Hybrid Interference Mitigation Model for Wireless Body Area Sensor Networks in high Mobility Multi-WBAN Scenarios

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

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DEDICATION

I dedicate this research project to my children Nadia and Terryanne, my wife Jane for endless support, sacrifices and persevering with my absence during this time, my brothers especially Justus and Samuel for their endless encouragement and inspiration, my parents for skipping my usual weekend visits so that I can accomplish research targets and my lastly employer, Tullow Kenya BV, for coping with me during this time when I had a lot on my desk.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACK	Acknowledgement
CAP	Contention Access Phase
DCHS	Dynamic Cluster Head Selection
EAP	Exclusive Access Phase
LST	Link-state
NAK	Negative Acknowledgment
OMNeT	Optical Micro-Networks
PDR	Packet Delivery Ratio
PHY	Physical Layer
PLR	Packet Loss Rate
PPDU	PHY Protocol Data Units
QoS	Quality of Service
RAP	Random Access Phase
RDMM	Random Direct Mobility Model
RF	Radio Frequency
RGMM	Random Gauss-Markov Mobility
RIP	Routing Information Protocol
RPGM	Reference Point Group Mobility model
RTS	Request to Send frame
RWMM	Random Walk Mobility Model
RWPM	Random Waypoint Mobility Model
SDM	Space-Division Multiplexing
SINR	Signal interference noise ratio
SMAC	Sensor Medium Access Control
SNR	Signal to Noise Ratio
SSCS	Service Specific Convergence Sub-layer
TDM	Time-Division Multiplexing
TDMA	Time division multiple access

TTL	Time to Live
UP	User Priority
UWB	Ultra-wideband
VANETs	Vehicular networks
WBAN	Wireless Body Area Network
WBASN	Wireless Body Area Sensor Network Wireless
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMAC	Wise Medium Access Control
WMTS	Wireless Medical Telemetry Services
WPAN	Wireless personal area networks
WSN	Wireless Sensor Network
XML	Extensible Markup Language
6LowPAN	Internet Protocol version 6 of Low-power Wireless Personal Area Networks

ABSTRACT

In the recent past, the field of Wireless Sensor Networks (WSNs) has revolutionized tremendously and has been adopted widely in various todays' applications due to the increasing demand for smart technology and increase for the need for adaptation of Internet of Things (IoT). Some of these fields include industrial, building automation, transport, environment and weather, security, wildlife management, medicine and health care among others. Among these, one of the most important and recent application is in the field of healthcare (or medical) through recent development of the IEEE 802.15.6 Wireless Body Area Networks (WBANs) standard specifically to address the special needs of the WBAN. The unique operational modality of the WBANs is that a few sensor nodes are placed in or around the body and that they are meant to operate within a limited condition while providing high performance in terms of WBAN life time, high throughput, high data reliability, minimum or no delay and low power consumption (due to miniature nature of the sensor nodes). This is because the WBAN in medical application is adopted in life saving applications where the body sensor network monitors vital physiological body behaviours and signs, reporting the same to a centralised or a remote health monitoring system. This means that the reliability, availability, quality of service (QoS) of the WBAN is of utmost importance and lifesaving. As most of the WBAN operates within the universal Industrial, Scientific and Medical (ISM) Narrow Band (NB) wireless band (2.4Ghz) frequency band, this has posed a challenge in respect to inter, intra and co-channel interference especially in dense areas and high mobility scenarios. As well, human body exhibits postural mobility which affects distances and connections between different sensor nodes within the body. By means of simulation, this thesis investigates these effects on the performance of WBAN under multi-WBAN and WBAN mobility scenarios and the results confirm degradation of the WBAN performance (bandwidth efficiency, network throughput and delay). The thesis thereafter presents a hybrid WBAN interference mitigation model (HIMM) based on two approaches, the CSMA/CA Contention Window (CW) with User Priority (UP) and dynamic cluster head selection (DCHS) based on Link-state (LS) approach. Using Omnet++ simulation tool with Mixim framework, the new HIMM model is evaluated in comparison to the current IEEE 802.15.6 WBAN technology in respect to bandwidth efficiency, network throughput and network delay performance metrics. The results show that the new HIMM WBAN interference mitigation model presented in this research outperformed the existing IEEE 802.15.6 based WBAN technology in the reference areas of network delay, bandwidth efficiency and network throughput. With bandwidth efficiency improvement from average of 30% to over 60% being achieved, network throughput improvement from 51Kbps to 110Kbps and network delay reduction from average of 30ms to 10ms. This is a significant contribution to the future and adaptability of IEEE 802.15.6 WBAN technology in the growing challenging modern operational environments.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The advancements in technology has really improved and has lead to its adaptation in the critical field of medical healthcare, hence leading to high life expectancy (Saboor *et al*, 2019). The wireless technology has been one of the recent technologies through the wireless sensor networks (WSN). The wireless sensor networks is a technology which consists of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location (Akyildiz and Kasimoglu, 2004). It incorporates a gateway (cluster head) that provides a wireless connectivity back to the wired world.

A rapidly growing application area of WSN is in the body area networks (BANs) which is used widely in the medical healthcare (Pervez *et al,* 2009; Negra *et al*, 2016). The BANs have since developed from the IEEE 802.15.4 general WSN technology. But due to the special needs of the healthcare applications, a special BAN technology called the wireless body area sensor networks (WBANs) was developed to majorly operate as the IEEE 802.15.6 standard as the IEEE 802.15.4 has been retained to operate in legacy WSN such as in industrial applications and other large scale environmental monitoring systems which can scale up to 100m in radius (IEEE Std 802.15.4, 2006; Buratti *et al*, 2009). The WBANs was intended only to address special needs of the wireless body area sensor networks such as low power, low cost, low complexity, high throughput and short-range wireless communication in and around the human body (Movassaghi *et al*, 2014).

Unlike the WSN where the sensor nodes are distributed in a wide area, WBAN consist of a small number of sensor nodes (most often about six) that are placed in or around the human body for remote monitoring (Darwish & Hassanien, 2011). Since the sensor monitoring includes lifesaving human body signs which may determine between life and death for the patient, high reliability is expected in both the sensing and data transmission (Khan & Pathan, 2018). Unfortunately, performance of these WBANs decreases in high interference scenario's such as densely populated areas and in the Industrial, Scientific and Medical (ISM) wireless band (2.4Ghz) as this frequency band has co-channel interference from other technologies using the same frequency, such as IEEE 802.15.1 (Bluetooth), IEEE 802.11 (wireless fidelity - Wi-Fi) and IEEE 802.15.4 (zigbee). As discussed by Cavallari *et al* (2014), the IEEE 802.15.6 operates on ISM frequency band which is prone to interference from other wireless networks which makes use of the same frequency band (2400MHz).

As opposed to the previous WSN technology used for body area networks such as IEEE 802.15.4, the IEEE 802.15.6 addresses these special needs for WBAN and is required to function properly within the transmission range of up to 5 meters when up to 10 WBANs are co-located, each with up to 256 sensors (IEEE Std 802.15.6, 2012). Thus, there is as well high possibility of interference amongst WBANs operating in close range and other technologies as well. This is because of the postural mobility of human and the joint mobility of the different body parts such as legs, head, arms among others which causes intra and inter-WBAN interference.

The advancement of wireless networks and electronics technology has led to the emergence of WSNs which have been considered as one of the most important technologies that can greatly change the future (IEEE 802.15.4e-2012). Generally, a WSN can be described as a network of nodes that cooperatively sense and may control the environment, enabling interaction between persons or computers and the surrounding environment (Broring *et al*, 2011). Among the biggest beneficiaries of the WSN technology is the idea of internet of things (IoT) introduced by Kevin Ashton (Ashton, 1999) and the medical applications (E-healthcare) among other industrial applications (Ayaz *et al*, 2017). In medical applications, these WSNs consist of very tiny battery-powered devices with limited computational power and radio communication technologies. The activity of each of the sensor node in a WSN includes sensing, processing, and communication. For the success in the medical application, the sensor nodes must sense the right environment at the right time, process the data without alteration and communicate the same effectively and reliably without losing the original value of the message. This means that the communication or the data relay is a crucial function of the WSN in healthcare as every second can be a lifesaving of the human life. As well receiving the data as it was recorded from the sensor device can be a trade-off between correct or wrong diagnosis.

The IEEE 802.15 standardization committee (work group 15) which concentrates on wireless personal area networks (WPAN) has created a number of wireless standards which includes IEEE 802.15.1 (Bluetooth) (IEEE Std 802.15.1-2005) and IEEE 802.15.4 (Zigbee) (Jose *et al*, 2004). To cope with the strong demands from both medical and healthcare societies, in year 2012, the WG15 formally set up a Task Group 6 (TG6), which was aimed to work out an international standard for body area network. This led to the development of the IEEE 802.15.6 standard, now commonly known as WBAN. The WBAN was meant to be a wireless sensor network composed of short range wireless communication, low power, and variable-data-rate sensors placed within, on, or around a human body to monitor biological signals and other functions such as movement patterns (Astrin, 2012). In one of the studies to compare the IEEE 802.15.4 and IEEE 802.15.6 standards, Cavallari et al (2014) in his study (by comparing the MAC protocols of the two standards) found that IEEE 802.15.6 is superior to IEEE 802.15.4 in terms of packet loss ratio, average delay, and network throughput.

Some of the most important requirements for WSNs are scalability, robustness, network lifetime, fault tolerance, latency, throughput, and mobility. But when it comes to the WBANs, the order of priority of these requirements is different (Movassaghi *et al*, 2016; Muhammad & Elyes, 2016). Table 1.1 shows the differences between Wireless Sensor Networks and Wireless Body Area Networks. The most important for WBANs is to establish and maintain reliable and timely data transfer between the sensor nodes and the coordinator node since these networks mainly deal with vital human signs. Sending and receiving the critical human vital signs on time might be the difference between life and death hence interferences and data loss are not tolerated. The coordinator node is often referred to as the cluster head (CH) and it is the coordinating node in each of a WBAN. It is a node which is dedicated to receiving data from all other sensor nodes within the WBAN and communicate to the external network of the WBAN. This central node (cluster head) must be a node which maintains most connections within the WBAN. The cluster heads collect the data from respective cluster's nodes and forward the aggregated data to base station.

Table 1.1: Schematic overview of differences between Wireless Sensor Networks and Wireless Body Area Networks (Guang-Zhong Yang, 2006)

Challenges / Parameter	**Wireless Sensor Network**	**Wireless Body Area Network**
Scale	Monitored environment (meters / kilometres)	Human body (centimetres/meters)
Node Number	Many redundant nodes for wide area coverage	Fewer, limited in space
Result accuracy	Through node redundancy	Through node accuracy and robustness
Node Tasks	Node performs a dedicated task	Node performs multiple tasks
Node Size	Small is preferred, but not important	Small is essential
Network Topology	Very likely to be fixed or static	More variable due to body movement
Data Rates	Most often homogeneous	Most often heterogeneous
Node Replacement	Performed easily, nodes even disposable	Replacement of implanted nodes difficult
Node Lifetime	Several years / months	Several years / months, smaller battery capacity
Power Supply	Accessible and likely to be replaced more easily and frequently	Inaccessible and difficult to replace in an implantable setting
Power Demand	Likely to be large, energy supply easier	Likely to be lower, energy supply more difficult
Energy Scavenging Source	Most likely solar and wind power	Most likely motion (vibration) and thermal (body heat)
Biocompatibility	Not a consideration in most applications	A must for implants and some external sensors

Security Level	Lower	Higher, to protect patient information
Impact of Data Loss	Likely to be compensated by redundant nodes	More significant, may require additional measures to ensure QoS and real-time data delivery.
Wireless Technology	Bluetooth, ZigBee, GPRS, WLAN, . . .	Low power technology required

1.2 Statement of the Problem

The IEEE 802.15.6 WBAN technology was meant for application among others, in healthcare, especially in the transmission of sensor medical data (Filipe, *et al*, 2015; Negra, *et al*, 2016) hence the quality and continuity of signals are extremely important. However, radio propagation in WBANs is dynamic because human body is mobile, and the sensor devices associated with different parts of the body are also mobile within a limited range. This means that in such conditions, intra-WBAN and inter-WBAN interference may severely affect data transmission. Also, in environments like healthcare facilities, where many WBAN are in use for patient monitoring, and in other public places where persons with WBAN may come in close range with other domains using the same frequency band, the likelihood of signal interference between the different carriers is very high. As well the likelihood of having two different WBANs in close range to one another and operating under same frequency bands is high hence the need for interference mitigation. In such operation conditions, intra and inter-WBAN interference may severely impair data transmission. As discussed by Cavallari *et al*, (2014), the IEEE 802.15.6 operates on ISM frequency band which is prone to interference from other wireless networks such as Bluetooth, Zigbee or Wireless Fidelity (Wi-Fi) which makes use of the same frequency band (2400MHz). These forms of interference should be mitigated to ensure that the data is transmitted reliably and of quality with no loss of packets. Also, there is need to mitigate this interference so as to improve the energy consumption and lifetime of the WBAN.

As human beings generally change their postures and as the human body moves (group mobility), the sensor connectivity amongst the nodes also varies. Research by

Kyriacou *et al* (2010) confirms that the moving patient (WBAN client) can experience packet loss rate of upto 20.15%. This data loss rate coupled by demand for high reliability of WBAN due to advancement in technology such as imaging and big data requires continuous improvement of the WBAN technology so as to cope with the increasing demand and requirements.

This thesis seeks to address this interference problem of the WBAN operating under the IEEE 802.15.6 technology by proposing a hybrid WBAN interference mitigation model (namely HIMM Model) which takes into account Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Contention Window (CW) and User Priority (UP) Based Strategy and a Link State based Dynamic Cluster Head Selection Strategy for the improving the WBAN reliability.

1.3 Justification

The human population has continued to grow in the past years with 2019 world population standing at 7.6 billion people (ourworldindata.org/world-population-growth) and projected to grow to 9.8 billion by 2050 (un.org). There has been undebatable need for better ways of providing services under this population growing trend. One of the major services has been health care service which is a basic human right. The provision of smart healthcare, commonly known as eHealth has been the recent technology under researcher's interest as a possible way to unlock this universal healthcare problem hence many solutions, technologies and standards have been proposed in recent past.

Specifically, monitoring of patients in a medical facility or remote monitoring of patients in areas challenged by the unavailability of medical facilities and the evaluation monitoring of the health condition of the elderly are some of the identified applications of eHealth care. These eHealth systems not only allow the elderly to live independently without need to be confined in a fixed place for longer, but they also have the potential to make healthcare services more sustainable by reducing the pressure placed on the overall health system by the elderly and dependent individuals.

The application of eHealth in medical facilities has enabled the reduction of legacy systems and now the many common alarm sounds of the different monitoring systems in the intensive care unit (ICU) or emergency units can now go silent as all the monitoring can go silent and digital while managed by minimial staff as opposed to the many staff previously needed to closely monitor the patients.

But to achieve a truly smart eHealth described here, several challenges still exist in many aspects of the technology. Also, new challenges have continued to grow as environments or conditions change. Such challenges include the remote monitoring environment (data acquisition and the environment) and the communication technology needed for the environment (reliability of data transmission in real-time).

One of the most challenging issues facing healthcare-based application of smart technology especially the WSNs based patient monitoring is the reliable and timely data transfer between the sensor nodes, the coordinator or cluster head node and the remote monitoring system. This is important to provide constant patient care or monitoring of the elderly or chronically ill whose every single data sent may be life saving for the person.

This research will therefore aim to explore the intra and inter-WBAN as well as inter-domain interference and how the WBANs can achieve interference free data transmission by the introduction of better interference mitigation methods. It is also understood that the higher the interference the high the energy consumption hence reduction of interference will increase the lifetime of the WBANs which is a crucial requirement for medical applications.

1.4 Research Objectives

1.4.1 General Objective

The general purpose of this research study is to develop an interference mitigation model that seeks to ensure effective and reliable communication within and between multiple WBANs by developing a better hybrid IEEE 802.15.6 WBAN interference mechanism model.

1.4.2 Specific Objectives

The specific objectives of this research are to:

1. By simulation, determine the effects of mobility, WBANs density and Wi-Fi interfering networks to WBAN
2. Analyse and identify collaborative approaches to WBAN and how they can be applied to the IEEE 802.15.6 WBAN to achieve interference mitigation
3. Design a hybrid IEEE 802.15.6 WBAN interference mitigation model (HIMM) for high mobility and Multi-WBAN interfering areas
4. Evaluate the performance of the new WBAN interference mitigation model under mobility and multi-WBAN conditions, against the existing IEEE 802.15.6 WBAN

1.5 Research Questions

The study focuses on the following research questions:

a. What are the challenges of IEEE 802.15.6 WBAN in its adaptation in high interfering mobility environments?
b. What unique approaches can be applied to the IEEE 802.15.6 WBAN to mitigate WBAN interference?
c. How can cluster head selection in the WBAN be improved to achieve efficient, and reliable WBAN?
d. How can the CSMA/CA improved, especially the WBAN MAC protocol to address the IEEE 802.15.6 interference problem

1.6 Scope of the Research

The scope of this research is interference mitigation schemes for IEEE 802.15.6 WBANs in a medical application scenario of highly mobile and high WBAN density environment. In specific we look in to inter-WBANs as well as interference from other wireless networks in the ISM frequency band. This research does not look in to interference in Medical Implant Communications Service (MICS), Wireless Medical

Telemetry Services (WMTS) and Ultra-Wideband (UWB) licensed frequency bands for the different specific countries. It does not also look in to interference mitigation in static scenarios. The research also does not cover in-body WBANs as the human body poses many wireless transmission challenges as the body is composed of several components that are unpredictable and subjected to change. Instead the research concentrates on on-body WBANs.

1.7 Research Assumptions

The assumptions made in this research include:

i) The number of WBANs used in the research (1WBAN, 9WBAN, 18WBAN and 25WBAN) to test the effects of increased Multi-WBAN on WBAN performance (objective one) and to evaluate the performance of the new HIMM model (objective four). The basic idea of selecting number of WBAN is selection of incremental number of WBAN which imply increased WBAN interference with the aim to observe the performance of WBAN on increased Multi-WBAN interference.

ii) It is assumed that the node mobility is regular as defined in the posture specification xml file.

iii) The research assumes the standard performance evaluation parameters which have also been adopted in previous existing work. These parameter values are shown and discussed in chapter three (IEEE 802.15.6 Modeling)

iv) Channel capacity is the same for all channels

v) Packet length is fixed and is the same for all WBANs, since health-care applications usually gather and transmit data periodically

1.8 Organization of the thesis

This thesis is organized as follows:

The second chapter reviews the literature related to WSN, WBAN and WBAN interference. The research stresses the importance of WBAN in medical applications and how this has led to enhanced efficiency and improved healthcare. It reviews the IEEE 802.15.6 WBAN technology framework and its interference mitigation mechanisms. The chapter concludes by summarizing the existing literature and then concludes with identifying the research gaps. These research gaps form the basis of the rest of this research work.

The third chapter presents the methodology used to achieve the research objectives. The research methods are stated in section 3.2. In section 3.3 the research design is presented while the simulation software and tools are presented in section 3.4. Section 3.5 shows the WBAN prototype and the characterization on the on-body WBAN. The IEEE 802.15.6 modeling and parameters used are presented in section 3.6. As WBAN mobility is a key factor in this research, the chapter concludes by presenting the mobility model selection and the WBAN mobility modeling in section 3.7 and 3.8 respectively.

