$$

Differentiating with respect to p_k and setting the result to 0, as demanded by KKT, we get

$$\left\lceil\frac{M}{N}\right\rceil\left(\frac{1}{R_b}\right)(1+\delta) - \left[1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]^{p_k} \ln\left[1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right] + \lambda\left\{\left\lceil\frac{M}{N}\right\rceil\left(\frac{1}{R_b}\right)(1+\delta)\right\} = 0 \quad (5.12)$$

Also,

$$\lambda\left\{\left(\frac{p_{k^*}\left\lceil\frac{M}{N}\right\rceil}{R_b} - 1\right).(1+\delta) + 1 - D_{max}\right\} = 0 \quad (5.13)$$

Equations (5.12) and (5.13) are the final results of the KKT optimization process.

Now, let

$$Q = 1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right) \quad (5.14)$$

$$R = \left\lceil\frac{M}{N}\right\rceil\left(\frac{1}{R_b}\right)(1+\delta) \quad (5.15)$$

where Q and R have been used to shorten the equations.

Then, from (5.12), we have

$$R - Q^{p_k}\ln Q + \lambda R = 0 \quad (5.16)$$

Also, from (5.13) by putting in the value of R, we have

$$\lambda\left\{\left(p_k - \frac{R_b}{\left\lceil\frac{M}{N}\right\rceil}\right)R + 1 - D_{max}\right\} = 0 \quad (5.17)$$

Assuming the constrained optimization case, (i.e. $\lambda \neq 0$), we have

$$p_k = \frac{D_{max}-1}{R} + \frac{R_b}{\left\lceil \frac{M}{N} \right\rceil} \tag{5.18}$$

or,

$$p_k = \frac{D_{max}-1}{\left\lceil \frac{M}{N} \right\rceil \left(\frac{1}{R_b}\right)(1+\delta)} + \frac{R_b}{\left\lceil \frac{M}{N} \right\rceil} \tag{5.19}$$

and from (5.16), λ as

$$\lambda = \frac{Q^{p_k} \ln Q - R}{R} \tag{5.20}$$

or,

$$\lambda = \frac{\left[1-y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]^{p_k} \ln\left[1-y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]}{\left\lceil \frac{M}{N} \right\rceil \left(\frac{1}{R_b}\right)(1+\delta)} - 1 \tag{5.21}$$

If we have, $\lambda > 0$, then the optimal packet length would be given by (5.19). This is for the constrained case, when the function might not have a clear minimum in the region of interest.

However, if $\lambda = 0$, for the unconstrained case, when there is a clear minimum in the defined region of interest, we have from (5.16)

$$R - Q^{p_k} \ln Q = 0 \tag{5.22}$$

This would the optimal packet length is given by

$$p_k = \ln\left(\frac{R}{\ln Q}\right) \Big/ \ln Q \tag{5.23}$$

or,

$$p_k = \ln\left(\frac{\left\lceil \frac{M}{N} \right\rceil \left(\frac{1}{R_b}\right)(1+\delta)}{\ln\left\{1-y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right\}}\right) \Bigg/ \ln\left\{1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right\} \tag{5.24}$$

Equation (5.24) gives the optimal packet length in the unconstrained case. In most cases, it has been seen that the optimal packet length is guided by equation (5.24).

5.6 Energy considerations

Since the SNR per bit already incorporates an energy term inside it, calculation of the energy per packet is quite easy. We have,

$$PER = 1 - \left[1 - y.erfc\left(\sqrt{\frac{E_b}{z.N_0}}\right)\right]^{p_k} \tag{5.25}$$

y and *z* depending on the modulation scheme as discussed before.

Thus,

$$\left(\frac{1-(1-PER)^{p_k}}{y}\right) = erfc\left(\sqrt{\frac{E_b}{zN_0}}\right) \tag{5.26}$$

or,

$$E_b = zN_0\left[erfc^{-1}\left(\frac{1-(1-PER)^{p_k}}{y}\right)\right]^2 \tag{5.27}$$

Assuming Bernoulli packet transmission, the average number of transmissions per packet for successful packet transmission [47] is $({}^{1}/{}_{1-PER})$.