Chapter four presents the contribution of this research work. Section 4.2 discusses the system model, Section 4.3 introduces the new model approach and its conceptual model of the proposed. The proposed model is HIMM model containing two improvement approaches, the CSMA/CA CW model for interference mitigation and dynamic cluster head approach for WBAN reliability improvement. The two approaches are discussed in detail in the same section. Section 4.4 then presents the flow chart of the HIMM model and the flow chart pseudo code. The chapter ends by presenting the implementation of the new model in section 4.5.

Chapter five presents the performance evaluation analysis and results. Section 5.2 shows the performance evaluation of the current model by use of bandwidth efficiency, network throughput and network delay performance metrics, a comparison of the results from single (1) WBAN, nine (9) WBAN, eighteen (18) WBAN and twenty-Five (25) simulation scenarios. Section 5.3 presents the performance evaluation of the CSMA/CA CW with user priority approach while section 5.4 presents the performance evaluation of the dynamic cluster head selection approach. Section 5.5 discusses the results.

In chapter 6 we conclude, present the research limitations and the future work. We also conclude by giving an account of how the research objectives have been net.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In this chapter, literature related to wireless sensor network, wireless body area networks and interference in WBANs is reviewed. The state-of-the-art literature of IEEE 802.15.6 interference mitigation schemes and their short comings is also reviewed. We show that there is still much to be achieved in IEEE 802.15.6 performance in regard to interference mitigation if the wireless body area network is to be reliably and efficiently used in healthcare application.

2.2 Wireless Sensor Networks (WSN) Overview

A Wireless Sensor Network (WSN) can be defined as a wireless network consisting of spatially distributed, autonomous and self-directed devices called sensor nodes to monitor physical or environmental conditions. It is a network of devices (called sensor nodes) which can sense an environment and communicate that information from that monitored field through wireless links (Sohrabi *et al,* 2000; Akyildiz *et al*, 2002; Tubaishat and Madria, 2003; Raghavendra *et al*, 2006; Verdone *et al,* 2008). A sensor is a miniature device that responds and detects a type of input from a physical or environmental condition such as pressure, humidity, heat, light, etc (Rubala *et al*, 2017).

From a radio communication networks perspective, the wireless sensor networks generally have various topologies including star topology, Tree topology and mesh topology (Reina *et al*, 2013) as shown in Figure 2.1.

The star topology is a type of network topology in which each of the sensor nodes are connected to a central node, commonly known as hub-spoke topology. In this topology, the central node acts as conduit for transmitting all communication or traffic to the remote medical monitoring system. The advantage of this type of topology is that when a wireless sensor connection fails, only that sensor that is affected.

The mesh topology is a type in which the network or sensor nodes are connected to most of the other nodes. As opposed to star topology, there is no central node in mesh topology. In sensor networks, this topology is not commonly used or recommended because of its high energy consumption nature.

The tree topology is a type of structure in which many network nodes are connected in a branch of a tree manner. This type of topology is majorly applicable in computer networks but rarely used because of high cabling needed, high maintenance and the backbone if the topology is a single point of failure even though it has the advantage of scalability. In computer networks it is also commonly known as star bus topology. The topology is not common in sensor networks because of its design nature.

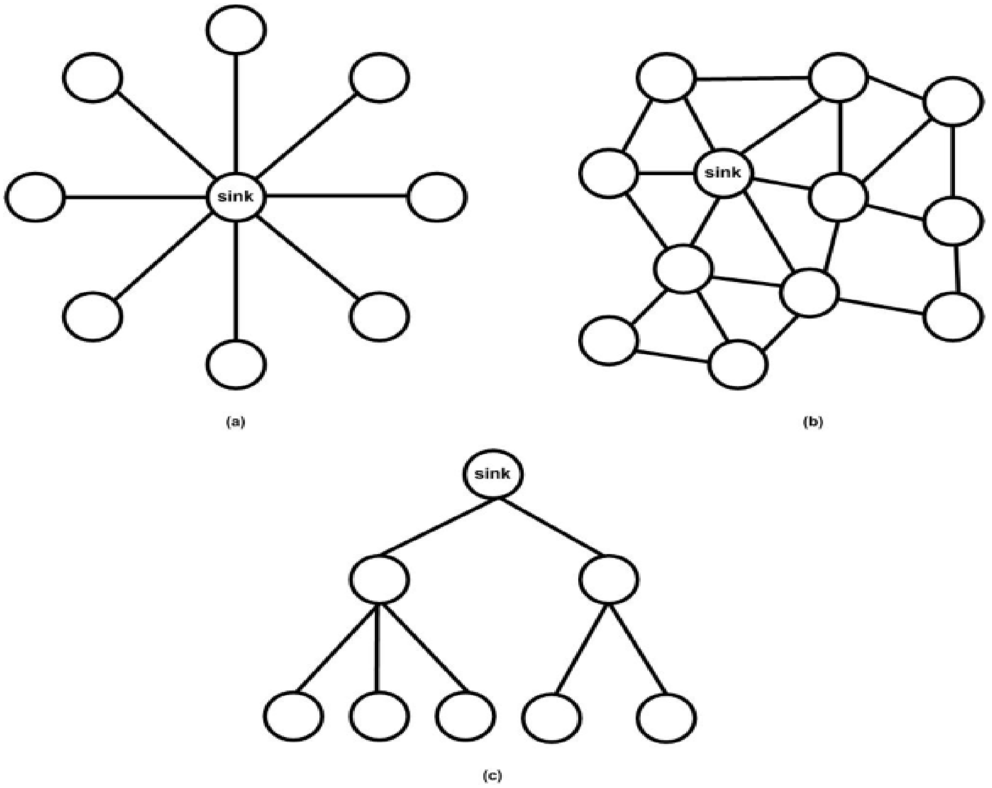

Figure 2.1: Wireless Sensor Network Topologies: (a) Star; (b) Mesh; (c) Tree Topology (Reina et al, 2013).

In WSN, data is forwarded from nodes, which are distributed over an area, via multiple hops to a sink node (Cluster head or coordinator) that can use it locally or is connected wirelessly to other networks (e.g., the Internet) through a gateway. Generally, a WSN can be described as a network of nodes that cooperatively sense and may control the environment enabling interaction between persons or computers and the surrounding environment (Buratti *et al*, 2009). A typical WSN is shown in Figure 2.2 and this shows the communication architecture of a wireless sensor network. The nodes can be used on different types of real-time application area to perform various tasks like smart detecting, data processing and storage, target tracking among other day-to-day tasks.

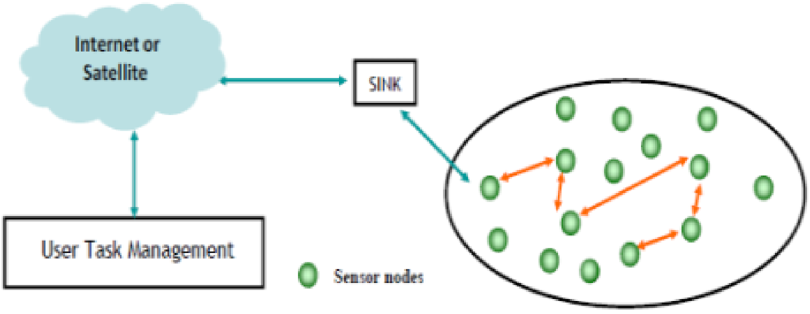

Figure 2.2. Typical Architecture of a WSN (Gowda, 2013)

The Figure 2.2 shows WSN as a network of tiny sensor nodes which are spatially distributed and work cooperatively as one network to communicate the gathered information from those sensor nodes, through wireless links to a central node (often called a coordinator or a sink node). The central node is connected to other networks over the internet to a remote management user or a remote system such as monitoring and/or control system.

Due to the wide variety of possible applications of wireless sensor networks, there have been several applications, and this continues to grow as this technology has attracted many researchers for different application areas such as animal tracking, precision agriculture, environmental monitoring, security and surveillance, smart buildings, health care and so on. (Minaie *et al*, 2013; Ramson & Moni, 2017). The taxonomy of wireless sensor networks applications is shown in Figure 2.3 where they are broadly classified as either monitoring or tracking application. In health care, wireless devices make less invasive patient monitoring and health care possible. For utilities such as the electricity grid, street lights, and water services, wireless sensors offer a lower-cost method for collecting system health data to reduce energy usage and better manage resources (Prabhu *et al*, 2016). Remote monitoring covers a wide range of applications where wireless systems can complement wired systems by reducing wiring costs and allowing new types of measurement applications. Remote monitoring applications include Environmental monitoring such humidity, temperature, air pressure and soil; building monitoring and bridges; Industrial machine monitoring; Process monitoring and Asset tracking.

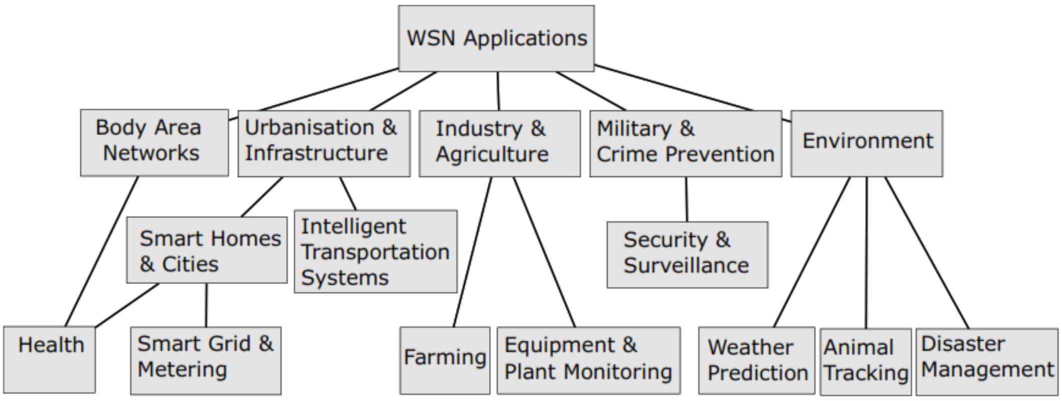

Figure 2.3. Applications of Wireless Sensor Networks (Rawat et al, 2014)

The main features of wireless sensor network are described as scalability (ability of the wireless sensor network to increase the number of nodes in the network), self-organization, self-healing, energy efficiency, a sufficient degree of connectivity among nodes, low-complexity, low cost and size of nodes (Buratti et al, 2009). The energy efficiency means low energy consumption which promotes long sensor network lifetime. Self-organizing network is one where a collection of nodes co-ordinate with each other to form a network that adapts to achieve a goal more efficiently (Collier & Taylor, 2004). A self-healing networks, also called “ad hoc” network is a network that can recover itself from a failure or down time (Elliott & Heile, 2000). Low-complexity is a term referring to simplicity nature of a network. The wireless sensor network started as a general technology under the IEEE 802.15.4 standard. This has since grown to other technologies depending on specific application, for example IEEE 802.15.6 (as Wireless Body Area Sensor Network (WBASN) technology) for medical healthcare application with IEEE 802.15.4 being left for industrial applications of wireless sensor network.

2.3 Types of Wireless Sensor Networks (WSNs)

There are different types of wireless sensor networks. The types depend on the environment such that those can be deployed in underwater, in the underground, on land among others. These types include Underground WSNs, Terrestrial WSNs, Underwater WSNs, Multimedia WSNs and Mobile WSNs (Harrop, 2012). These five types are presented in Figure 2.4.

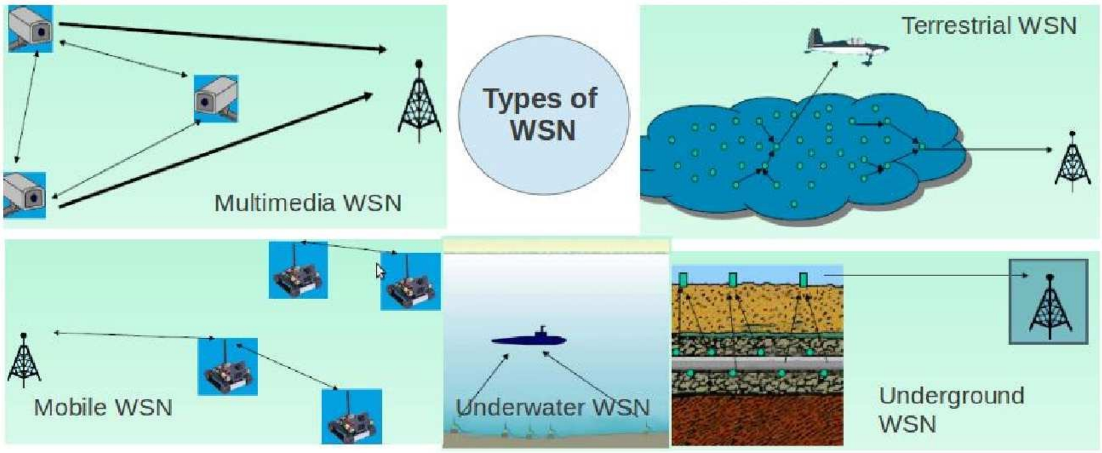

Figure 2.4. Types of Wireless Sensor Networks (Berberidis & Ampeliotis, 2009)

As shown in Figure 2.4, the Terrestrial WSN (Akyildiz *et al*, 2002) is sensor network that consists of hundreds to thousands number of wireless sensor nodes that are deployed on land in a given geographical area in an ad-hoc design. In these terrestrial WSNs, the sensor nodes must communicate the data back effectively to the base station in a dense environment. Because of the limitation of the battery power, the terrestrial sensor nodes are usually equipped with backup or secondary power source such as the solar cells. The adaptability of multi-hop routing in this type of WSNs ensures optimal routing in cases of failures. This type of sensor networks is mostly applied in environmental sensing and monitoring, industrial monitoring and surface explorations.

The Underground wireless sensor network is a sensor network that consists of several sensor nodes that are deployed in underground or caves or mines or any beneath the earth to monitor the underground conditions such as soil and mineral content (Akyildiz & Stuntebeck, 2006; Li & Liu, 2007). The data or information from the underground sensor nodes is relayed to the terrestrial base station which are above the ground. This type of WSN is usually more expensive than terrestrial WSNs because they require appropriate equipment to ensure reliable communication through the soil, rocks and water to the surface. This type of WSN experiences challenges because of the high attenuation and signal fading as the signal is transmitted from the underground sensor nodes to the terrestrial base station. This type is applied in underground monitoring of soil, water, minerals, underground ice, landslides, earth quakes and volcano eruptions. It can also be applied in military border monitoring, agriculture monitoring and landscape management.

Underwater wireless sensor network is the type of WSN which consists of sensors deployed underwater, for example, under-sea or into the ocean environment (Akyildiz *et al*, 2004; Heidemann *et al*, 2005). These type of sensor nodes are very expensive because of their expected design nature expected to safely operate underwater. Very few of these nodes are deployed and in most cases in underwater vehicles are used to explore or gather data from undersea. The Underwater wireless sensor communication uses the acoustic waves that presents various challenges such as limited bandwidth, long propagation delay, high latency, and signal fading problems due to the nature of the operating environment. These sensor nodes must be able to self-configure and adapt to extreme conditions of ocean or undersea environment which most times its rough and salty waters. The biggest challenge of these sensor nodes is limited battery life as the batteries cannot be replaced or recharged requiring energy efficient underwater communication and networking techniques. Applications of underwater wireless sensor network include pollution monitoring, under-sea surveillance and exploration, disaster prevention and monitoring, seismic monitoring, equipment monitoring, and underwater robotics.

Another type of sensor network is the Multimedia wireless sensor network. This type of sensor network consists of low cost sensor nodes which are equipped with cameras and microphones, deployed in a pre-planned manner to ensure or guarantee coverage (Akyildiz *et al*, 2007). These multimedia sensor nodes are capable of storing, processing, and retrieving multimedia data such as audio, video, and images. The biggest requirements or challenges of this type of wireless sensor network is high bandwidth demand, high energy consumption, quality of service (QoS) as expected of voice and video traffic, data processing and compressing techniques, and cross-layer design. It is required to develop transmission techniques that support high bandwidth and low energy consumption in order to deliver multimedia content such as a video stream. The QoS is also necessary because of the variable communication link capacity as a result of capacity limitation nature of WSN and sensor network delay. An acceptable level of QoS must be achieved for reliable multimedia content delivery which depends on the kindly of content and its acceptable levels. These Multimedia wireless sensor networks are mostly used in applications such as tracking and monitoring.

Mobile wireless sensor network is another type of sensor network which is made of mobile sensor nodes that can move around and interact with the physical environment (Harrop, 2012). In this type of wireless sensor network, the mobile nodes have the capability to reposition and organize themselves in the network as well as sense, compute, and communicate. Because of its mobile nature, it must employ a dynamic routing algorithm, unlike fixed routing in static WSN which do not need. The mobile WSNs face many challenges including deployment, mobility management, localization with mobility, navigation and control of mobile nodes, maintaining adequate sensing coverage, minimizing energy consumption in locomotion, maintaining network connectivity, and data distribution. Examples of applications of mobile WSN include monitoring (for example environment, underwater), military surveillance, target tracking, search and rescue.

2.4 The IEEE 802.15.4 Technology for Wireless Sensor Networks

The IEEE 802.15.4 technology was introduced as the standardization framework for the wireless sensor technology, including the wireless sensor networks. It is a short-range communication system intended to provide applications with throughput and latency requirements in wireless personal area networks (WPANs) (Gutierre *et al*, 2001). The IEEE 802.15.4 is a specification for low-rate wireless personal area networks at short range (up to 100m) (IEEE std 802.15.4, 2006). It has been widely used in industrial wireless sensor networks (WSN) in automation processes as well as initially in Body Area Networks (BAN). The IEEE 802.15.4 provides for a fixed setup scenario hence has been successful in this application because of the distances supported (up to 100m).

The key features of 802.15.4 wireless technology are low complexity, low cost, low power consumption, low data rate transmissions. The IEEE 802.15.4 Working Group for this standard focused on standardization of the lower layers of the OSI protocol stack. The options for the upper layers include the Zigbee protocols and Internet Protocol (IPv6) version of Low-power Wireless Personal Area Networks (6LoWPAN). The 6LowPAN was released in 2007 as the open standard for IPv6 over 802.15.4. Figure 2.5 shows an example of the ZigBee protocol stack.

From the IEEE 802.15.4 protocol stack shown in Figure 2.5, the upper layers cover the network layer and the application layer. The network layer is responsible for the network configuration and the message routing while the application layer provides the intended functionality of the sensor device (Sirpatil, 2006). The 802.2 LLC refers to an IEEE 802.2 Type 1 logical link layer (LLC) can access the MAC sublayer through the service specific convergence sublayer (SSCS) (IEEE Std 802.15.4, 2006). The physical layer (PHY) of the protocol stack is the initial layer in the OSI reference model (Day & Zimmermann, 1983) which is used worldwide. The PHY layer is a service which provided the PHY data transmission service and the management service. The data service allows the transmission and reception of PHY protocol data units (PPDU) over the physical radio channel.