Thus, the total energy per successful transmitted bit [47] is given as

$$E_{b\_total} = \frac{zN_0}{1-PER}\left[erfc^{-1}\left(\frac{1-(1-PER)^{p_k}}{y}\right)\right]^2 \tag{5.28}$$

5.7 Observations

The objective function $f(p_k)$ has been plotted in Fig 5.5 for the BPSK modulation case. The values of the parameters used are a bit rate of 30Kbps, a backoff of 28ms, 8 nodes and 3 available channels. It is seen that the functions possess a certain minima in the region shown in the figure. The reason for this is the opposing nature of the PER and delay

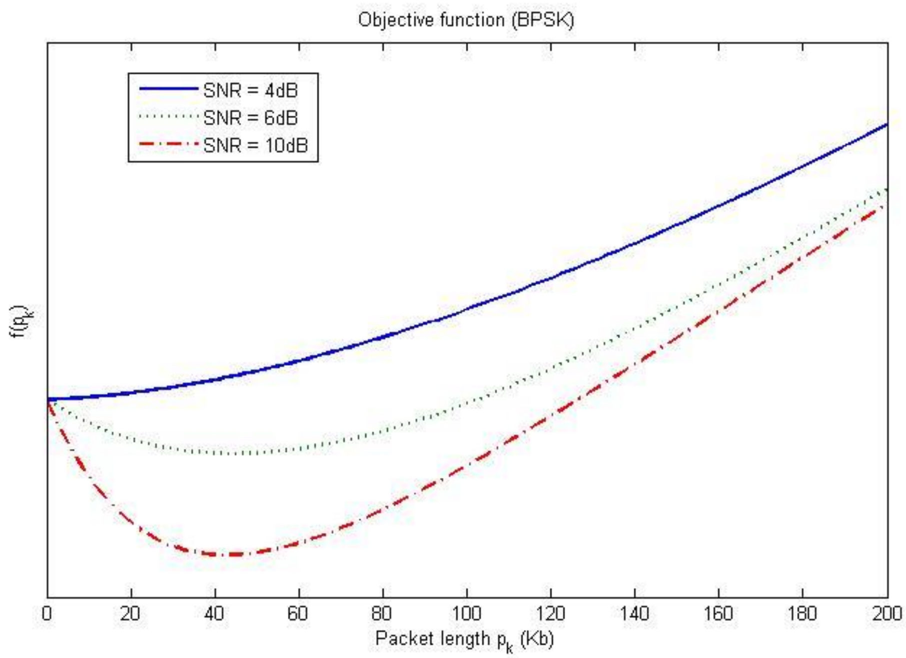

Figure 5.5 Objective function for BPSK

functions. With the increase in packet length, the delay increases but the PER decreases. Thus, the unconstrained solution as given by equation (17) would be applicable. For example, when the SNR per bit is 10dB, and there is no constraint on the delay or PER, we would have an optimal packet length of 44Kb, as can be seen in the figure. This optimal length changes to 39Kb when the SNR per bit becomes 6dB. It is seen that with the increase of the SNR per bit, the optimal packet length decreases. This can explained in the following way: as the SNR per bit increases, the PER decreases (the PER being a decreasing function with respect to to the packet size, whose rate of decrease increases with the increase in SNR per bit, we get low PER even at smaller packet sizes when the SNR per bit is increased). Thus, with higher SNR per bit and thus lower PER, we get smaller packet sizes. This is also favorable for the delay condition, as the delay increases with the packet length.

Fig. 5.6 shows the objective function for the QPSK modulation case. The parameters

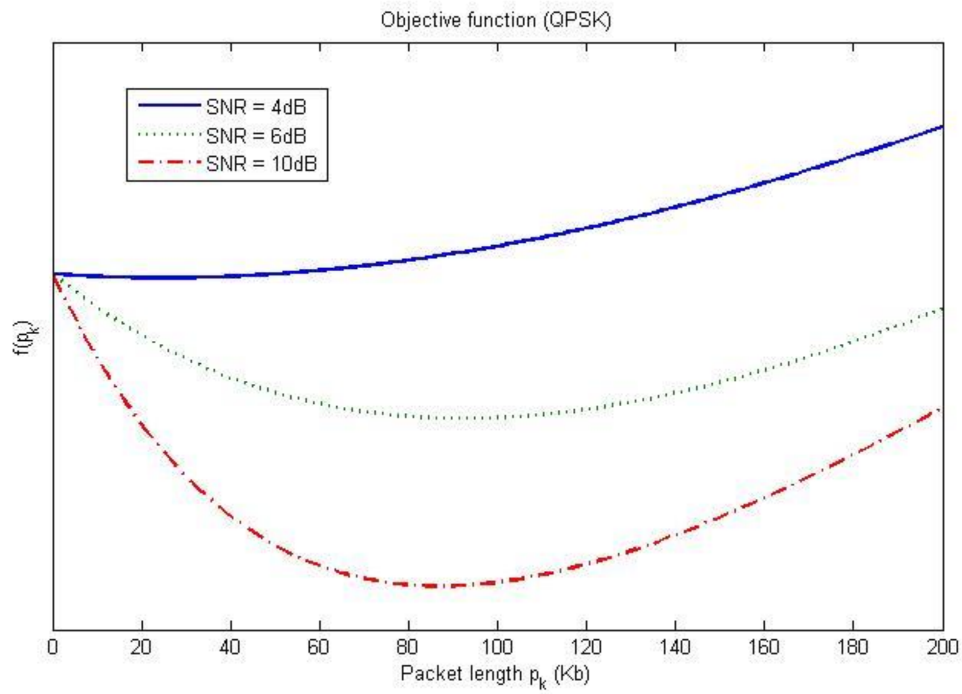

Figure 5.6 Objective function for QPSK

for the network are same as before. It is seen that the optimal packet length for the 6dB SNR case is 92Kb, while for the 10dB case it is 85Kb. The packet lengths increase in case of QPSK, because the PER is higher at a given packet length for QPSK as compared to BPSK, as was already shown in Fig. 5.4.

It is to be noted that in the figures just discussed, the unconstrained solution can be obtained very easily because of the presence of a minima. In case a minima is not present in a given region, or an additional constraint needs to be imposed, the constrained optimization equation derived i.e. equation (12) has to be used. For example, if an additional constraint needs to be imposed, like the delay needs to be below a certain value, say D_{MAX}, then the entire solution space can no longer be utilized. For example, in Fig.5.7 let us assume that the packet length *p_D* gives the maximum delay allowed, such that it lies to the left of the unconstrained solution. In such a case, only solutions to the left of the said packet length can be accepted, and the solution would be obtained by considering the constrained