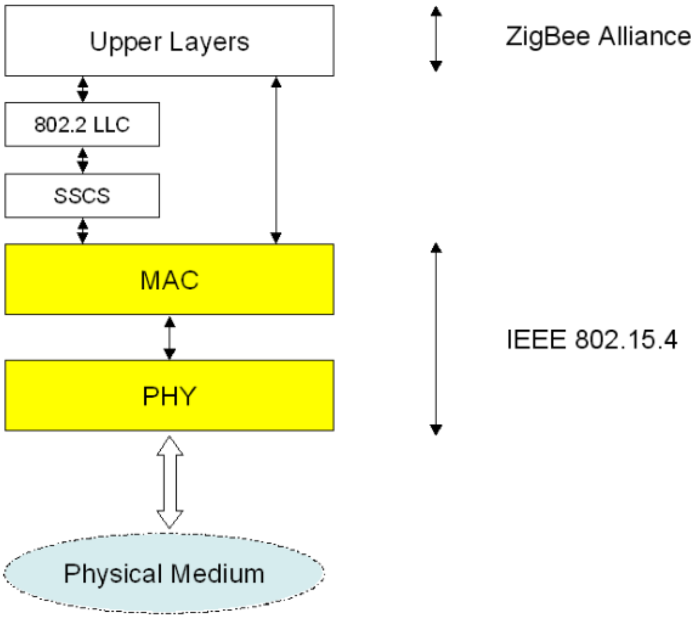

Figure 2.5. IEEE 802.15.4 protocol stack (Buratti et al, 2009).

The IEEE 802.15.4 protocol specifies up to 27 half-duplex channels across the following three physical layer unlicensed bands in which it operates (Buratti *et al*, 2009). These are:

- The 868 MHz band: In this band, only a single channel with data rate 20 kbps is available; -92 dBm RF sensitivity required and the ideal transmission range is approximatively equal to 1 km;
- The 915 MHz band: Here, ten channels with rate 40 kbps are available; the receiver sensitivity and the ideal transmission range are the same as rge 868 MHz band;
- The 2.4 GHz ISM band: In this frequency band, sixteen channels with data rate 250 kbps available; minimum -85 dBm RF sensitivity required and ideal transmission range equal to 220m.

During the development of the IEEE 802.15.4 wireless technology, the application of the WSN in Medicare and the challenges around this application were not visible. Hence with the advancing technology, when it came to medicare, IEEE 802.15.4 proved not ideal because of its nature of design (Fourati *et al*, 2015). The order of priority of the requirements for wireless body area networks (WBAN) is different as compared to the requirement application in industrial WSN (which was the main purpose for WSN application). The most important for WBANs is to establish and maintain reliable and timely sensor data transfer between the sensor nodes and the coordinator node (Filipe *et al*, 2015). However, the IEEE 802.15.4 standard lacks various key factors that are essential for wireless patient monitoring such as life time of sensors (Ghamari *et al*, 2016). The IEEE 802.15.4 provides no provision for mobility which is a crucial property in WBANs as the areas of application are highly mobile (as in the case of medical applications of WBAN). This led to the development of IEEE 802.15.6 wireless technology (now commonly known as WBAN technology).

2.5 Wireless Body Area Networks (WBANs)

The WBAN is a special type of wireless sensor networks which provides remote monitoring of physiological parameters such as body temperature, ECG (Variation of electrical heart vector, heart work rate), pulse rate (heart work rate), respiratory rate, respiratory volume (minutely respiratory volume gauge), body temperature, high blood pressure (systolic and diastolic) etc. (Toumanari & Laif, 2016; Dosinas *et al*, 2006). The WBAN is composed of several biosensors that can be categorized into in-body or/and on-body sensors capable of extracting, computing and transferring the measured data towards the destination through single-hop or multi-hop architecture where further analysis take place and responsible personnel are notified in case of emergency (Bhoir & Vidhate, 2014; Shen *et al*, 2014). Figures 2.6 and 2.7 shows examples of in-body and on-body sensors respectively. In Figure 2.6, the sensor is implanted inside of the body and invisible to the human eye from outside. Implanting such sensors requires a medical procedure as it is inscribed inside the body skin, and often there is no chance of changing the sensor battery (Hiep & Kohno, 2014). The on-body sensors, example shown in Figure 2.7, are usually very small (De Micheli, 2015) and are implanted on the body skin and can be in many forms such as skin implanted, as a wrist watch or band, necklace, rig, belt among other forms as appropriate for the application scenario of the measured.

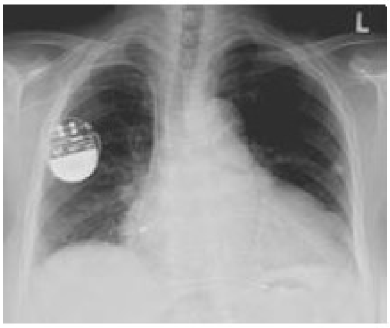

Figure 2.6. X-Ray Image showing an implantable Pacemaker in-body Sensor

Figure 2.7. On-body Sensor

The WBAN common architecture consists of three tiers communications, namely; Intra-BAN communications, Inter-BAN communications and beyond-BAN communications (Negra *et al*, 2016). This architecture is described in Figure 2.8. The Intra-BAN communication refers to the communications among wireless body sensors and the master node (also referred to as the central node or cluster head or the coordinator node) of the WBAN. The Inter-BAN communications involve communications between the master node and personal devices such as notebooks, Wi-Fi, Bluetooth devices or other surrounding WBANs, and so on. The beyond-BAN tier connects to the remote central monitoring system such as the ambulance, medical emergency monitoring room or a patient monitoring system within a medical facility or over the internet. The differet types of WBAN interference occurs among each of these levels intra-BAN, inter-BAN and the beyond BAN communication. In this research, the intra-BAN, inter-BAN are explored in an attempt to find intereference mitigation mechanism for the same.

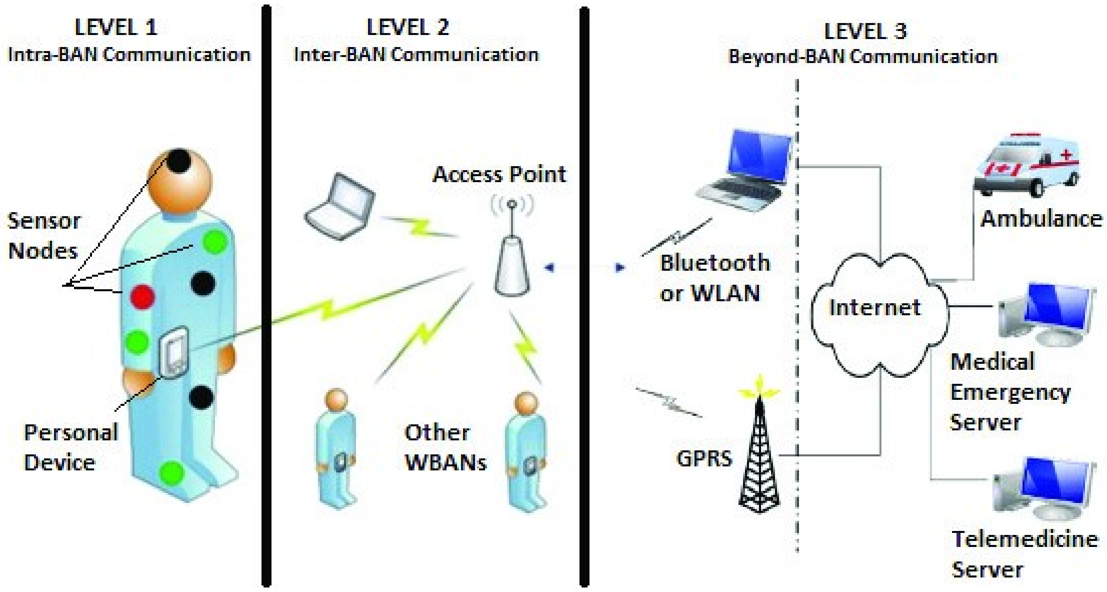

Figure 2.8: The general architecture for Wireless Body Area Networks (Negra et al, 2016)

The WBAN is a high sensitive and reliable application of technology in telemedicine and because it continuously tracks patients chronic disease, a sudden variation of a sensible parameter might lead to a serious damage if not death of the patient. Using such Wireless medical technology provides patient with more freedom, allowing him to perform casual activities without worrying about a wired device being plugged in (Chan *et al*, 2007).

The WBAN sensor nodes are generally very diminutive which means miniature battery size, therefore, the WBAN are severely constrained in terms of energy (Olivo *et al*, 2011; Lee and Annavaram, 2012). The WBANs are very mobile in nature hence the network topology is dynamic and changes fast. Among the basic is high reliable communication, and low power consumption (Juneja & Jain, 2015), which is a directly related to the minute nature of the WBAN sensor devices' battery size. Relating to low power consumption, many techniques have been proposed to minimize the energy consumption among WBAN sensors involving finding optimal network architecture for data transmission, conceiving an adequate design for RF transceiver, and implementing efficient communication protocols (Marinkovic *et al*, 2012; Huynh *et al*, 2016; Wu *et al*, 2016; Chen *et al*, 2011; Kim *et al*, 2017; Abiodun *et al*, 2017).

2.5.1 Importance of WBAN in Medicare Applications

In the current world, the technology plays a very critical in the improvement of medical field hence resulting in high or improved life expectancy. Wireless network is one of these technologies which have enabled the use of technology in the medical field by enabling the remote monitoring of health problems (Saboor *et al*, 2019). The wireless sensor networks are now involved in many areas of wireless healthcare systems for both medical and non-medical purposes (Khan & Yuce, 2010) as it could be used to track people over long distances via an implanted sensor as well as indicating the status of certain physiological parameters when an athlete is in process of performing some moves corresponding to numerous mobility patterns. In the healthcare application, the sensors nodes are implanted within the body hence have been renamed as the Body Area Network (BAN) or the Body Sensor Network (BSN) or the Wireless Body Area Networks (WBAN). The medical application of the wireless sensor networks allows for continuous monitoring of one's physiological attributes such as blood pressure, blood sugar, heartbeat-rate and body temperature among other chronic diseases' signs. The measured parameters on the body can be internally or externally. Some of the existing types of sensors can be in one's wrist watch, mobile or earphone which are connected wirelessly to enable monitoring of the person anywhere, anytime and with anybody. In cases where abnormal conditions are detected, data being collected by the sensors is sent to a gateway device. The gateway then delivers its data to a monitoring server in a local or remote location such as an emergency centre or doctor's room on which an action can be taken (Chen *et al*, 2011; Latre *et al*, 2011; Ullah *et al*, 2010; Xing and Zhu, 2009; Wang *et al,* 2007). Figure 2.9 shows an abstract view of the WBAN and its framework in an example application on healthcare monitoring. The diagram shows the WBAN (running human) with the different sensors for ECG (Electrocardiography), EEG (Electroencephalogram), EMG (Electromyography), Blood Pressure (BP) among others, all communicating to central node in the form of a mobile phone. The central node then sends the sensor data over the internet to a remote home computer or physician or emergency monitoring room or the information is saved to a medical information database where it is monitored in real time. This scenario monitors the physiological or health state of an athlete.

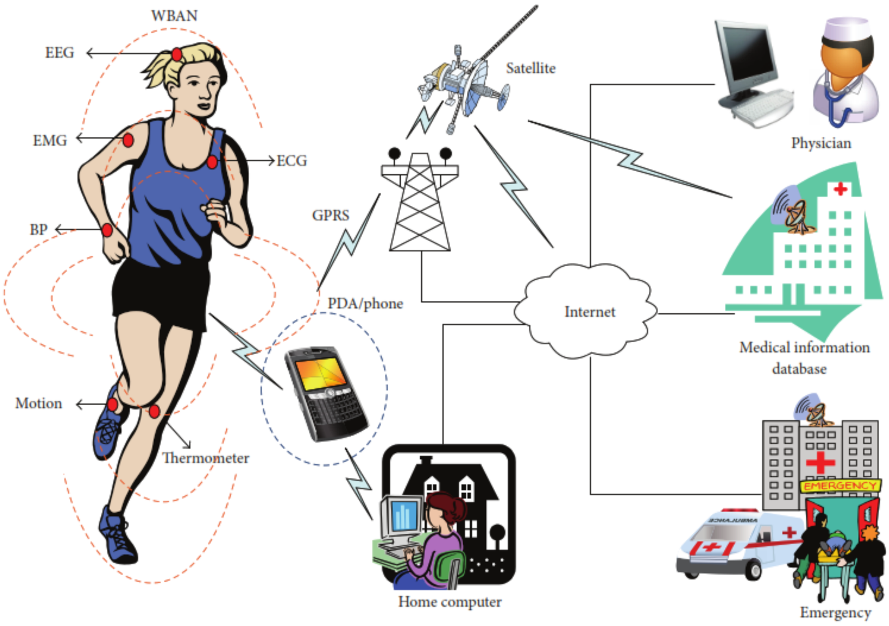

Figure 2.9: An abstract view of WBAN and its framework in healthcare applicability (Khan *et al*, 2015)

The stated by Kwak *et al* (2010), WBAN technology application in healthcare has enabled the monitoring of life threatening diseases and providing the real-time monitoring of patients without the need of having the patients present in hospital or the need to stay under observation (Kwak *et al*, 2010) as well as delivering Medicare to the remote and vulnerable groups. It was expected to augment healthcare systems to enable more effective management and detection of illnesses, and reaction to crisis rather than just wellness (Dishman, 2004; Otto *et al*, 2005).

In one of the recent survey research by Sathya and Evanjaline, (2018), Wireless Body Area Network in Healthcare system is reviewed. The duo concluded that WBAN is being a very useful technology with many benefits for medical applications, patients and society by continuous monitoring and early detection of diseases. By using WBAN medical healthcare system will improve patients' performance and will be useful for reducing death rate.

The IEEE standard for WBAN has been IEEE 802.15.6 (Akyildiz *et al*, 2002). This technology has been developed specifically for WBAN due to its unique nature.

The WBAN includes the sensor nodes and a coordinator node. The coordinator node also called the cluster head, interacts with the user upon receiving data from the sensors and provides feedback in the network by acting on sensor data (Latre *et al*, 2011). For some signals like for electrocardiogram (ECG), Electromyography (EMG) and electroencephalogram (EEG) is more complicated in comparison to parameters such as pulse rate and temperature signals. The information from these nodes requires a continual and undisturbed sampling period as high as 400 samples per second, each sample of size 10bits will require a connection speed of 400bps and to allow for MAC overhead and packet retransmission, the baud rate (i.e. data rate) for the radio frequency (RF) link should be at least twice this rate. Figure 2.10 shows Live monitoring of multi-patient's hearts (Cardiac Patients) in real-time in the "Aurora Grafton Medical Center" using the new technology. By use of the sensor technology, this has relieved off a lot of pressure off the nurses who had to do the work of monitoring each single patient at the Intensive Care Unit (ICU) as all are now managed by a single person. It has also helped silence the many hospital alarms (as commonly it is the case in all intensive care units or high dependency units) leading to better health.

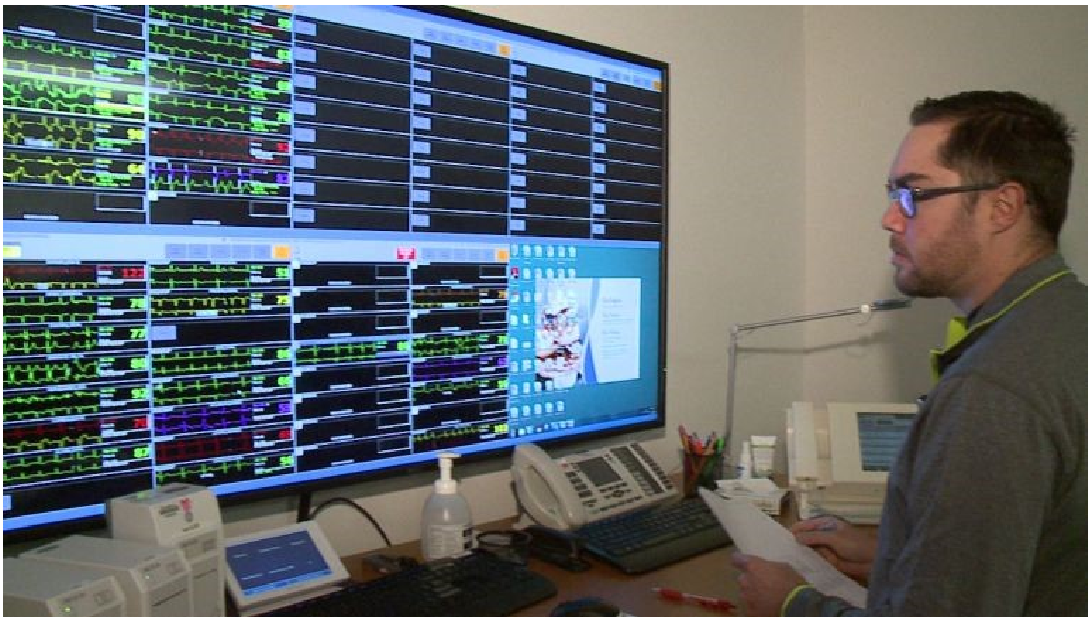

Figure 2.10. Live monitoring of multi - patients hearts (Cardiac Patients) in real-time in a Aurora Grafton Medical Center using the new technology (Source: fox6now.com)

2.5.2 The effects of body activity and body fluids in IEEE 802.15.6 WBANs

The body sensor networks are categorized as either on-body or in-body sensor networks.

The in-body sensor networks are those that are implanted inside the human skin and beyond. There is a big challenge in accommodating the in-body sensor nodes as they are implanted and out of physical contact with the outside environment. The path loss inside a human body results in improper channel assignment. As well, the human body poses many wireless transmission challenges as the body is composed of several components that are unpredictable and subjected to change. Also, the electrical properties of the body affect the signal propagations. The in-body sensor networks beyond the scope of this study.

The on-body sensor networks are those that are implanted outside the human skin, these may be implanted on top of the skin or wearable on the form of watches, bangles, rigs etc. (Ghamari *et al*, 2016).

2.6 The IEEE 802.15.6 Wireless Sensor Technology for WBANs

Due to the high demands for wireless technology driven patient monitoring in the past, the IEEE 802.15.4 standard was used. But because the IEEE 802.15.4 standard lacked very essential factors that are critical for wireless patient monitoring such as the life span of the sensors, the IEEE 802.15.6 wireless body area network (WBAN) standard was introduced to enhance and facilititate the increasing demand of the wireless driven patient monitoring. Other important factors that lacked in IEEE 802.15.4 standard included reliability, low power, the size of the sensors, data rate, latency, interference and lack of traffic flows. The IEEE standards related to the technical requirements of WBANs are listed in (Lewis D., 2010) (IEEE 802.15.6 Draft, 2010). It was meant to provide support for the medical applications, but also it has been adapted in military, entertainment and sports (Kiani *et al*, 2018; Salayma *et al*, 2017; Movassaghi *et al,* 2014). In the application of medical field, the WBAN consists of a few sensors communicating with a gateway device to the internet. A typical medical WBAN is stated to have 6 nodes and scalable to 256 nodes. IEEE 802.15.6 Draft, 2010 stated the requirements of WBANs as operating range of 3m for WBANs of upto10 piconets per person and supporting 256 nodes in each net within 6m^3 (Zhen *et al*, 2008; Zhang *et al* 2010; Hanlen *et al* 2010). Figure 2.11 shows the scenario of ten (10) coexisting WBANs in a 6m^3 spacing as depicted it the standard scenario. As well Movassaghi *et al* (2014) states that the requirements of WBANs based on the IEEE 802.15.6 standard are (a) the bit rate of a link is in the range of 10 kbps to 10 Mbps, (b) packet error rate should be less than 10% for a 256 octet payload for 95% of links, and (c) the time to join or leave a network should be less than 3s. Also, according to the IEEE 802.15.6 standard, the nodes can be organised into one or two-hop star WBANs with a single coordinator or hub controlling the entire operation of each of the WBAN (Sana *et al*, 2013).