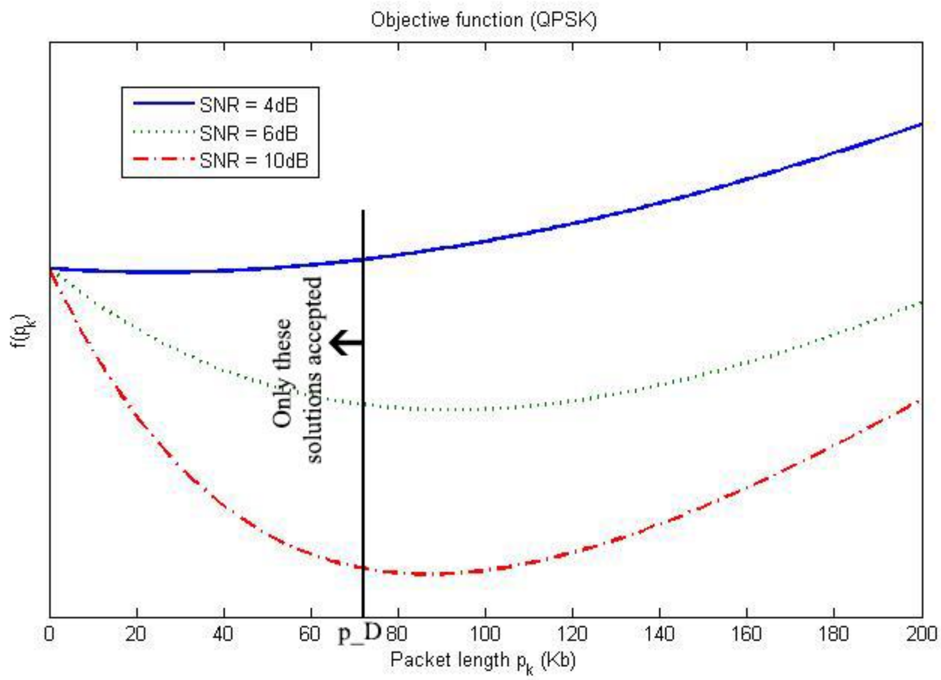

Figure 5.7 Constrained optimization illustration

optimization solution.

The energy characteristics have been shown in Fig 5.8, for different PER's for BPSK modulation, while a comparison between BPSK and QPSK has been shown in Fig. 5.9 for a PER of 0.001. It is seen that the energy per successful bit decreases as the packet size increases. This can be attributed to the number of retransmissions per unit time decreasing when the packet size increases. More energy is required per bit in the QPSK system than the BPSK system as seen in Fig. 5.9. This can also be realized from the fact that at the same packet length and PER, more energy per bit is required for QPSK than BPSK, as evident from equation (19).

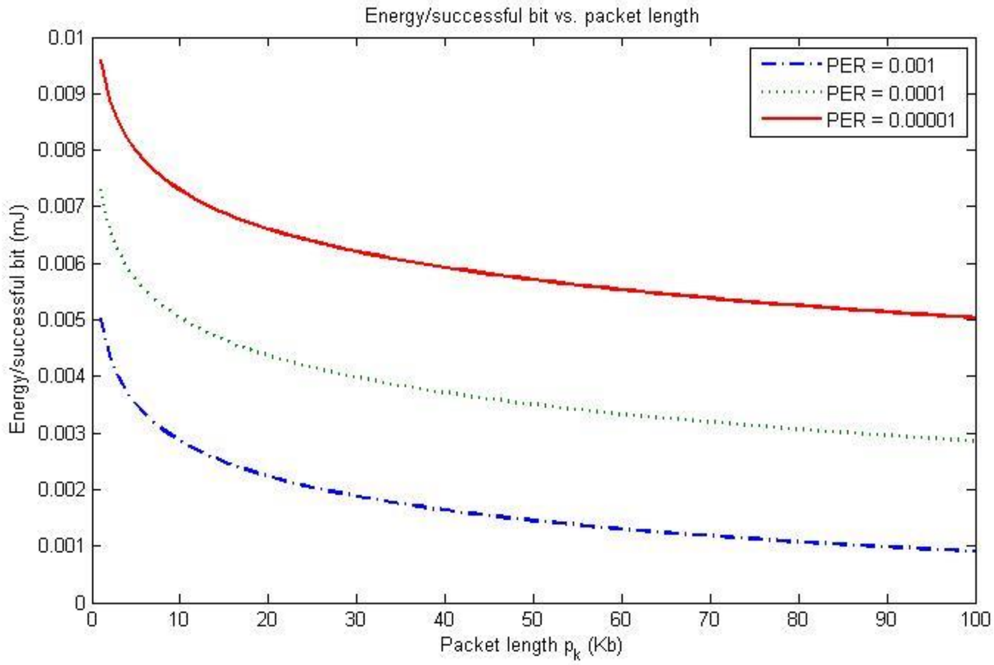

Figure 5.8 Energy per successful bit vs. packet length

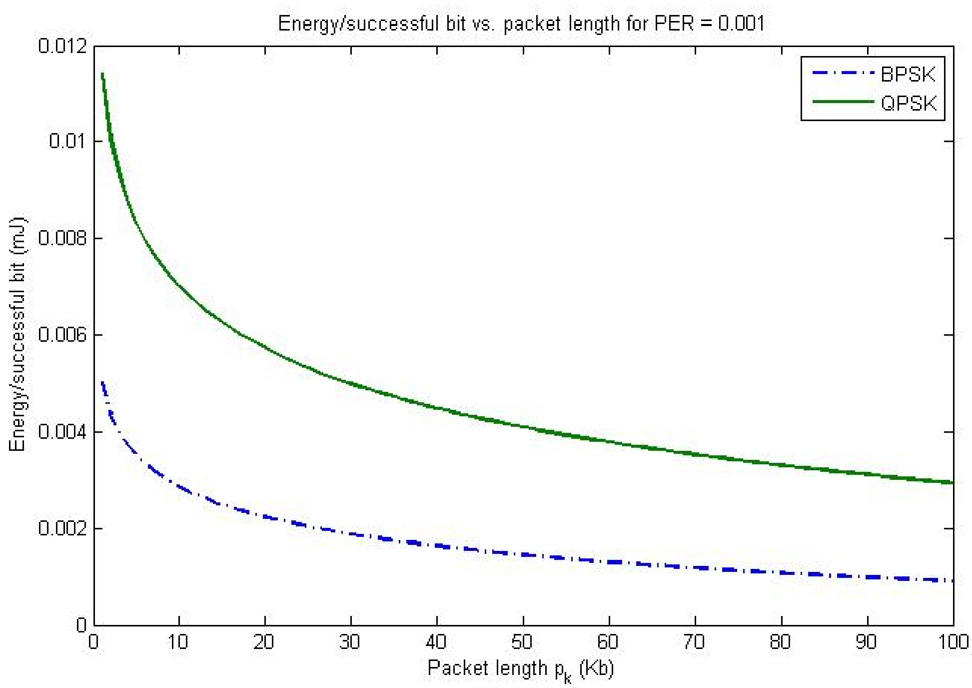

Figure 5.9 Energy per successful bit for BPSK and QPSK

5.8 Conclusion

It has been that the packet length optimization provides a robust and optimal solution to provide the WBAN network with optimal delay and PER characteristics. In case further restrictions need to be imposed on these parameters, a constrained optimization approach can be taken as well. Energy based calculations were performed as well, by varying several parameters. Comparison between various modulation schemes in the context of the proposed WBAN network were also studied, and the obtained results match are found to be quite intuitive as well.

CHAPTER 6

CONCLUSION & SCOPE OF FUTURE WORK

With the simultaneous rapid advancement of wireless communication and semiconductor technologies, the area of sensor networks has received a tremendous boost in the recent years. The market for healthcare devices is also growing parallelly, thus driving the need for faster and more efficient techno-healthcare solutions. Bridging the gap between the supply and demand for such robust healthcare solutions that are driven by technology have thus become essential. The entire WBAN network was proposed and developed upon by IEEE to provide easy to use, cost effective solutions for people and was aimed at making healthcare affordable for the masses. This would help bring in automation in the healthcare industry as well, as reliable and verifiable data can be collected and reviewed by professionals if deemed necessary.

The thesis aimed at making the WBAN network more customizable and adaptable while simultaneously fine tuning some of its parameters to offer better performance. Several aspects of the network were considered and optimized with the aim of providing a better and more robust WBAN solution.

The WBAN system that was designed and analyzed in this thesis can be used for ubiquitous medical purposes and is flexible in the sense that it can be configured to adjust its parameters based on the user requirement. The data gathered from individuals can even be processed at the gateway level and stored for future use or analyzed to identify characteristics or symptoms of unwanted conditions present in the individual. As can be well understood, the ultimate aim of a WBAN system is to provide an all-round medical solution for individuals and thus improve their quality of life in the long run.