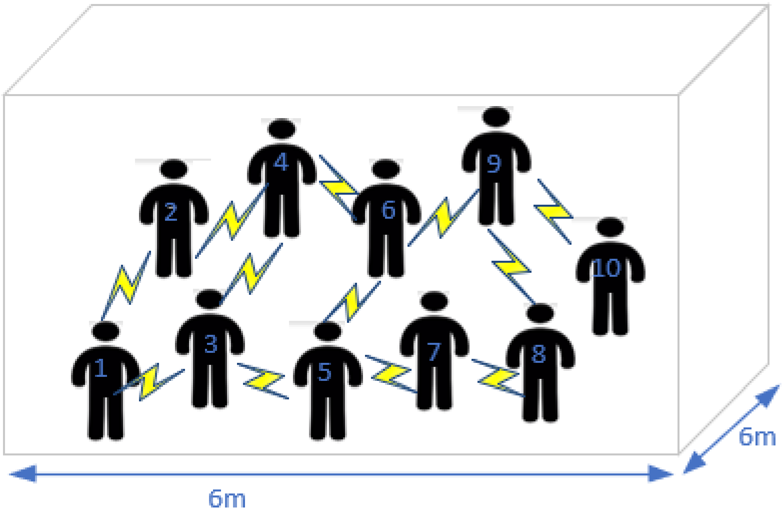

Figure 2.11: Scenario of ten Coexisting IEEE 802.15.6 WBAN in a 6m^3 cube

The WBAN operates different frequency bands in different countries (Arthur *et al*, 2009). A summary of some of the frequency bands available for WBAN in different countries are shown in Figure. 2.12. Medical Implant Communications Service (MICS) band is a licensed band used for implant communication and has the same frequency range (402-405 MHz) in most of the countries. Wireless Medical Telemetry Services (WMTS) is a licensed band used for medical telemetry system. Both MICS and WMTS bandwidths do not support high data rate applications. The Industrial, Scientific and Medical (ISM) band in 2.4 GHz frequency range supports high data rate applications and is also available worldwide. However, the chances of interference are very high as many wireless devices including IEEE 802.1 and IEEE802.15.4 operate at the same ISM band.

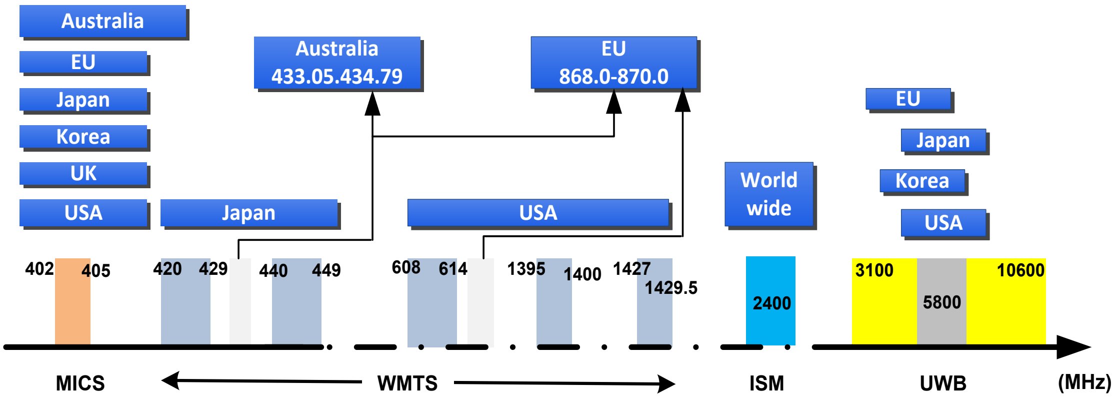

Figure 2.12: Frequency bands for WBAN (Arthur et al, 2009)

The Industrial, Scientific and Medical (ISM) band in 2.4 GHz frequency range as well has a maximum of 79 possible channels hence the channel planning is not an ideal intereference mitigation mechanism. Table 2.1 shows the number if available channels in each of the frequency band.

Table 2.1. The number of available channels per frequency band

Frequency Band (MHz)	Number of channels
402 to 405	10
420 to 450	12
863 to 870	14
902 to 928	60
950 to 958	16
2360 to 2400	39
2400 to 2483.5	79

In respect to the channel frequency, the scope of this research is the Industrial, Scientific and Medical (ISM) band. Therefore, the MICS, WMTS and UWB frequency bands are out of scope of this study.

2.7 The WBAN Mobility

The Mobility in WBAN is one of the important aspect to consider in achieving a near real life simulation of the WBAN environment (Boulemtafes *et al*, 2015). This includes individual mobility as well as group mobility where a body moves in the surrounding environment. Individual mobility is whereby the sensor nodes are deployed on different parts of the body where there is a great aspect of mobility in terms of movement of the different parts of the body. An ideal WBAN mobility model should capture both aspects of individual and group mobility.

For an accurate performance evaluation simulation of WBAN, a good mobility model is essentially a prerequisite. The purpose of these mobility models is to try mimic almost the exact or real movement of a mobile WBAN node.

In wireless body area network, the sensor nodes are implanted on different parts of the body to report on different physiological signs of the human body. The movement of the body is a constant characteristic hence the node mobility is high, leading to high frequency of network topological variations over a period. A proper WBAN protocol stack should be able to manage the expected type of mobility. Some of the movements can lead to complete change of the WBAN network topology and node connectivity within the human. In such a case, the MAC layer and the routing protocol of the WBAN should be very flexible without any strong assumption about the location of the nodes and their connectivity.

There are several existing studies on mobility models. Camp *et al* (2002) presented a survey review of these early models. In this research, brief general review of the commonly used models are presented, which include Random Walk Mobility Model (RWMM) (Zonoozi & Dassanayake, 1997), Random Waypoint Mobility Model (RWPM) (Hyytiä & Virtamo, 2007), Random Direct Mobility Model (RDMM) (Royer *et al,* 2001), Random Gauss-Markov Mobility (RGMM) (Liang & Haas, 1999), Reference Point Group Mobility model (RPGM) (Hong *et al*, 1999) and the Mobility Model for BANs (MoBAN) (Nabi *et al*, 2011). These mobility models are generally categorized as either singular node or group mobility models. The Random Walk Mobility Model, Random Waypoint Mobility Model and Random Direct Mobility Model are categorized as singular node mobility models while Reference

Point Group Mobility model and the Mobility Model for BANs (MoBAN) are group mobility models (Nabi *et al*, 2011).

The Random Walk Mobility Model (Zonoozi & Dassanayake, 1997) is a singular node mobility model in which a node uniformly randomly selects an arbitrary direction and a velocity value from a given range. The node then moves either with a specified fixed time interval or until a given distance is traveled. The node then repeats the random selection and movement process. The movement takes place within a given rectangular space, which is the simulation area. If the node reaches a boundary of the simulation area, it continues along a new path with an angle determined by the direction of hitting the border (Najafabadi, 2013).

The Random Waypoint Mobility Model adapts the Random Walk Mobility Model by inserting pause time between the changes in direction and speed. From a given range a time, the pause time is selected randomly. In Random Waypoint Mobility Model, a destination is selected randomly from the simulation area. The node then moves toward that position with a randomly chosen speed. All random selections are primarily done using uniform distributions. A specific relation between the pause time and the speed can be applied based on a specific application, to fit the model towards either a more stable network or a network with frequent topology changes (Hyytiä & Virtamo, 2007).

Both the Random Walk Mobility Model and the Random Waypoint Mobility Model have a node concentration problem. In Random Waypoint Mobility Model, the destination points are distributed randomly over the simulation area. The nodes in this model traverse direct paths toward the selected destination and with a high chance they pass the central part of the area. For this reason, the clusters are formed near the center of the area. The Random Direction Mobility Model (RDMM) (Royer et al, 2001) attempts to alleviate the concentration problem and provide a more even distribution of nodes over the entire simulation area. This is done by forcing the nodes to meet a border in each movement step. The node uniformly randomly selects a direction (similar to Random Walk Mobility Model) and starts to travel to the border of the area in the selected direction. When the node reaches the simulation boundary, it stops there for a given time. Then the node picks another direction and repeats the process (Najafabadi, 2013).

These Random Walk Mobility Model and the Random Waypoint Mobility models discussed are memory-less, meaning that the completed movement step does not have any impact on the decision about the movement of the next step. In (Liang & Haas, 1999), the Random Gauss-Markov Mobility (RGMM) model was proposed in which subsequent movement steps are not independent. Using the Markovian behavior, the speed and direction at each movement step were adapted to determine their value for the next movement step. For adapting the movement parameters, a random Gaussian distribution was used. This model can eliminate sudden stops or sharp direction changes, which happen in the Random Walk Mobility Model and Random Waypoint Mobility Model models.

Several group mobility models have been proposed in the past in effort to model the movement patterns of humans in certain specific scenarios. These models have been presented by (Sánchez & Manzoni, 2001) and include the Column Mobility Model, the Pursue Model, and the Nomadic Community Model. Other recent models which have been based on the concept of higher node density in more popular locations such as the home location include the Small World In Motion (SWIM) model (Mei & Stefa, 2008) which proposes a mobility model based on the fact that humans go more often to locations near their home and to locations in which they can meet many other people. Another model, the N-Body (Zhao & Sichitiu, 2010) mobility model tries to capture the diversity of the distance between different nodes by analysing real human movement traces.

In this research, Mobility Model for BANs (MoBAN) (Nabi *et al*, 2011) is adapted to model the WBAN mobility. The model can be configured to model mobility patterns in various scenarios of the wireless body area networks.

2.8 The Mobility Model for WBANs (MoBAN)

In this research, the MoBAN (Nabi *et al*, 2011) mobility model for BAN has been used (as an OMNET++ add-on) to simulate the motion of WBAN's. The MoBAN model is constructed by two basic control units, namely the posture selector and the global movement module.

The MoBAN model Structure is discussed by Nabi *et al* (2011) and shown in Figure 2.13. As shown in the Figure, the MoBAN structure consists of five main parts, namely, the coordinator module, the config file, the posture specification file, the input mobility pattern file and the Local MoBAN file. These are discussed in sections 2.8.1 through 2.8.4.

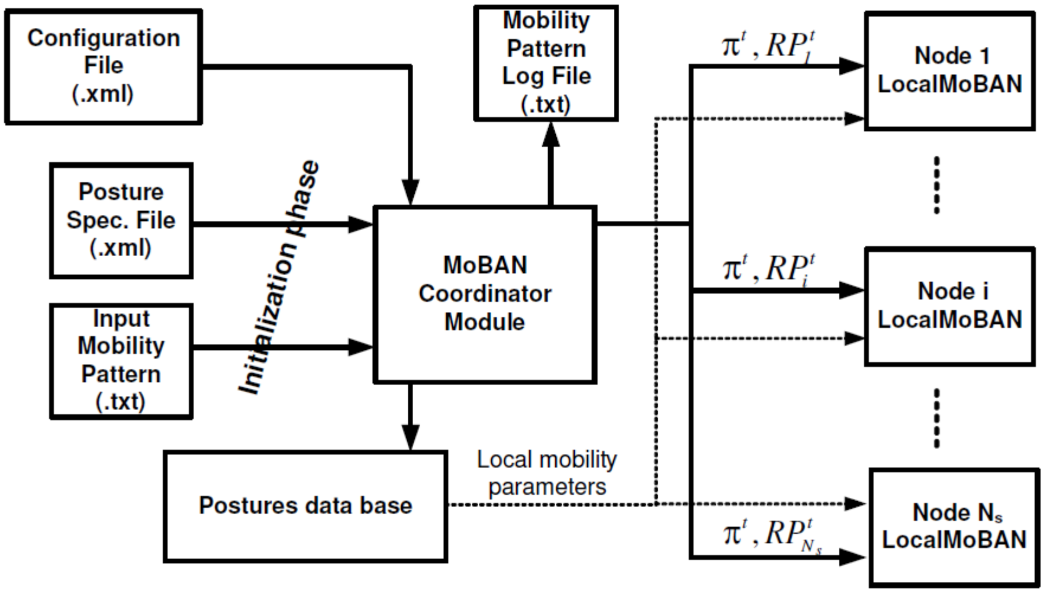

Figure 2.13. Block diagram of the OMNeT++ implementation of the MoBAN mobility model (Nabi *et al*, 2011).

The MoBAN mobility posture database in the architecture (Figure 2.13) keeps the different history of the different postural changes.

The posture specification of the MoBAN defines the different postures and the posture change pattern as later discussed in this section. The postural selector process determines the current posture at any instance of time. The individual movement (the random motion vector) of every sensor node is subsequently determined according to the selected posture. On the other hand, the global movement process is responsible for controlling the mobility of sensor nodes on the body as a whole (i.e. moving the logical center of the group) (Nabi *et al*, 2011).

In this mobility model, as shown in Figure 2.14, a mobility pattern would start the process of selecting the posture selector. Once the posture is selected for the next mobility phase, information related to the selected posture is retrieved. If the posture has been defined as a stable posture, such as *lying down*, the posture selector process keeps the control and waits a time duration. It then selects another posture based on its strategy. In the case of a mobile posture, such as *walking*, the global movement control module starts moving the whole WBAN by considering the parameters for that specific posture. The movement behavior, like the destination, speed, and the path to that destination, depends on the specific strategy for the running application scenario. Once the WBAN reaches the destination point, the posture selector module gets the control to select the next posture and the process is continued. Figure 2.14 presents the Structural process of MoBAN which is then expressed in Algorithm 1.

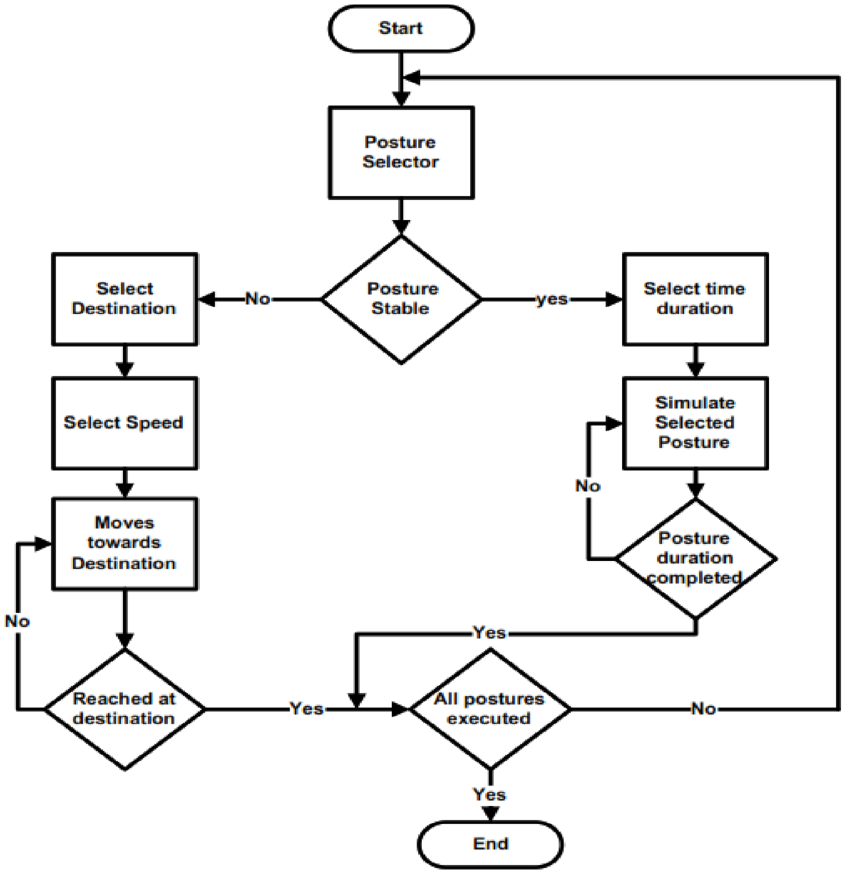

Figure 2.14. Structural process of MoBAN (Shakir *et al*, 2016)

Algorithm 1: The MoBAN structural process (Nabi *et al*, 2011)

```
Data:
$\tau$ : posture selection step
        ($\tau \in \mathbb{N}$)
$\pi^{\tau}$ : WBAN posture at step $\tau$
$A^{\tau}$ : Simulation area type at step $\tau$

while True do
    $\pi^{\tau} = \mathrm{SelectPosture}(\pi^{\tau-1}, A^{\tau-1})$;
    if IsStable($\pi^{\tau}$) then
        $T_S$ =SelectDuration() ;
        wait for $T_S$ seconds ;
```

```
    else
        $Dest^{\tau}$ = SelectDestination();
        $V^{\tau}$ = SelectSpeed($\pi^{\tau}$);
        Move the $LC$ toward $Dest^{\tau}$ with velocity $V^{\tau}$ ;
        Wait until $Dest^{\tau}$ is reached ;
    end
end
```

This research study adopted posture selections of the *running*, *walking*, and *standing*, *sitting* and lying human postures to simulate near real life scenario for the WBAN. These postures are well developed in the MoBAN mobility model unlike any other mobility model. As well, the ability of the MoBAN mobility model to support both the postural selector and group mobility made it good for WBAN. In MoBAN mobility model, this research has adopted the posture selections as lying down, walking, standing, running and sitting as they are discussed by Nabi *et al* (2011).

2.8.1 The Posture Specification

The posture specification of MoBAN is presented in (Nabi *et al*, 2011) and in Omnet++ it is a xml file defining the possible postures for the MoBAN model and determines the specification for each posture. Let assume $S = \{s_1, s_2, \ldots\ldots, s_{N_s}\}$ is a set of N_s sensor nodes in a WBAN. In the mobility model, let there be Np different postures $\pi = \{\pi_1, \pi_2, \ldots, \pi_{NP}\}$.

For each posture, the parameter that should be defined is the speed range of the global movement of the WBAN in the simulation area, and the parameters of all nodes in the WBAN. The relative position of each node (3D coordination of the reference point), the speed of local (individual) movement of each node, and the radius of the sphere around each node that node can move inside are parameters that should be set individually for each posture as shown in Tables 2.3 to 2.7.

The table 2.2 shows the notations that are used for the posture specification parameters in the MoBAN mobility model used in this research. The table gives the notations for maximum and minimum velocity of the WBAN, the velocity of the node, radius of the movement sphere and the relative reference point of the node in the postures as used in the specification posture.

Table 2.2. The basic specification of postures πj (Najafabadi, 2013)

Notation	**Description** $(1 \leq i \leq \mid C \mid, 1 \leq j \leq N_p)$
$RP_{i(\pi_j)}$	Relative reference point of node C_i in postures π_j
$V_i (\pi_j)$	Velocity of node C_i
$r_i (\pi_j)$	Radius of movement sphere of node C_i
$V_{min} (\pi_j)$	Minimum velocity of the WBAN
$V_{max} (\pi_j)$	Maximum velocity of the WBAN

Where π_j is the posture that can be set as mobile by specifying the speed values $V_{max}(\pi_j)$ of its global movement. The typical mobile postures are the walking, running, sitting and lying down. These postures have been adopted in this research study. Each posture is defined by a set of specification parameters which are application dependent and they are specified by the user.