To conclude with this thesis, some points can be gathered that can be worked upon in the future for further modification and improvement of the proposed WBAN system. This includes further exploring the multi-channel network to allocate resources according to the incoming traffic density and rate. An adaptable system, that automatically estimates the incoming traffic and provides the best possible channel allocation can be designed, that can dynamically adapt by also including channel aggregation techniques.

In the backoff interval adjustment problem, as already noted before, it would help if an estimate of the traffic load on each channel can be obtained and the parameters varied in real time to obtain maximum network throughput. The system would need to be dynamic in that case instead of being completely static. However, such a design may be quite unfeasible due to power limitations on the end nodes. In such a case, algorithms that require minimum node interaction and perform most of the adaptive operations on the BNC have to be thought of. In the optimization problem, more constraints can be built into the system and tested to make it more suitable for practical applications and deployment.

REFERENCES

[1] Goldsmith, Andrea. Wireless Communications. Cambridge University Press, 2005.

[2] Abhishek Kaushik, Parvin Kumar Kaushik and Sanjay Sharma. "History Based Contention Window Control Protocol for Energy Efficiency in Wireless Sensor Network." International Journal of Advance Research in Science and Engineering, March 2014: Vol. No. 3, Issue No. 3.

[3] Reva Kachroo, Dr. Rohit Bajaj, "A Novel Technique for Optimized Routing in Wireless Body Area Network using Genetic Algorithm", Journal of Network Communications and Emerging Technologies (JNCET) Volume 2, Issue 2, June (2015)

[4] Guo, Y., Wu, D., Liu, G., Zhao, G., Huang, B., & Wang, L. (2012). A low-cost body inertial-sensing network for practical gait discrimination of hemiplegia patients. Telemedicine and e-Health, 18(10), 748-754.

[5] Felisberto, F., Costa, N., Fdez-Riverola, F., & Pereira, A. (2012). Unobstructive Body Area Networks (BAN) for efficient movement monitoring. Sensors, 12(9), 12473-12488.

[6] Egbogah, E. E., & Fapojuwo, A. O. (2011). A survey of system architecture requirements for health care-based wireless sensor networks. Sensors, 11(5), 4875-4898.

[7] Ko, J., Lim, J. H., Chen, Y., Musvaloiu-E, R., Terzis, A., Masson, G. M., ... & Dutton, R. P. (2010). MEDiSN: Medical emergency detection in sensor networks. ACM Transactions on Embedded Computing Systems (TECS), 10(1), 11.

[8] Hu, F., Jiang, M., Celentano, L., & Xiao, Y. (2008). Robust medical ad hoc sensor networks (MASN) with wavelet-based ECG data mining. Ad Hoc Networks, 6(7), 986-1012.

[9] Lee, D. S., Liu, Y. H., & Lin, C. R. (2012). A wireless sensor enabled by wireless power. Sensors, 12(12), 16116-16143.

[10] Song, J., Han, S., Mok, A., Chen, D., Lucas, M., Nixon, M., & Pratt, W. (2008, April). WirelessHART: Applying wireless technology in real-time industrial process control. In 2008 IEEE Real-Time and Embedded Technology and Applications Symposium (pp. 377-386). IEEE.

[11] M. Nabi, "A Robust Protocol Stack for Multi-hop Wireless Body Area Networks with Transmit Power Adaptation," in 5th Annual International ICST Conference on Body Area Networks, Corfu Island, Greece, 2010.

[12] L. Yan, "Energy Comparison and Optimization of Wireless Body-Area Network Technologies," in the Proceedings of the ICST 2nd International Conference on Body Area Networks (BodyNets '07), Florence, Italy,2007, pp. 1-8.

[13] S. Ullah, “A Study of MAC Protocols for WBANs," Sensors vol. 10, pp. 128-145, International Journal of Ad hoc, Sensor & Ubiquitous Computing (IJASUC) Vol.3, No.3, June 2012.