The parameter that should be defined for each posture is the speed range of the global movement of the WBAN in the simulation area, and the parameters of all nodes in the WBAN. The relative position of each node (3D coordination of the reference point), the speed of local (individual) movement of each node, and the radius of the sphere around each node that node can move inside are parameters that should be set individually for each posture.

In this research, the configuration code for the postures specification xml file (referred to Posture3.xml in the Omnet++ simulation program) used for this study is shown in appendix IV.

In the MoBAN model, the distribution for the time duration of each posture according to the application scenario is specified. This can be a constant time duration or a uniform distribution, or a more precise distribution closer to real-life posture duration. In this research performance evaluation experiment, node parameters are used for each of the scenario as seen in Postures Spec xml File and as in in Tables 2.3 to 2.7. From 3D perspective, X is the axis that goes side to side, Y is up to down and Z is forward to backward.

In the simulation of intra-WBAN communication protocol, in the simulation setup, only one MoBAN coordinator module is required as it is only single WBAN involved in intra-WBAN scenario. In chapter 3 on methodology, this research study proposed the use of Mixim Framework on OMNET++ discrete event simulator due to its wider adaptation on wireless sensor networks and specifically WBANs. The parameters adopted in each posture specifications are recommended OMNET+++ MoBAN mobility model (Nabi *et al*, 2011). The OMNeT++ Implementation of MoBAN code is available from the portal.

(i) Running Posture

Node parameters for running posture ID 0 (refer to posture spec file) are shown on Table 2.3.

The running property of the posture is mainly defined by the speed parameter. The other X, Y and Z positions defines the variations in the mobility in each direction parameter. Node 0 through 6 represent the sensor nodes in a WBAN. The speed demonstrates the WBAN change of mobility against time.

Table 2.3: Node parameters for running posture

Node #	Position X	Position Y	Position Z	Radius	Speed
0	300	220	100	5	10
1	295	260	70	00	00
2	330	260	100	10	25
3	270	260	100	10	25
4	300	280	100	00	00
5	320	330	100	20	20
6	280	330	100	20	20

(ii) Walking Posture

Node parameters for walking posture ID 1 (refer to posture spec file) are shown on Table 2.4. In this walking posture, the X, Y and Z directional changes defines the variations in the mobility in each direction parameter, but the speed is recorded to be lower than the running posture as the difference between the two postures (running and walking) is the speed and the radius. Node 0 through 6 represent the sensor nodes in a WBAN.

Table 2.4: Node parameters for walking posture

Node #	Position X	Position Y	Position Z	Radius	Speed
0	300	220	100	5	10
1	295	260	70	00	00
2	330	260	100	7.5	15
3	270	260	100	7.5	15
4	300	280	100	00	00
5	320	330	100	15	15
6	280	330	100	15	15

(iii) Standing Posture

Node parameters for standing posture ID 2 (refer to posture spec file) are shown on Table 2.5. The posture is static or stationary in nature hence there would be almost no speed variations of the WBAN. The ideal practical scenario would not have a zero speed but almost zero value. Node 0 through 6 represent the sensor nodes in a WBAN.

Table 2.5: Node parameters for standing posture

Node #	Position X	Position Y	Position Z	Radius	Speed
0	300	220	100	5	10
1	295	260	70	00	00
2	330	260	100	7.5	01
3	270	260	100	7.5	01
4	300	280	100	00	00
5	320	330	100	15	05
6	280	330	100	15	05

(iv) Sitting Posture

Node parameters for sitting posture ID 3 (refer to posture spec file) are shown on Table 2.6. The posture is also static or stationary in nature with a slightly more mobility in some parts of the body like the upper part consisting of hands, elbows and head hence some of the WBAN would have slight increase in speed parameter compared to standing posture.

Table 2.6: Node parameters for sitting posture

Node #	Position X	Position Y	Position Z	Radius	Speed
0	300	290	100	5	10
1	295	310	70	00	00
2	330	330	100	02	01
3	270	330	100	02	01
4	300	330	100	00	00
5	320	360	100	02	03
6	280	360	100	02	03

(v) Lying down

Table 2.7 shows the node parameters for lying posture as seen in posture spec file ID 4. These parameters would be ideally almost similar to sitting but there would no speed at all in this posture as the body is completely under rest with zero movement.

Table 2.7. Node parameters for lying posture

Node #	Position X	Position Y	Position Z	Radius	Speed
0	450	340	100	0	0
1	420	330	70	0	0
2	410	370	100	0	0
3	410	330	100	0	0
4	400	340	100	0	0
5	350	330	100	0	0
6	350	320	100	0	0

2.8.2 The MoBAN Coordinator Module

The coordinator module is the main module that provides the group mobility and correlation between nodes in a WBAN. In the initialization phase, it reads three user defined input files namely, the postures specification file, the configuration file which includes all required parameter for specific distributions, and the previously logged mobility pattern. WBAN instances in the same situation can use the same input files.
After the initialization phase, the MoBAN coordinator decides about the posture and the position of the Logical center of the group (WBAN). The absolute position of the reference point of each belonging node is calculated by adding the current position of the logical center by the reference point of that node in the selected posture. The coordinator publishes the position of the reference point as well as the speed and the radius of the local movement of nodes to their blackboards. The MoBAN coordinator module contains the network description (NED) file, the header file (.h) and the .cc file.

The network description file is instantiated in the top-level simulation network. Table 2.8 shows the NED class files used in this research in referencing the input files postures specification file, the configuration file and the mobility pattern file.

Table 2.8. Files used in the NED class

Type	File Name
Xml	postureSpecFile
Xml	configFile
String	mobilityPatternFile

From Table 2.8, the PostureSpecFile is the input file that includes the specification of all Postures. The configFile is the configuration file for setting probability vectors, distributions and correlations while the mobilityPatternFile is the input file for mobility pattern if it is going to be used.

The detailed configuration code for the MoBAN coordinator is shown in appendix IV.

2.8.3 Config File

This is an XML file that provides the configuration options for the MOBAN model. In this Omnet++ simulation program, this has been referred to as "ConfigMoBAN3.xml" and is shown in appendix IV. It defines the X, Y and Z sizes for the different area types for example living room and bedroom; time domains for example night and day time domain; as well as combinations of area type and time domain, for example bedroom on day time, bedroom on night time, living room for day time among others. The MoBAN also uses the Markov matrices which are defined in this config file.

2.8.4 Local MoBAN

This is the local mobility module of the MoBAN. It is instantiated in each node that belongs to a WBAN. The NED parameter "coordinatorIndex" determines to which WBAN (MoBANCoordinator) it belongs. The current implementation uses the Random Walk Mobility Model (RWMM) for individual (local) movement with a sphere around the node, with given speed and sphere radius of the current posture. The reference point of the node it the current posture, the sphere radius, and the speed is given by the corresponding coordinator through the blackboard. RWMM determines the location of node at any time relative to the given reference point. The configurations used for the MoBANLocal is shown in appendix IV.

2.9 The CSMA/CA Media Access Control (MAC) Protocol

The Hybrid Interference Mitigation Model (HIMM) proposed in this research is a combination of Carrier-sense multiple access with collision avoidance (CSMA/CA) approach and dynamic cluster head selection in WBAN. More on the HIMM is discussed in chapter 4. Therefore, in this section we review the basic knowledge on CSMA/CA protocol.

The CSMA/CA is a distributed Medium Access Control (MAC) protocol which uses MAC algorithm and that was designed for use in WiFi wireless network technology (IEEE802.11). In other words, it is a network multiple access method which uses carrier sensing to sense idle or busy channel before transmitting a frame. The CSMA/CA also tries to avoid collisions by carefully tuning the timers used by CSMA/CA devices.

The MAC protocol contains three mechanisms, namely the Carrier sense mechanism, the media access mechanism and the collision avoidance mechanism. The Collision avoidance (CA) of the protocol is used in the MAC protocol to improve the performance of the CSMA method by attempting to divide the channel equally among the transmitting nodes and within the collision domain.

The Carrier Sense mechanism is a mechanism in which, prior to transmitting, a node first listens to the shared communication channel to determine whether another node is transmitting or not. This means that this is used to verify that the channel is in idle state before the packets could be transmitted over the channel.

The Collision Avoidance is the next mechanism after the carrier sense. Under this mechanism, if another node is heard (from the listening), the sensing node waits for a period (usually random time) for the heard node to stop transmitting before listening again for a free communications channel. The process is repeated.

In the transmission, if the communication medium is sensed as being idle, the back-off counter is decremented by one at the end of each time slot. The communication channel is also idle when the node has received a Clear To Send (CTS) to explicitly indicating it can send, in which it sends the frame in its entirety. Once the packet is transmitted and received successfully by the receiver, the receiver sends back an ACK immediately to indicate that the packet was received, and checksum is checked. If the acknowledgement does not arrive on time, it is assumed that the packet collided with some other transmission, causing the node to enter a period of binary exponential back off prior to attempting to re-transmit. The back-off counter continues the count down once the channel is sensed idle again and the transmission of a node is initiated when the back-off counter of that node is finally reduced to zero (Bianchi, 2000).

Figure 2.15 demonstrates the operation of the ideal base access scheme for CSMA/CA protocol. In this figure, an ideal CSMA/CA protocol means a protocol without propagation delay. From the figure, Node 1 and Node 2 are neighbouring nodes with overlapping transmission ranges. The channel starts at idle state, the channel is idle and both nodes generate a random back-off interval. The back-off interval is 4 for Node 1 and 7 for Node 2. When Node 1 finishes its back-off, the channel is sensed idle and its packet is transmitted. The ACK is received immediately after the packet transmission. Then, a new back-off interval is generated for Node 1. During the packet transmission of Node 1, the back-off counter of Node 2 is frozen at 3. When the ACK is received by Node 1 and the channel becomes idle again, the back off counter for Node 2 continues to decrease until it reaches 0 and the packet transmission is initiated.

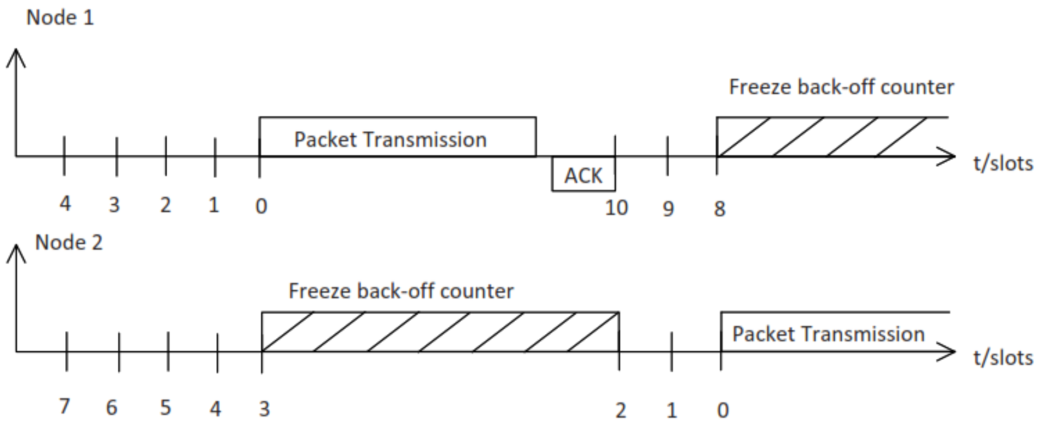

Figure 2.15. Basic Operation Scheme of a CSMA/CA Protocol (Shao, 2015)

Figure 2.16 shows the flow chat algorithm of the base CSMA/CA protocol. The figure shows that the CSMA/CA process starts by Listen for idle channel. If the channel is idle, "Request to Send" request is send to access point to reserve a time period on channel. Other devices see RTS request and wait. These RTS are very small so the chances of collision with other RTS is very minimal. The access point hears the RTS and determines whether it wants to grant access (Clear to send, CTS) or not (no response). If "Clear To Send" is received from Access point (within given time). Then Use channel to send frame of data. We send an end of frame and the process starts again at assembling frame. Otherwise if the channel is not sensed to be idle, the access point denies channel or probably RTS collides with another one and got garbled hence making the access point unable to respond.

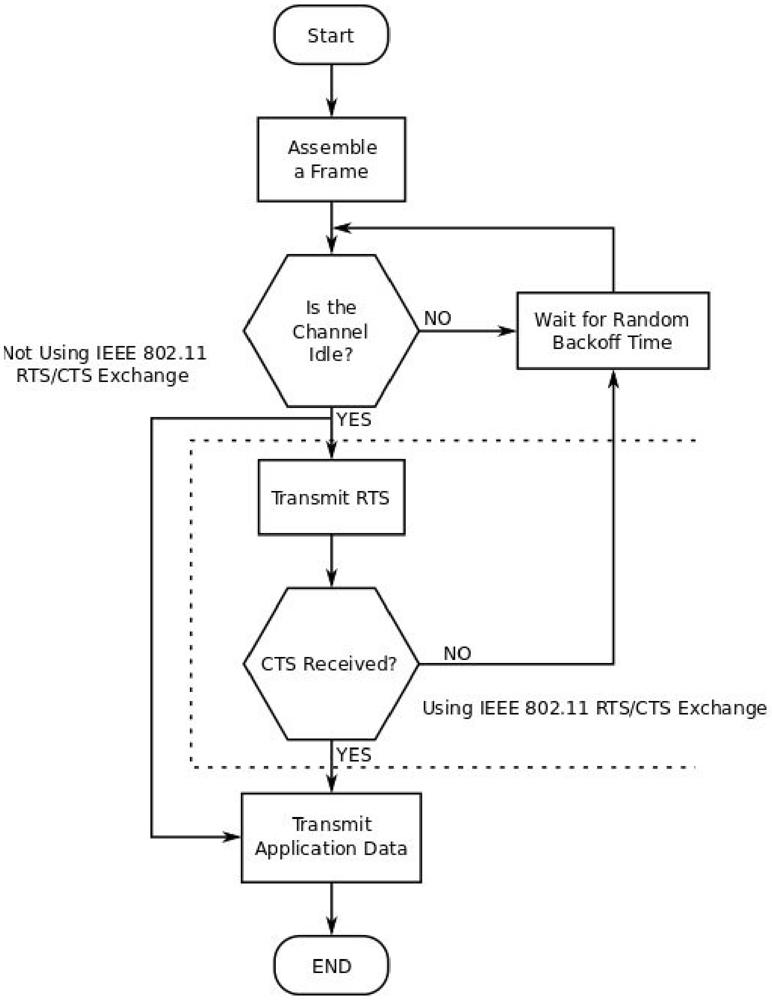

Figure 2.16. The Ideal CSMA/CA Process Algorithm (Younus *et al*, 2015)

2.10 The WBAN Interference and Interference Mitigation

2.10.1 Wireless Body Area Network Interference

With the advancement and popularization of telemedicine Medicare and eHealth, the adaptation of modern technologies in medical applications and patient monitoring has been rapidly increasing. It can be foreseen that the WBAN interference will become a serious problem as a result. There were approximately 11 million active WBANs in 2009, and the amount of active WBANs was predicted to grow tremendously by 2021 (Dong and Smith, 2012). Thus, it is inevitable that several WBANs coexist in places such as a crowded bus, a hospital ward, or a meeting room, (Shen *et al*, 2014) hence suffering from the WBAN interference. Rajalakshmi *et al* (2019) literated that when a patient moves from one place to another, it may affect the accuracy of WBAN monitoring results which lead to increased delay, due to poor channel conditions resulting from channel or WBAN interference, which cane be refered to as negative WBAN mobility effect.

One of the common causes of on-body WBAN interference is the body postural mobility where a human body experiences movement. The whole-body movement is experienced by a walking, running or commuting of human skeleton or any other form of movement which results into biomechanical mobility of a WBAN client/carrier as a whole to another position. This movement of the body makes the individual WBAN susceptible to other WBAN leading to inter-WBAN interference (interference between different WBAN) or co-channel interference (interference as a result of other interfering networks such as Wi-fi, mobile, Bluetooth or any other technology utilizing the same frequency band) in the case the body moved to other interfering networks. Also, in multi-WBAN, there are many nodes (over 200) meaning that you cannot use different channels for different nodes hence the nodes have to share channel which high likely may lead to channel interference as multiple nodes can transmit at the same time.

Another common body based WBAN interference is as a result of movement of the different body parts such as the hands, legs, head and other body parts under a stationary or a human body in motion (Filipe *et al*, 2015). This can be a scenario of a person eating, in a meeting, writing, bathing, turning sides while on hospital bed or chair among others. These results into intra-WBAN interference and signal loss in which the different sensor nodes in a single WBAN interfere with each other's frequency band impending the continuous transmission of sensor data. An example is when a hand moves it can sometimes come close to the chest, arm or stomach sensor nodes hence interfering with their transmission and causing non-line-of-sight (NLOS) between the coordinator and the sensor nodes.

Figures 2.17 and 2.18 shows the different network models of interference scenarios in wireless body area networks. In Figure 2.18, the inter-WBAN interference sensor links are illustrated between the two WBANs sensor nodes. The two big circles in both Figures 2.17 and 2.18 represent the transmission range of each respective WBAN.

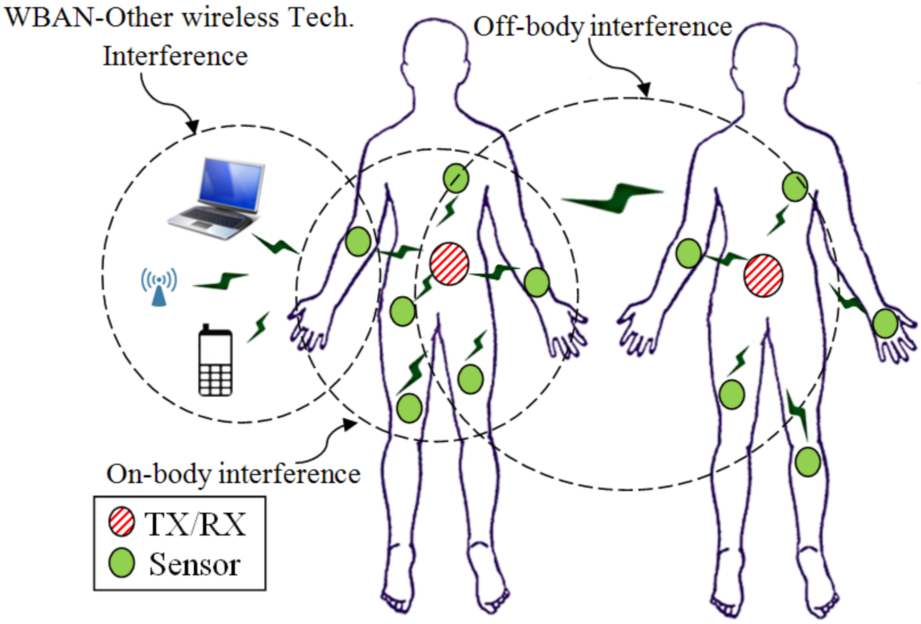

Figure 2.17: Interference in WBANs (Movassaghi *et al*, 2014)

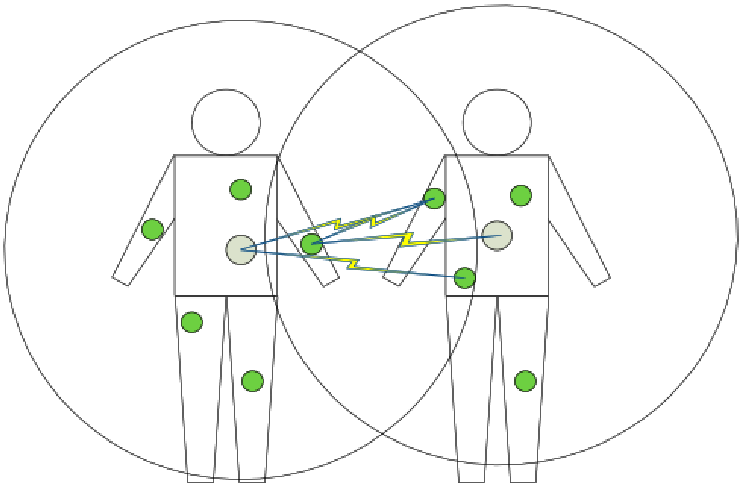

Figure 2.18: Inter-WBAN Interference of WBANs (Le & Moh, 2016))

Figure 2.17 illustrates WBAN interference between different sensor nodes within a WBAN (Intra-WBAN interference) and interference between two different WBAN and other interfering sources (Inter-WBAN interference). All these can lead to degraded performance of WBAN leading to low reliability.

Figure 2.18 illustrates a simple inter-WBAN interference scenario between two WBANs when there is only one frequency band available. Since the communication range of WBAN 1 covers the sensors and the smart phone in WBAN 2, when the sensors in WBAN 1 communicate with the smart phone in WBAN 1, the smart phone in WBAN 2 receives the transmitted signal as well. Thus, if the sensors in WBAN 2 start the transmissions at the same time, inter-WBAN interference happens at the smart phone in WBAN 2. The same interference happens for WBAN 1 as well. A direct cause of the inter-WBAN interference issue is the high mobility characteristic of WBAN (Moungla *et al*, 2014) as human beings generally change their postures as shown in Figure 2.19. As the human body moves, the wireless connectivity amongst the nodes also varies. Also, since the wearers can move around freely, the communication ranges of two or more WBANs can overlap. In literature, this harmful effect is referred to as inter-WBAN interference, inter-network interference, co-channel interference, coexistence, or dynamic coexistence (Shao, 2015). In this thesis, inter-WBAN interference is used exclusively to describe this harmful effect.

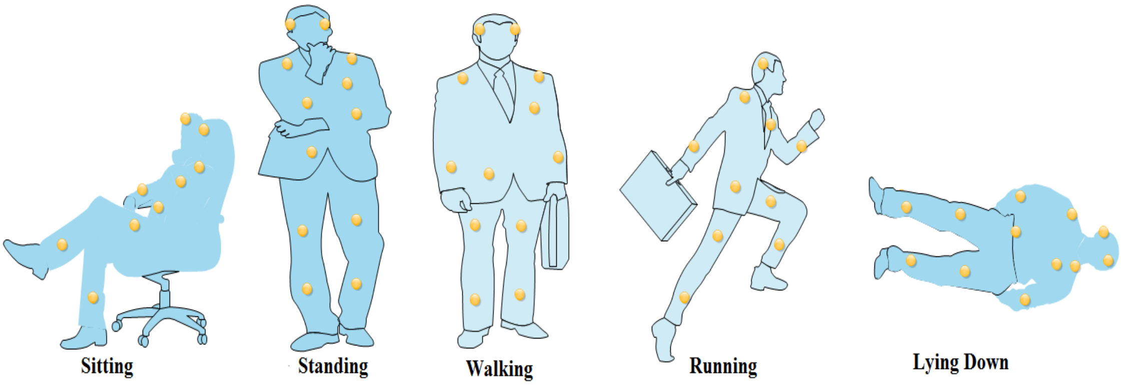

Figure 2.19. Human Body Posture

The WBAN interference has also been caused by the interdomain interference whereby other technologies operating in the same 2.4Ghz frequency band overlap with the WBAN. These include the Wi-Fi, ZigBee and Bluetooth technologies. This WBAN interference scenario is as expressed in Figure 2.20. From the figure, the WBAN is within the Wi-Fi interference range hence high interdomain interference levels.

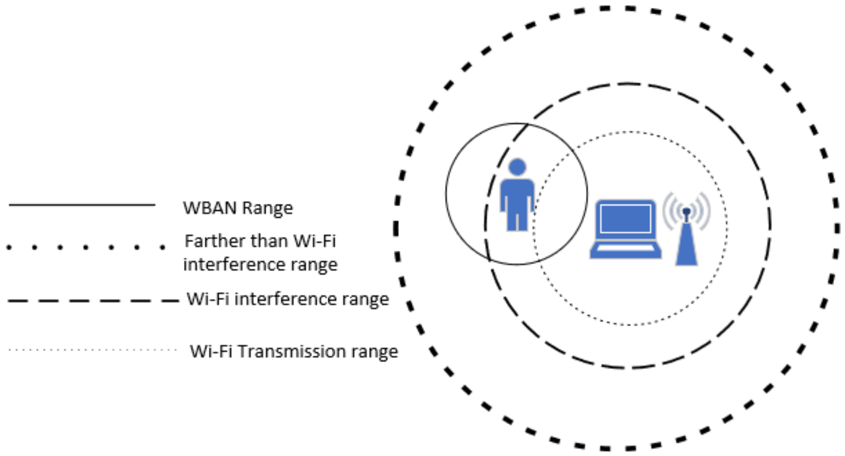

Figure 2.20. WBAN within Wi-Fi transmission range

The effects of the shared communication channel within WBAN and Wi-Fi causes the interdomain interference which leads to packet loss, inability to access transmission channel within the WBAN, high packet retransmission leading to high power consumption in the WBAN sensor nodes.

The IEEE 802.15.6 technology being the WBAN driving force and scope of this research, in the following section, we discuss the IEEE 802.15.6 WBAN technology interference mitigation models.

2.10.2 The IEEE 802.15.6 WBANs Interference Mitigation Models

The coexistence of WBAN across multiple WBANs is an important problem as WBANs become more ubiquitous. Several enhancements for the WBAN interference mitigation have been presented.

The IEEE 802.15.6 standard has defined three coexistence methods which include beacon shifting, channel hopping and active superframe interleaving (Kim *et al*, 2012). These three methods are regarded as non-collaborative methods. In the Non-collaborative coexistence techniques, multiple nodes manage coexistence without any interaction. The non-collaborative techniques are usually based on pre-defined strategies.

In Collaborative coexistence techniques, multiple nodes interact with each other to manage coexistence (Alam and Hamida, 2017). An example is CSMA/CA based coexistence strategy.

Of these standard WBAN coexistence methods, channel hopping has been the most supportable for capacity and mobility because of its all narrow band frequencies applicability (Astrin, A., 2012). When a WBAN shifts its sensor node to free channel, it consequently achieves interference and collision free WBAN from other WBANs (Deylami & Jovanov, 2014). By pre-arranging channel switching information, a seamless communication between the coordinator and sensors could be provided (Mahapatro *et al*, 2012). Wei *et al* (2012) affirms that channel hopping mechanisms can reduce the interference among Wireless Body Area Networks (WBANs) and they proposed an enhanced channel hopping mechanism that allowed multiple WBANs coexisted in the same channel. However, the researchers again agree that channel hopping brings issues such as energy wastage, long latency and communication interruptions in WBANs.

In the beacon shifting coexistence methods, WBAN exchanges its beacon in a regular time interval. In the case where many networks use the same channel, there are high probabibility of repeated collisions in the beacon and scheduled slots. In response to this, the IEEE 802.15.6 proposed a beacon shifting scheme (IEEE 802.15 WPAN Task Group 6, 2008) where by the coordinator node transmits its beacon in a different offset time relative to the beginning of the beacon period. Each beacon contains information of the next beacon period, and the offset time is decided by a beacon sequence that is not being used by neighbors. Through this process, it is expected that collisions with other networks will be reduced.

In the active super frame interleaving, many wireless body area sensor networks share the same channel by interleaving their active super frames. The Command-Active super frame Interleaving Request frame and Command-Active Super frame Interleaving Response frame are used to exchange the acknowledgments of active and inactive periods among coexisting WBANs. The hub adjusts its beacon period (super frame) length and inactive duration to enable the offered active super frame interleaving before sending its response. In B2IRS (Grassi *et al*, 2012), the hub keeps its radio on so that it can detect the other coexisting WBANs. Once it receives a beacon from a neighbouring WBAN, it reschedules the active period after the neighbour. Thus, WBANs in the same channel would not overlap their active periods. However, active super frame interleaving provides coexistence resolution only for static WBANs in residential environment or hospital with single patient node and fixed bedside hub.

Another interference mitigation proposed in the existing IEEE 802.15.6 standard is the frequency channel hopping scheme. This is a typical interference mitigation scheme used in Bluetooth. The basic concept is that a WBAN periodically modifies its operating frequency for interference mitigation (Kim *et al*, 2012). In the IEEE 802.15.6 draft, a hub selects a frequency hopping sequence that is not being used by its neighbor, and delivers beacons including the next frequency hopping information to the sensor nodes. The WBAN changes its operating frequency in the defined number of beacon periods (Kim *et al*, 2012). However, the different frequency hopping sequence also has the possibility of being overlapped by adjacent WBANs because of the limited length of the frequency. Moreover, we cannot ignore frequency hopping overheads such as energy waste and delay. In a static WBAN environment, IEEE 802.15.6 performs energy detection or channel scanning to seek an unoccupied channel before creating a new WBAN. If there is no unoccupied channel, a coordinator requests time sharing with a WBAN that already occupies a channel (Kim *et al*, 2012). These methods can benefit from static WBANs but would pose a challenge in mobility scenarios. In summary, we conclude that even though the channel hopping technique reduces interence among the wireless body area networks, it introduces other issues such as energy comsumption, high latencies and communication interruptions (Wei *et al*, 2017). Other variants of channel hopping have been proposed. An example is Wei *et al*, 2017 proposed enhanced channel hopping mechanism that allowed multiple WBANs coexisted in the same channel. Wei *et al*, 2017 proposed extending the application of channel hoping technique from 1-tolerated channel conflict to *m*-tolerated channel conflict model.

There have been limited studies that have targeted the interference problem in WBANs especially in application areas with mobility. These studies have been categorized to physical layer approaches and MAC layer approaches. Several previous works on the inter-WBAN interference issue mainly focus on physical layer analysis.

Conventional co-channel interference mitigation mechanisms have already been proposed in IEEE 802.15.2 (IEEE 802.15 WPAN Task Group 2) and Wireless Personal Area Networks (WPANs) (Chiasserini *et al*, 2003). In a WPAN, the basic interference mitigation mechanisms can be classified into three categories: space-division multiplexing (SDM), frequency-division multiplexing (FDM), or time-division multiplexing (TDM). In SDM, each network or node can share restricted space by adjusting its transmission power (Xiao et al, 2009) (Quwaider *et al*, 2010). However, it could not eliminate interference from outside of the network because the human body absorbs radio signals and moves around. FDM allocates a dedicated frequency to each network in order to avoid interference. This technique wastes a great deal of time and resources in modifying the frequency. For this reason, it is unsuitable for the short-term interference environment of BANs. TDM is a method of sharing a limited time slot using a scheduling policy. In general, it is typically divided into a contention-based protocol, such as carrier sense multiple access (CSMA), and a schedule-based protocol, such as time division multiple access (TDMA). TDMA is difficult to schedule with heterogeneous networks (Kim *et al*, 2012).

There are other studies that have been done in order to improve the performance of IEEE 802.15.16 WBAN in different perspectives.

A study by Braem & Blondia (2011) analysed three variants of the MAC protocol for mobile WBANs, in regard to the channel utilization and energy efficiency for both static and mobile scenarios. They ascertained that most of the current WBAN MAC protocol research focuses on single-hop or star topology networks with slotted, Time Division Multiple Access (TDMA) medium access (Bian *et al*, 2015) (Li & Tan, 2010) (Ullah *et al*, 2009). The researchers noted that single-hop topologies are not always viable because of the high path loss around the human body leading to a quite a number multi-hop WBANs protocols been proposed as seen in (Takahashi et al, 2008) (Braem *et al*, 2007) (Tang *et al*, 2005). Due to the always moving nature of the human body, the WBAN sensor nodes are considered mobile.

In one of the research study by El Azhari *et al* (2014) proposed a way of mitigating the delay generated by CSMA/CA during the contention-based period in an effort to enhance the WBAN performance in respect to end-to-end delay. According to this research, this was a research effort to enhance the performance of CSMA/CA protocol when applied during Random Access Phase (RAP) as a way of mitigating the transmission delay problem in WBAN in circumstances of data with high priority. RAP is the second part of the IEEE 802.15.6 Superframe structure, which consists of a beacon, two consecutive periods each consisting of an Exclusive Access Phase (EAP), Random Access Phase (RAP), Type I/II access phases, and an optional B2 frame that precedes the Contention Access Phase (CAP). The performance evaluation results showed improvement in the efficiency of the proposed schema in respect to latency especially for data with high priority where the end-to-end delay is a crucial constraint. The research did not evaluate any other performance evaluation to determine if there was a trade-off in the other evaluation metrics such as throughput, bandwidth efficiency and energy consumption. The research also did not address how the other various priority levels of data should be treated hence not the best mechanisms for multi-priority traffic.

Other studies by (Sarra *et al*, 2014; Sarra and Ezzedine, 2016; Ali *et al*, 2015) showed that interferences decreased the reliability of packet reception, increased transmission delay and consumed more energy. They asserted that data losses caused by interferences disrupt the correct operation of time-constrained WBAN applications; specially, in medical applications, it disrupts the delivery of critical data (like heart beat measurements) to the concerned server and provokes delayed reception.

One of the recent research by Sarra and Tahar, 2018 proposed a method to mitigate Wi-Fi interferences in WBAN by adaptive adjustment of parameters in WBAN based IEEE 802.15.4 Protocol. They ascertained that some of the default parameters in WBAN network contribute to the increase of interference effects hence some adequate adjustment of the values is a simple method that helps to optimize coexistence of WBAN with the interfering networks.

Other research studies have been carried out in an effort to address the interference problem in WBAN. Some of these have been evaluated by Alam and Hamida (2017) as summarized in Table 2.9.

Table 2.9: State-of-the-art works related to the performance evaluation of the coexistence strategies for the WBAN using IEEE 802.15.6 standard (Alam and Hamida, 2017)

Reference	**Co-channel interference**	**Channel models**	**IEEE 802.15.6 coexistence evaluated?**	**Mobility pattern?**	**Operating Frequency Bands**	**Pereformance metrics**
Martelli & Verdone, 2012	No	IEEE 802.15.6	No	NA	NB	SINR, PLR, delay, energy
Jie & Smith, 2013	Yes	NA	No	NA	NB	SINR, PLR, delay
Davenport *et al*, 2009	Yes	NA	No	Static	NB	PLR
Wanh & Tai, 2011	Yes	NA	No	NA	NA	SINR
Dotlic, 2011	Yes	IEEE 802.15.6	No	NA	Ultra wide band	PLR
Alasti *et al*, 2014	Yes	NA	No	NA	NB	
Jamthe *et al*, 2014	Yes	NA	No	NA	Ultra wide band	SNR, BER, EbNo

Other research related to WBAN interference mitigation have been carried out as discussed in the rest of this section.

A research to investigate the issue of interference avoidance in body area networks was contacted by Kim *et al* (2012). The research presented a novel distributed TDMA-based beacon interval shifting scheme that reduces interference in the BANs. The goal for the scheme was to avoid the wakeup period of each BAN coinciding with other networks by employing carrier sensing before a beacon transmission. It analyzed the beacon interval shifting scheme and investigated the proper back-off length when the channel is busy. The research compared the performance of the proposed scheme with the schemes presented in IEEE 802.15 Task Group 6. The simulation results showed that the proposed scheme had a lower packet loss, energy consumption, and delivery-latency than the schemes of IEEE 802.15 Task Group 6. The short coming of the proposed interference mitigation scheme is that it did not factor the multi-WBAN with high mobility scenarios which is typical of a WBAN.

In one of the early studies by Xuan and Lin (2011), focused on interference analysis of co-existing wireless body area networks. The research agreed with the idea that many WBANs which operate densely may lead to a high mutual interference and that excessive interference may severely degrade the network performance, which is called the network co-existence problem. It investigated the network interference and co-existence problem for the scenarios with densely deployed WBANs. The research looked into the dense co-existing WBANs and proposed a geometrical probability distribution model. The research model approximated the total inter-cell interference through gamma distribution. Specifically, it modelled the probability distribution of interference among co-existing WBANs. However, and Xuan and Lin (2011) study was limited to static scenarios. The research did not consider mobility scenarios and none of the coexistence method was evaluated and the considered performance metric was only limited to packet delivery ratio (PDR). The impact on the energy efficiency, throughput and delay were not addressed.

In the research study by Flavia and Verone (2012), they looked at the coexistence issues that may arise for WBANs operating at the 2.4 GHz ISM band. The aim of the research was to characterize WBAN performance achievable when interfering sources are present. The research specifically looked into interference due to IEEE 802.11(Wi-Fi) and IEEE 802.15.4 (Zigbee) networks, suitably characterised both in the frequency and in the time domain (Flavia and Verdose, 2012). The research dealt with coexistence issues that may arise for WBANs operating at the 2.4 GHz ISM band and that it did not look into inter-WBAN and intra-WBAN co-channel interference issues.

Movassaghi *et al* (2013) presented the challenges of deploying multiple WBANs in close vicinity to each other. This research concurs with Movassaghi *et al* that WBAN is most likely to encounter other WBANs hence inter-WBAN interference and scheduling is of utmost importance. This research also agrees with Movassaghi *et al* that interference mitigation schemes proposed for other networks cannot be deployed in WBANs because of the WBANs operational differences. This is because WBAN has more frequent topology changes and a higher moving speed whilst a WSN has static or low mobility scenarios (Movassaghi *et al*, 2013). As well, due to the limitations of WBANs in terms of cost, size and energy consumption, the function of each sensor node need to be very simple. In the study, Movassaghi *et al* only presented the challenges in deploying multiple WBANs in each other's vicinity and the WBANs interference mitigation schemes proposed up to that date for WBANs. The research concluded by the assertion that the future of WBANs is to allow for reliable, cost effective and energy efficient communication amongst all co-located WBANs.

Liang *et al*, 2014 looked at the inter-WBAN interference in dense deployments in small areas such hospitals due to the high dynamics of such environments. They then proposed a robust and lightweight interference mitigation scheme for realistic WBSN systems through adaptive channel hopping. They used a testbed to set up an environment to investigate the impact of inter-WBAN interference on various performance metrics when different severity levels of interference are present. Based on the measurement results they received, they proposed a distributed interference detection and mitigation scheme without any central controller.

Jamthe *et al*, 2014 proposed a method to solve the problem of inter-WBAN scheduling and interference by the adoption of a QoS based MAC pre-emptive priority scheduling approach. The authors proposed a QoS based MAC scheduling approach to avoid inter-WBAN interference and introduce a fuzzy inference engine for intra-WBAN scheduling so as to avoid interference within WBANs. Although their research was based on both intra-WBAN and inter-WBAN, they did not address co-channel interference as well as that they did not take in to account mobility considerations.

In 2014, Mucchi and Carpini commended that BANs for healthcare applications are becoming a reality and that it is allowing patients to be monitored continuously without forcing them to stay in bed. The research as well agreed that the hospital, and in particular the emergency ward, is a harsh environment for wireless communications and that information over the air in a hospital is very important because of the increasing number of wireless medical devices especially in the ISM band. The research investigated the coexistence of BANs with the existing wireless devices. The research proposed an interference model based on real time measurements carried out in the emergency ward of a modern city hospital (Mucchi and Carpini, 2014). The short coming of this study was that it considered static-case and that mobility of patients and BANs was not factored. This is an important consideration as patients are highly mobile because of their movements within the hospital environment or ward as well as mobility nature of the different body parts such as arms, legs e.t.c, hence this is an important factor in interference mitigation. They also did not evaluate of the coexistence method as well as that the research did not address the impact on the energy efficiency and delay.