[14] Wei Ye; Heidemann, J.; Estrin, D., "An Energy-Efficient MAC protocol for Wireless Sensor Networks,” in INFOCOM 2002. Twenty-First Annual Joint Conferences of the IEEE Computer and Communications Societies. Proceedings, IEEE, Volume: 3, Pages: 1567 - 1576 ,2002

[15] B. Antonescu and S. Basagni, “Wireless body area networks: challenges, trends and emerging technologies,” in Proceedings of the 8th International Conference on Body Area Networks, pp. 1–7, Boston, Mass, USA, September 2013.

[16] Xiuming Zhu, Song Han, Pei-Chi Huang, Aloysius K. Mok and Deji Chen, “MBStar “A Real-time Communication Protocol for Wireless Body Area Networks” Euromicro Conference on Real-Time Systems, 2011, pp. 57-66, 2011

[17] Moshaddique Al Ameen, Niamat Ullah, M Sanaullah Chowdhury, SM Riazul Islam and Kyungsup Kwak, "A power efficient MAC protocol for wireless body area networks”, EURASIP Journal on Wireless Communications and Networking 2012. Open access http://jwcn.eurasipjournals.com/content/ 2012/1/33

[18] Gabriel E. Arrobo and Richard D. Gitlin, “Improving the Reliability of Wireless Body Area Networks” 33rd Annual International Conference of the IEEE EMBS, Boston, Massachusetts USA, August 30 -September 3, 2011.

[19] P. Bahl, R. Chandra, and 1. Dunagan, "SSCH: slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks," International Conference on Mobile Computing and Networking, 2004(MobiCom'04), pp.216-230, Sept. 2004.

[20] S.L. Wu, C.Y. Lin, Y.C. Tseng, and J.P. Sheu, "A new multichannel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks," Parallel Architectures, Algorithms and Networks, 2000(l-SPAN 2000), pp.232-237, July 2000.

[21] L. Ma, X. Han, and C.-C. Shen, "Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks," New Frontiers in Dynamic Spectrum Access Networks, 2005(DySPAN 2005), pp.203- 213, Nov. 2005.

[22] J. Goodman, A. G. Greenberg, N. Madras, and P. March, “Stability of binary exponential backoff,” J. Assoc. Comput. Mach., vol. 35, no. 3, pp. 579–602, July 1988.

[23] D. Raychaudhuri and K. Joseph, “Performance evaluation of slotted ALOHA with generalized retransmission backoff,” IEEE Trans. Commun., vol. 38, pp. 117–122, Jan. 1990.

[24] J. Hastad, T. Leighton, and B. Rogoff, “Analysis of backoff protocols for multiple access channels,” SIAM J. Comput., vol. 25, no. 4, pp. 740–774, Aug. 1996.

[25] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, “MACAW: a media access protocol for wireless LANs,” in Proc. ACM SIGCOMM ’94, 1994, pp. 212–225.

[26] S. Xu and T. Saadawi, “Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?,” IEEE Commun. Mag., vol. 39, pp. 130–137, June 2001.

[27] D. G. Jeong and W. S. Jeon, “Performance of an exponential backoff scheme for slotted-ALOHA protocol in local wireless environment,” IEEE Trans. Veh. Technol., vol. 40, pp. 470–479, Aug. 1995.

[28] B. Bensaou, Y. Wang, and C. C. Ko, “Fair medium access in 802.11- based wireless ad hoc networks,” in Proc. ACM MobiHoc 2000, 2000, pp. 99–106.

[29] P. Lettieri and M. B. Srivastava, "Adaptive Frame Length Control for Improving Wireless Link Throughput, Range and Energy Efficiency," in INFOCOM (2), pp. 564-571, 1998.

[30] D. Qiao, S. Choi, and K. G. Shin, "Goodput Analysis and Link Adaptation for IEEE 802.11a Wireless LANs," IEEE Trans. on Mobile Computing (TMC), vol. 1, no. 4, 2002.

[31] J. P. Pavon and S. Choi, "Link Adaptation Strategy for IEEE 802.11 WLAN via Recieved Signal Strength Measurement," in Proc. IEEE ICC '03, pp. 1108-1113, May 2003.