In another recent study, (Alasti *et al*, 2014), the authors looked in the lack of coordinating mechanisms among multiple co-located BANs. The research reported that interference caused by co-channel transmission in adjacent BANs could impact the reliability and in general quality of the service experienced by a receiver node within an individual BAN. The research agreed that currently, there are no mechanisms for interfering BANs to explicitly coordinate their transmissions. This may result in unacceptably high interference; and therefore, high link outage probability by the intended receiver. The research therefore proposed two uncoordinated approaches that could help to ease cross-interference among multiple adjacent BANs. The first approach, a semi-random strategy was used to reallocate the slots in TDMA mode. Whereas, in the second approach, a minimum interference slot assignment algorithm was selected instead of randomly assigning the slot. Even though these approaches were a good starting point for co-channel interference, however, the research did not factor crucial aspects such as mobility and realistic channel variations in the simulation parameters.

A recent study by Kamran *et al* (2014) addressed the issue of co-channel interference from multiple co-located BANs. The research asserted that interference caused by co-channel transmission in adjacent BANs could impact the reliability and in general quality of the service experienced by a receiver node within an individual BAN. The research presented a simulation platform that allowed for statistical evaluation of interference in multi-BAN scenarios and performance of possible mitigation algorithms.

In another related study, Mohamad *et al* (2015) looked at the dynamic channel access scheme for interference mitigation in relay-assisted intra-WBANs. The research looked at the problems related to interference mitigation in a single WBAN. The research then proposed a distributed combined carrier sense multiple access with collision avoidance (CSMA/CA) with Flexible time division multiple access (TDMA) scheme for Interference Mitigation in relay-assisted intra-WBAN, namely, CFTIM. In their proposed CFTIM scheme, non-interfering sources communicate use CSMA/CA while high interfering sources and best relays use flexible TDMA to communicate with coordinator through using stable channels. While the evaluation of the proposed scheme showed minimised interferences, extended WBAN energy lifetime and improved throughput, it only looked at the intra-WBAN scenario where by it only factored interference between sensor nodes in a single WBAN. The study also assumed a static scenario of sensor nodes (within a WBAN) which is not often ideal in most of the situations.

Sabin and Sangman (2016) looked at the need for a differentiated quality of service (QoS) for the various forms of traffic coexisting in a WBAN. The research ascertained that a QoS-aware MAC protocol is essential for WBANs operating in the unlicensed Industrial, Scientific, and Medical (ISM) bands, because different wireless services like Bluetooth, Wi-Fi, and Zigbee may coexist there and cause severe interference. This research agree with Sabin and Sangman that sharing the ISM band leads to unpredictable service interruptions because of mutual interference between coexisting systems. The research then proposed a priority-based adaptive MAC (PA-MAC) protocol for WBANs in unlicensed bands which allocates time slots dynamically, based on the traffic priority. Although their performance evaluation results showed that the proposed PA-MAC outperforms the IEEE 802.15.4 MAC and the conventional priority-based MAC in terms of the average transmission time, throughput, energy consumption, and data collision ratio, they assumed that the coordinator and sensor nodes are within the communication range and their mobility is not critical for communication between the coordinator and sensors. Any security and privacy mechanisms are not considered, either. The study as well did not address the issue inter-WBANs and the inter-domain interference.

Muhammad and Elyes (2016) did an investigation on interference mitigation and coexistence strategies proposed in IEEE 802.15.6 standard within the context of co-channel interference. The research carried a comparative evaluation of the reference scenario (which does not use any coexistence scheme), two non-collaborative (i.e., Time Shared, Random Channel) and one implicitly collaborative (i.e., CSMA/CA) based coexistence schemes in five co-located bodies. An accurate simulation platform was developed through mobility traces which provide dynamic distances, space and time variations under walking, sitting, and standing, running scenarios. The research agreed that the fundamental problem of having multiple bodies interact and/or being close to each other is that the sensors connected on one body interfere with the sensors connected on the other bodies and therefore can interrupt the intra and inter body communications. The research concluded that there is trade-off between coexistence schemes. For example, Time Shared and Random Channel provides much better packet reception ratio and energy efficiency, though they suffer in meeting the delay constraints of the IEEE 802.15.6 standard. Whereas, CSMA/CA based implicit collaborative approach is able to achieve the delay requirements however, it does not perform well both in terms of packet reception ratio and energy consumption.

Essafi and Ezzedine (2018) proposed a method for mitigation of Wi-fi interferences in IEEE 802.15.4. The research affirmed that it is crucial to mitigate the interference between WBAN and Wi-Fi networks in order to maintain the efficiency and the reliability of the WBAN system. There proposed method included the adjustment of the adaptive parameters of the IEEE 802.15.4 protocol. According to the researchers, simple, their method was a low cost and dynamic method that adaptively adjusted the specific parameters in the Medium Access Control (MAC) layer in the IEEE 802.15.4 standard. Using MiXiM framework of OMNet++ simulator, their evaluation showed improved Wi-Fi interference mitigation. Although this research showed improvement from interferences as a result of 2.4 GHz Industrial Scientific and Medical (ISM) band, the research was very narrow and concentrated on Wi-Fi interference only. It did not address interference resulting from other WBAN due to multi WBAN neither did it address interference caused by WBAN mobility. Another weakness is that it concentrated on IEEE 802.15.4 standard while the current and future WBAN operates on IEEE 802.15.6 standard.

In one of the most recent research studies, Ansar *et al*, 2018 proposed a mechanism which was two different protocol techniques. Firstly, to reduce the overhead of WBAN control packets by using block acknowledgement for data packets and prioritizing the nodes according to most vital signs by means of assigning low and high transmission power with enhanced IEEE802.15.6 CSMA/CA. They prioritized critical or emergency traffic using contention windows (CW) technique. Secondly, they introduced a Mobility Link Table (MLT) for selecting a sink-node to communicate with the coordinator node. They then compared their proposed scheme with existing IEEE802.15.6 CSMA/CA technique and results showed the proposed technique lead to improved mean power consumption, reduced network delay and increased network throughput. The short coming of the study was that it only considered Intra-WBAN and that Inter-WBAN and co-channel interference were not considered. This meant that in the cases of multi-WBAN with group mobility (which are common), the achieved improvement above will be eroded away and the overall WBAN will perform dismally.

2.11 The Summary

From sections 2.1 to 2.9, the review of existing literature, WBAN interference and WBAN interference mitigation schemes are presented. The research has presented the IEEE 802.15.4 and 802.15.6 WSN and WBAN technologies interference mitigation respectively. The review highlighted the short coming of the existing literature as summarized in the Tables 2.10, 2.11 and 2.12.

Table 2.10 summaries the intra and inter-WBAN interference mitigation literature, Table 2.11 ISM band 2.4 GHz channel interference mitigation literature review summary while Table 2.12 shows the interference mitigation schemes literature review summary. The shortcoming for each has been highlighted and confirms that out of the existing interference mitigation schemes, limited study exists on IEEE 802.15.6 WBAN and especially on the mobility based multi-WBAN scenarios. From Table 2.10, most of the existing schemes have not considered mobility but only static scenarios which is not ideal and far from reality in most WBAN scenarios which involve mobility of the humans using the healthcare application in the free ISM band. More so, these research studies on WBAN interference have emphasized on adjacent channel interference mainly based on IEEE 802.11 and IEEE 802.15.4 technologies.

In Table 2.11, we look at the existing literature for interference mitigation schemes in the 2.4 GHz ISM frequency band. We specifically choose to review ISM band because of its wide applicability and free license nature of the band worldwide and it is the reference frequency band in this research study. Of the limited research on this category, much is still lacking in the in the interference mitigation in WBAN application in high mobility-based scenarios. There has been a lot of research done on interference mitigation in the legacy IEEE 802.15.4 WSN, but this has been demonstrated to be not ideal as the application scenarios of the legacy methods are not idea for adaptation in WBAN. For instance, in legacy WSN, because of the static nature of the WSN deployment, channel planning has been adopted as a mechanism for interference mitigation. This poses a challenge in adopting the same in WBAN as WBAN is mobile in nature and the reliability and performance of the WBAN would be a challenged.

Table 2.10: Intra and Inter-WBAN interference mitigation literature review summary

Reference	Interference	Performance metrics	Mobility pattern?	Comments/Critic
Xuan and Lin (2011)	Inter-WBAN	SINR	No	The weakness of this study was that it was limited to static scenarios. They didn't consider mobility scenarios. The study also only considered inter WBAN interference scenario
Movassaghi *et al* (2013)	Inter-WBAN	N/A	N/A	Study was only review study paper on co-channel challenges of deploying WBANs in close to each other. The research did not propose any new models of interference mitigation.
Alasti *et al* (2014)	Inter-WBAN	PLR	No	The research proposed two uncoordinated approaches that could help to ease cross-interference among multiple adjacent BANs. The research did not factor important aspects such as mobility and realistic channel variations in the simulation parameters
Kamran *et al* (2014)	Inter-WBAN	N/A	No	The research presented a simulation platform that allows for statistical evaluation of interference in multi-BAN scenarios and performance of possible mitigation algorithms but did not propose a new interference mitigation mechanism.
Anagha *et al* (2014)	intra and inter-WBAN	SNR, BER, EbNo	No	Proposed QoS based MAC scheduling approach to avoid inter-WBAN interference and introduce a fuzzy inference

				engine for intra-WBAN scheduling so as to avoid interference within WBANs.
Mohamad *et al* (2015)	Intra-WBAN	Throughput, SINR	No	The research looked into interference mitigation in a single WBAN. The study did consider static scenario only and that they didn't consider mobility scenarios.
Sabin and Sangman (2016)	Intra-WBAN	Throughput, energy consumption, and data collision ratio	No	The research studylooked at the need for a differentiated quality of service (QoS) for the various forms of traffic coexisting in a WBAN operating on ISM band and proposed a MAC protocol which treats traffic according to their priority levels so that high priority traffic are treated first. The research did not address the issue inter-WBANs and the inter-domain interference. Also most of the WBAN traffic is critical hence QoS not a good method of avoiding interference as most of the WBAN are used to detect lifesaving body signs
Muhammad and Elyes (2016)	Intra and Inter-WBAN	Energy consumption, packet reception ratio, latency	Yes	The research study did investigation on interference mitigation and coexistence strategies proposed in IEEE 802.15.6. The research evaluated a reference scenario (which does not use any coexistence scheme), two non-collaborative (i.e., Time Shared, Random Channel) and one implicitly collaborative (i.e., CSMA/CA) based coexistence schemes.

				The research proposed accurate biomechanical mobility (i.e., for on-body) and group mobility (i.e., for body-to-body communication), which are based on real-time motion captured system. **Conclusion of the evaluation:** That there is a problem when multiple bodies interact and/or are close to each other in that the sensors connected on one body interfere with the sensors connected on the other bodies and therefore can interrupt the intra and inter body communications
Ansar *et al*, 2018	Intra-WBAN	Throughput, energy consumption, and network latency	Intra-WBAN node mobility only	The research proposed a mechanism which combined the control packets overhead reductiuon and prioritization of the threshold values of vital signs by assigning low and high transmission power. They also introduced a Mobility Link Table (MLT) for selecting a sink-node to communicate with the coordinator. While the evaluation of their proposed showed improvement in relation to power consumption, latency and throughput, their mechanism did not consider group mobility, inter-WBAN and cochannel interference which are ideal in todays WBAN application

Table 2.11: ISM band 2.4 GHz channel interference mitigation literature review summary

Reference	Interference mitigated	Performance metrics	Mobility pattern?	Comment/Critic
David *et al* (2009)	2.4GHz ISM band	Packet delivery ratio (PDR)	No	Study was limited to static scenarios. They didn't consider mobility scenarios. Study only covered co-channel interference
Flavia and Verdose (2012)	2.4GHz ISM band	SINR, PLR, Delay	No	The study only looked at co-channel coexistence issues that may arise for WBAN operating at 2.45GHz ISM band. The research did not look at inter and intra WBAN interference issues neither did they propose any new mechanism.
Mucchi and Carpini (2014)	2.4GHz ISM band	Was not evaluated	No.	Although they proposed an interference model based on real time measurements carried out in the emergency ward of a modern city hospital, the study only covered co-channel interference by investigating the coexistence of BANs with the existing wireless devices.

Table 2.12: Interference Mitigation Schemes Literature Review Summary

Reference	Proposed Scheme	Description	Critic
Mohamad *et al* (2015)	Scheme for Interference Mitigation in relay-assisted intra-WBAN - CFTIM	Proposed a distributed combined CSMA/CA with Flexible time division multiple access (TDMA) scheme for Interference Mitigation in relay-assisted intra-WBAN, namely, CFTIM. The proposed CFTIM scheme, non-interfering sources communicate use CSMA/CA while high interfering sources and best relays use flexible TDMA to communicate with coordinator through using stable channels.	**Positive**: (a) Evaluation showed minimised interferences, extended WBAN energy lifetime and improved throughput. **Negative**: (a) It only looked at the intra-WBAN scenario where by it only factored interference between sensor nodes in a single WBAN. (b) It also assumed a static scenario of sensor nodes (within a WBAN) which is not often ideal in most of the situations.
Sabin and Sangman (2016)	Priority-based adaptive MAC (PA-MAC) protocol for WBANs	They then proposed a priority-based (QoS-aware) adaptive MAC (PA-MAC) protocol for WBANs which allocates time slots dynamically, based on the traffic priority	**Negative**: (a) Was evaluated against the IEEE 802.15.4 but not IEEE 802.15.6 WBAN. (b) Considered that mobility of sensor nodes was not critical hence not factored. (c) Only considered scenario of intra-WBAN and that inter-WBAN and inter-domain were not considered.

2.12 Conclusion

From the summary, it is evident that WBAN interference is still a challenge in today's WBAN application in narrow band. Because of the constrained nature of WBANs in terms of energy, size and cost, advanced antenna techniques cannot be used for interference mitigation as well as power control mechanisms used in cellular networks are not applicable to WBANs. Also, the environment often changes in recent times due to the changing world hence continued research is vital in keeping to the pace of the growing modern challenges.

Therefore, novel methods and schemes are required for interference mitigation in WBANs, specifically in the Multi-WBAN IEEE 802.15.6 in high mobility scenarios especially under the ISM 2.4GHz frequency band. A continued research is still needed to achieve better performance in medical field application of the technology.

The summary critique has shown that the current research work in intra and inter-WBAN has lacked reality of its application in mobility-based scenarios. The research mostly concentrated on static scenarios. As well most of these have been based on IEEE 802.15.4 as well as single WBAN.

In the next chapter three, the methodology of this research is presented. The methods used for the research, the research design, the software tools used, the IEEE 802.15.6 modeling as used in this research and the mobility modeling are presented. The new model is then presented in chapter four and evaluated in chapter five to determine its performance against models.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

The previous chapter discussed in detail the wireless body area networks, especially the current IEEE 802.15.6. It has also discussed the wireless body sensor area network interference problem and how this has continued to pose a challenge in today application characterised by high mobility and multi-WBAN. The chapter concluded that still the problems persist even with the current available interference mitigation models for networks. This chapter presents the methodologies used in addressing these challenges. The methodologies include the design methods for the proposed HIMM WBAN interference mitigation model presented in chapter 4 as well as the methodologies used in performance evaluation of the same as presented in chapter 5. You will note that the success of any research depends on the methodologies used to carry out the research.

Research methods are broadly categorized in two ways; (i) qualitative or quantitative research and (ii) Theoretical or Empirical methods. The qualitative research method is majorly exploratory as it is used to uncover trends in thought and opinions using unstructured or semi structured techniques and used to gain an understanding of underlying opinions or reasons, while the quantitative method is used to quantify the problem by generating numerical data or data that can be transformed into usable statistics by collecting cold, hard facts.

In the Theoretical versus Empirical methods, the Theoretical methods involve creation of formal models (mathematics or logic), discrete mathematics like basic set theory, relations, functions, graphs, algebra, combinatorics, category theory, etc., and defining concepts within these concepts and proving properties of the concepts, while Empirical methods involve performance of experiments, getting the results and drawing conclusions out of the results.

The experimental techniques can be either simulation, emulation or live network testing and are used in design and validation of new and existing networking ideas.

According to Guruprasad et al. (2005), network simulation provides a repeatable and controlled environment for network experimentation. It proves the implementation feasibility considering the technicality limitations if the real network testing. It is easy to configure and allows a protocol to be constructed at some level of abstraction, making simulation a rapid prototype and evaluate environment. Ease of use also allows for exploration of large parameter spaces. It also provides realistic results

Network emulation (Amin et al., 2002; Fall, 1999) is a hybrid approach that combines real elements of a deployed networked application - such as end hosts and protocol implementations - with synthetic, simulated, or abstracted elements such as the network links, intermediate nodes and background traffic (Guruprasad et al., 2005). The fundamental difference between simulation and emulation is that while the former runs in virtual simulated time, the latter must run in real time. In the emulation, it is impossible to have an absolutely repeatable order of events due to its real-time nature and, often, a physically-distributed computation infrastructure.

3.2 Methods Used for the Research

This research adopted quantitative research method as it seeked to use quantitative statistical data from the empirical (simulations) results to draw conclusions.

The research used both the theoretical and simulation empirical techniques to evaluate the performance if the proposed WBAN model. The theoretical review helped identify the gaps in the existing research on interference mitigation in WBANs. In addition, empirical method was used to model the existing and new models through simulation experimental technique while highlighting the performance of the existing interference model and during the performance evaluation of the current and existing model.

3.3 The Research Design

As discussed in the research objectives, to achieve the intended objectives, the design of this research was two-stage.

The first stage involves the use of both quantitative and simulation empirical research methods in investigating the effects of mobility and multi-WBAN in performance of wireless body area sensor network. The simulation method has been used to setup the WBAN scenarios where (1) WBAN, nine (9) WBAN, eighteen (18) WBAN and twenty-Five (25) simulation scenarios are done.

The second stage of this research is the performance analysis of the new HIMM model by use of both quantitative and simulation empirical research methods as well. The two proposed approaches, namely CSMA/CA Contention Window with User Priority queues approach and the dynamic cluster head selection approach, used for the new model are evaluated based on the current models.

3.4 Simulation Framework, Software and Tools

The simulation software or tools are often used as an alternative way of implementing and testing new ideas. They allow a repetitive nature of tests which is essential for performance analysis evaluations.

This thesis did a search for a simulation software and/or tool which could model the IEEE 802.15.6 WBAN. Amongst the well-known network simulators available are OPNET (Modeler, 2009), QuaNet (QualNet), NS2 (Berkeley *et al*, 1998) and OMNET++ (Varga, 2001). Unfortunately, OPNET and QuaNet are commercial software's whereas OMNET++ and NS2 are open source software's. The commercial products require licensing and registration before use hence this thesis considers use of open source OMNET++ and NS2.