[32] M. Lipprandt, M. Eichelberg, W. Thronicke, J. Kruger, I. Druke, D. Willemsen, C. Busch, C. Fiehe, E. Zeeb, and A. Hein, “Osamid: An open service platform for healthcare monitoring applications,” in 2nd Conf. on Human System Interactions (HSI’09), pp. 139–145, IEEE, 2009.

[33] “IEEE standard for local and metropolitan area networks: Part 15.6: Wireless body area networks,” IEEE submission, Feb. 2012.

[34] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, and K. Kwak, “A comprehensive survey of wireless body area networks,” J. of Medical Systems, pp. 1–30, 2010.

[35] D. Lewis, “802.15.6 call for applications in body area networks response summary,” in 15-08-0407-05-0006, Nov. 2008.

[36] K. Kwak, S. Ullah, and N. Ullah, “An overview of IEEE 802.15.6 standard,” in 3rd Int. Symp. on Applied Sciences in Biomedical and Communication Technologies (ISABEL), pp. 1 –6, Nov. 2010.

[37] D. Smith, L. Hanlen, J. Zhang, D. Miniutti, D. Rodda, and B. Gilbert, “First- and second-order statistical characterizations of the dynamic body area propagation channel of various bandwidths,” Ann. Telecommun., vol. 66, nos. 3/4, pp. 187–203, Apr. 2011.

[38] D. Smith, L. Hanlen, J. Zhang, D. Miniutti, D. Rodda, and B. Gilbert, “Characterization of the dynamic narrowband on-body to off-body area channel,” in Proc. IEEE Int. Conf. Commun., Jun. 2009, pp. 1–6.

[39] D. Smith, D. Miniutti, T. Lamahewa, and L. Hanlen, “Propagation models for body area networks: A survey and new outlook,” IEEE Antennas Propag. Mag., vol. 55, no. 5, pp. 97–117, Oct. 2013.

[40] Kleinrock, L., & Tobagi, F. (1975). Packet switching in radio channels: Part I-carrier sense multiple-access modes and their throughput-delay characteristics. IEEE transactions on Communications, 23(12), 1400-1416.

[41] J. F. Kurose, A. Shrivastava, and D. Towsley, “Stack algorithm for random multiple-access networks in the presence of asymmetric feedback,” IEEE Trans. Commun., vol. 38, pp. 1308–1313, Sept. 1990.

[42] S. Xu and T. Saadawi, “Does the IEEE 802.11 MAC protocol work well in multihop wireless ad hoc networks?,” IEEE Commun. Mag., vol. 39, pp. 130–137, June 2001.

[43] H. Takagi and L. Kleinrock, “Output processes in contention packet broadcasting systems,” IEEE Trans. Commun., vol. COM-33, pp. 1191–1199, Nov. 1985.

[44] L. Kleinrock and F. A. Tobagi, “Packet switching in radio channels - Part I: Carrier sensing multiple-access modes and their throughput-delay characteristics,” IEEE Trans. Commun., vol. COM-23, pp. 1400–1416, Dec. 1975.

[45] Li, Y., Zhou, G., Zheng, N., & Hong, L. (2014). An adaptive backoff algorithm for multi-channel CSMA in wireless sensor networks. Neural Computing and Applications, 25(7-8), 1845-1851.

[46] B. Zhang, C. Li, Z. Liu, X. Yuan and L. Yang, "On energy-delay efficiency for WBAN: A multi-channel scheme," 2015 IEEE/CIC International Conference on Communications in China (ICCC), Shenzhen, 2015, pp. 1-5.

[47] N. Zogovic, G. Dimic and D. Bajic, "Packet length and transmission power adaptation for energy-efficiency in low-power wireless communications," 2011 10th International Conference on Telecommunication in Modern Satellite Cable and Broadcasting Services (TELSIKS), Nis, 2011, pp. 497-500.

[48] E Egbogah, Emeka & Fapojuwo, Abraham. (2011). A Survey of System Architecture Requirements for Health Care-Based Wireless Sensor Networks. Sensors (Basel, Switzerland). 11. 4875-98. 10.3390/s110504875.