Therefore, in this research, the proposed WBAN interference mitigation model was implemented using MiXiM (Andreas et al, 2008) framework on top of the OMNeT++ (Varga, 2001) network simulator because of its advanced support of the WBAN modelling. The OMNeT++ is an open source discrete event simulator that has a rich modular component-based C++ library for designing frameworks for simulating wired or wireless networks. OMNeT++ is a widely used simulation platform in networking community. There are several frameworks provided by the community on top of OMNeT++, each well-suited for simulating specificnetworks. As examples, we mention the INET framework (INET Framework) that provides many protocols for wireless networks (e.g., UDP, TCP/IP, Ethernet, 802.11, etc.), INETMANET [2] based on the INET framework for Mobile Ad-Hoc Networks (MANETs), Veins (Veins) for vehicular networks (VANETs), and MiXiM (Andreas et al, 2008) for wireless mobile sensor networks.

The MiXiM framework provides detailed models of the wireless channel, node mobility, and several networking protocols for wireless mobile networks. It also provides templates and base modules for developing different layers (e.g., physical, MAC, routing, etc.) of network protocols, which further simplify implementing a WSN protocol stack in the OMNeT++ simulator. It makes it suitable for implementing, debugging, and testing our mechanisms.

The OMNET++ network simulator does not have freely available WBAN mobility model for simulating WBANs which important component of this research hence the research adopted the MoBAN mobility model as an add-on to the mobility framework of the OMNeT++ network simulator.

In the simulation of the performance of the new model, the same methodology of quantitative and empirical simulation methods of research were used through the use of the OMNET++ network simulation tool with Mixim framework to simulate the model. The Mixim framework provides detailed models of the wireless channels, node mobility and many other networking protocols for wireless mobile networks.

In the OMNET++ network simulation tool, the WBAN structure includes several modules including; the NEtwork Description (NED), the MAC Layer, the network topology, the Mobility module and the power/battery module.

3.5 WBAN Prototype and Characterization of On-Body Network Topology

We constructed a WBAN prototype by simulating the deployment of sensor nodes on a human body (on head, left bicep, right bicep, waist, left wrist, right wrist, on left knee, right knee, left ankle, right ankle and chest).

In this research, a hybrid CSMA/CA Contention Window with Priority and cluster head selection model has been presented in chapter 4, the cluster head is meant to be dynamic, changing depending on the changes in the link state table. Link state is a technique in which each sensor node shares information with other nodes about the reachability of other nodes. As discussed in the next chapter, the cluster head node collects the sensor data from all the connected nodes and sends it to an out-of-body (remote) server using a wireless link. The topology changes are dynamic and are based on the human postural movements. In this research, we have developed and simulated five of the human postures (running, walking, standing, sitting and lying down).

3.6 The IEEE 802.15.6 Modeling

The new HIMM model was validated by carrying out a performance evaluation with the existing IEEE 802.15.6 model and the recent IEEE 802.15.6 CSMA/CA MAC based model proposed by Ansar *et al*, 2018. This meant that the uniformity and the practicality of the parameters used was very important. In the performance evaluation, the same metrics for the network throughput, network delay and bandwidth efficiency were used as well as for the mobility model. These were as indicated in the next sub-section 3.6.1 and 3.6.2. We define delay as the time it takes the packet to reach the destination after it leaves the source (Dai, 2009) while network throughput can be regarded as total number of bits received per second by the destinations of all the multi-hop flows in the network. Bandwidth efficiency is the information rate that can transmitted over a given bandwidth (Li & Sinha, 2003).

3.6.1 Performance Metrics

The performance metrics adopted in this research were network throughput, network delay and bandwidth efficiency. Power consumption was also considered in the performance evaluation of the cluster head selection approach.

According to Deveriya (2006), Latency (also commonly known as network delay) is the amount of time it takes for a packet to traverse from source to destination. The time is calculated as the sum of all delays including the average backoff delay, time taken to transmit the data, the acknowledgement time, the interframe spacing time and the propagation delay.

Throughput is one of the most common metrics used in the study of network performance evaluation. It helps to understand the amount of data travel across a network connection or between two network hosts. According to Blum (2003), the throughput of a network represents the amount of network bandwidth available for a network application at any given moment, across the network links. In the research, network throughput is calculated as the ratio of the data payload side to the delay.

Bandwidth Efficiency is the rate at which the data can be transmitted over a given bandwidth in a WBAN and is expressed as a percentage. In the WBAN, this is calculated as percentage ratio of the throughput and the data rate.

3.6.2 Notations and Parameters used

There are a variety of important notations and parameters used in the simulation and listed in in Tables 3.1 and 3.2 respectively. These are notations and parameters which have been defined universally and commonly used hence the reliability and practicality of this evaluation.

Table 3.1. Notations used in equations

Abbreviation	Meaning
T_p	Preamble transmission time
R_s	Preamble transmission symbol rate
T_{PHY}	PHY layer header transmission time
R_{hdr}	Header rate of PHY layer
R_{DATA}	Transmission rate of data
T_s	Slot length
T_{pSIFS}	Short inter-frame spacing time
MHR	Mac header
FTR	Mac footer
τ	Propagation time
x	Payload Size
$CW_{\min}$	Contention Window

From Table 3.1, Preamble (also refered to header) is a section of data at the head of a packet. The length of the preamble affects the time it takes to transmit data by increasing the packet overhead. Therefor, Preamble transmission time is the time it takes to transmit that header data while Preamble transmission symbol rate is the rate of transmission of the header data. PHY layer header transmission time is the Physical Layer header transmission time while PHY header rate is the rate of transmission of the PHY header packets. The main data is transimitted at transmission rate of data of R_{DATA}.

Short Interframe Space (SIFS) time is the amount of time required for a WBAN node to process a received frame and to respond with a responseframe. Both the SIFSTime and aSlotTime are constant per physical layer. It is measured in microseconds. This research adopted 50 microsecond SIFS time as recommended.

The MAC header (Media Access Control header) can be described as the data fields added at the beginning of a WBAN packet in order to turn it into a frame to be transmitted. It is often refered to as Ethernet header. This MAC header is an extra overhead in the data transmission. Similarly, a MAC footer is the data field added at the end if the data packet of the MAC layer beacon frame and contains the Frame Check Sequence (FCS).

In WBAN, the Propagation time (or commonly refered to propagation delay, and abbreviate as τ) is described as the amount of time it takes for the head of the packet to travel from the source sensor node to the receiver node (the central node or cluster head). It is computed as the ratio between the link length and the propagation speed over the WBAN transmission medium.

The Payload Size (abbreviated as x in this study) is actual data transmitted over the communication medium. This is the data exclusive of any overheads such as headers and footers.

Table 3.2 Simulation parameters

Parameter Name	Value	Unit of Measure
Saturation	-90 dB_m	decibel-milliwatts
Alpha	3	-
Carrier frequency	2.412	Gigahertz (GHz)
Time R_x to T_x	0.00021	Seconds
Time R_x to Sleep	0.000031	Seconds
Time T_x to R_x	0.00012	Seconds
Time T_x to Sleep	0.000032	Seconds
Time Sleep to R_x	0.000102	Seconds
Time Sleep to T_x	0.000203	Seconds
Battery Voltage	3.3	Volts
T_{pMIFS}	20	microsecond (μs)
T_{pSIFS}	50	microsecond (μs)
T_p	88bit/ R_s	-
τ	1	microsecond (μs)
T_{PHY}	31bits/ R_{hdr}	-
Mac Queue Length	5	-
Slot Duration	0.00035	Seconds
Max T_x Attempts	14	Count
R_{DATA}	187500	bit per second (bps)
$CW_{\min}$	16	-
T_x Power	1	Milliwatt (mW)
MHR	56	bytes
FTR	16	bytes
R_s	187500	bit per second (bps)
Pdelay	0.000001	Seconds
x	2000	bytes

Saturation is a WBAN node condition which occurs when its frame arrival rate exceeds or is equal to its frame departure rate. The Time RX to TX is the time a packet takes from receiver to transmitter, Time RX to Sleep is the time a node takes from the time it receives the last packet and the time the node goes to sleep mode as a result of idleness. The Time TX to RX is the reverse of Time RX to TX and is the time packet takes to travel from the transmitter to receiver. The Time TX to Sleep is the time the node takes from sleep mode to transmission time. The Time Sleep to RX is the time the node takes from sleep mode to receiving packets. Sensitivity is the ability of a receiver to pick up weak signals which get affected by channel attenuation. The Max Tx Power is the maximum transmission power if the WBAN sensor node.

Delay Formula used to calculate delay normally, is given in equation (1) is calculated in (Shakir *et al*, 2016) as follows;

$$\mathrm{Delay}(x) = T_{avg\_backoff} + T_{DATA} + T_{iack} + 2T_{pSIFS} + 2\tau \text{ -- } (1)$$

The average back off time can be found as shown in equation (2);

$$T_{avg\_backoff} = \frac{CW_{min} \times T_s}{2} \text{ -- } (2)$$

The transmission time of data is T_{DATA} and can be obtained as in equation (3);

$$T_{DATA} = T_p + T_{PHY} + \frac{(MHR + x + FTR)}{R_{DATA}} \text{ -- } (3)$$

The transmission time of immediate acknowledgement can be obtained as in equation (4);

$$T_{iack} = T_P + T_{PHY} + \frac{((MHR + FTR)*n)}{R_{DATA}} \text{ -- } (4)$$

Maximum throughput (MT) of network is directly related to overhead.

The MT is defined as the ratio of payload size (x) to the total transmission delay per payload size Delay(x), as given below in equation (5) (Shakir *et al*, 2016);

$$MT = \frac{x}{\mathrm{Delay}(x)} \text{ -- } (5)$$

The bandwidth efficiency is inversely proportional to the basic data rate as in equation (6);

$$\rho=\frac{MT}{R_{DATA}} \text{ -- } (6)$$

Hence as a percentage ratio this becomes:

$$\rho=\frac{MT}{R_{DATA}}*100 \text{ --- } (7)$$

3.7 The Mobility Model Selection

As seen in chapter one, mobility is an important consideration in this research as discussed in section 2.1 on body activity. The accurate mobility, path-loss and radio link modeling are very key requirements in order to get more insight into the performance of WBAN under real deployment and operating assumptions (Alam and Hamida, 2014; Hamida and Chelius, 2010). Modeling the mobility and posture behaviors of real human bodies is a very complex task. One solution consists of exploiting real-time motion capture data and coupling them with geometrical transformation and analysis techniques to properly investigate the performance of the WBANs under different mobility scenarios.

3.8 Modeling the WBAN Mobility

One of the very important features of the human beings and animals is locomotion. This means that the sensor nodes embedded or implanted on or in a human body exhibit mobility as a result of human body movement and the movement of the different body parts like the arm, leg, among others causing nodal mobility. As mobility is an important factor in WBAN, a good mobility model is an essential prerequisite for evaluation of protocols for wireless networks with node mobility. Without mobility, the nodes will be stationary. The importance of mobility can be judged from the fact that even in stationary postures such as sitting and standing, where movement of the patient is limited mobility plays a significant role. For instance, when a person is sitting, he/she can be doing some work while seated. They might be moving their arms and head and therefore mobility comes into play. Similar cases can arise for standing posture. Individual movement of any sensor node within the WBAN depends on the selected posture.

For the running posture, we know that some parts of our body such as arms and legs do a lot of work. Similarly, the nodes implanted on these parts had to efficiently coordinate data with other nodes and send to the out of body server. This posture is depicted in Figure 3.1. In this posture nodes on some of the organs have to monitor data very accurately as there is a rapid contraction and relaxation of the human muscles.

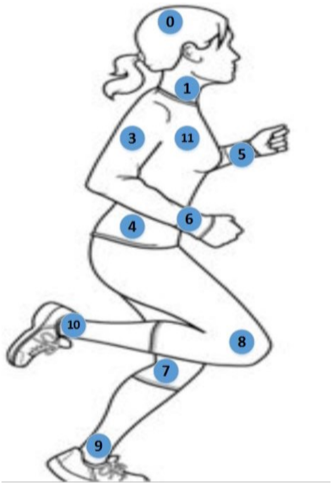

Figure 3.1: Running Posture

Like running, walking is another mobile posture that we have adapted in this experiment. The posture is shown in Figure 3.2. Here we can observe that as compared to running posture, nodes on the arms, legs and chest have to do most of the coordination as in the case of running. Nodes on the arms and feet are involved much more in mobility as compared to rest of the nodes. So, in order to accurately monitor the physical condition these nodes have to perform their functionalities more accurately and efficiently.

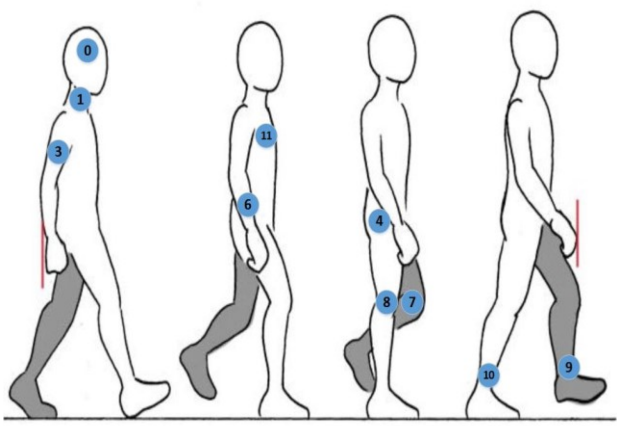

Figure 3.2: Walking Posture

As it can be seen from Figure 3.3 the node 2, 3, 5 and 6 are placed on the arms in the standing posture. Although standing posture is a stationary posture still different positions in the standing postures can be described e.g. arms straight, arms crossed (on the chest), left faced and right faced with respect to the viewer. In depiction of these different positions the involvement of nodes depends upon the postural locality of the nodes e.g. the nodes on arms will contribute more in the mobility depicting various standing actions.

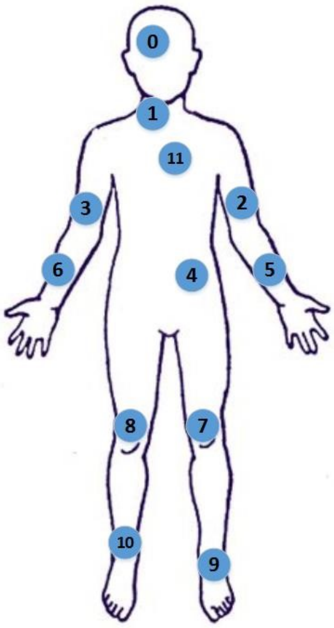

Figure 3.3: Standing Posture

After dealing with the mobile postures, we come across the stable postures such as sitting standing and lying. For the case of sitting posture, the patient is not mobile, and nodes do not have to encounter frequent topological changes. This posture is shown in Figure 3.4.

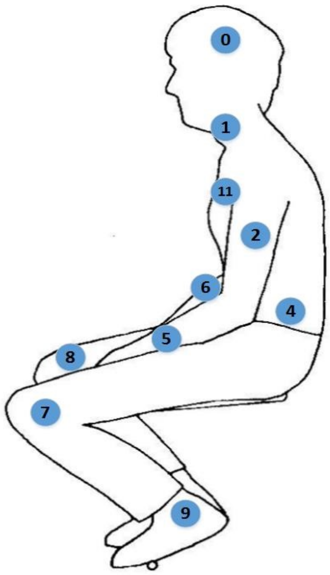

Figure 3.4: Sitting Posture

One of the stable postures is lying. For such postures the node movement is very limited. This posture is depicted in Figure 3.5.

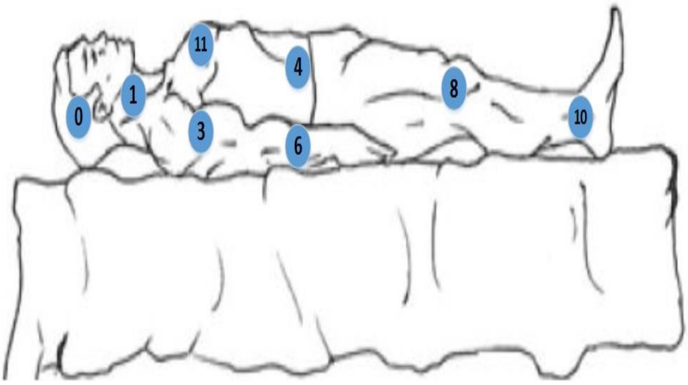

Figure 3.5: Lying Posture

All these postures were executed in sequence during the MoBAN mobility of the WBAN during the simulation testing.

3.9 Summary

This chapter presented the methodology used to achieve the research objectives. The research design and the software tools were also presented. A WBAN prototype was created by simulating the deployment of sensor nodes on a human body (on head, left bicep, right bicep, waist, left wrist, right wrist, on left knee, right knee, left ankle, right ankle and chest) for single WBAN, 9 WBAN, 18 WBAN and 25 WBAN on-body scenarios. The IEEE 802.15.6 WBAN was also modelled. The performance metrics network throughput, network delay and bandwidth efficiency used in the performace evaluation of the new model was discussed and the metrics used also shown. The WBAN mobility formed important part of this research hence the mobility modeling was presented where MoBAN mobility model was discussed.

After the research methods were defined in this chapter, the chapter 4 presented the new Hybrid WBAN Interference Mitigation Model (HIMM Model) which is the main contribution of this research.

CHAPTER FOUR

THE WBAN INTERFERENCE MITIGATION MODEL

4.1 Introduction

In this chapter, the Hybrid WBAN Interference Mitigation Model (HIMM Model) and the approaches to the improvements as the contributing factor in this research are discussed. In the rest of the research, the new model is presented as “HIMM model”.

The chapter is organised as follows: section 4.2 discusses the system model. In section 4.3 the HIMM model is presented. The two areas of improvement in the IEEE 802.15.6 WBAN are discussed. In section 4.4, the HIMM model flow chart and pseudo code are presented. While in section 4.4, the two approaches used in achieving the HIMM model are discussed in detail. The section shows the implementation of the HIMM model. Firstly, the CSMA/CA Contention Window (CW) with User Priority (UP based approach is introduced in section 4.5.1, while the second improvement which is based on dynamic cluster head using Link-State approach is discussed in section 4.5.2.

4.2 The System Model

Compared to the traditional wireless sensor network, the wireless body area network introduced three new characteristics, namely, energy limitation, high mobility, and group-based movement (Cheng & Huang, 2013). Another feature which came with the WBAN is high concentration nature of the sensor nodes with a short range of one another as they reside and communicate within the different parts of the body as compared to the traditional WSN in which the different sensor nodes are several meters away from one another, for example in an industrial controls and monitoring application scenario. As discussed in the chapter 2, these new characteristics are the key contributors to the new performance challenges of WBAN as discussed in chapter 1 and 2. In our new HIMM model, we take these into consideration.

The WBAN is majorly used in medical applications and is responsible for the delivery and analysis of vital physiological signals hence two most key requirements for these

WBAN applications are highly reliable communication and low power consumption (Juneja & Jain, 2015). The energy limitation characteristic is because of the physical size limitation of the sensor nodes and the deployment modes of on or in-body. The reliable communication would include timely delivery of sensor data with no significant network delay, reliable network throughput and bandwidth efficiency.

4.3 The New HIMM IEEE 802.15.6 WBAN Interference Mitigation Model

In this research, the HIMM WBAN model that uses two approaches to achieve improved Multi-WBAN performance is presented. The two approaches are:

(i) The CSMA/CA Contention Window (CW) and User Priority (UP) Based approach

(ii) A dynamic WBAN Cluster Head Selection based on Link State for the WBAN

These two approaches when applied on a WBAN lead to an improved performance as discussed in the rest of this chapter. Figure 4.1 illustrates the HIMM IEEE 802.15.6 WBAN interference mitigation model.

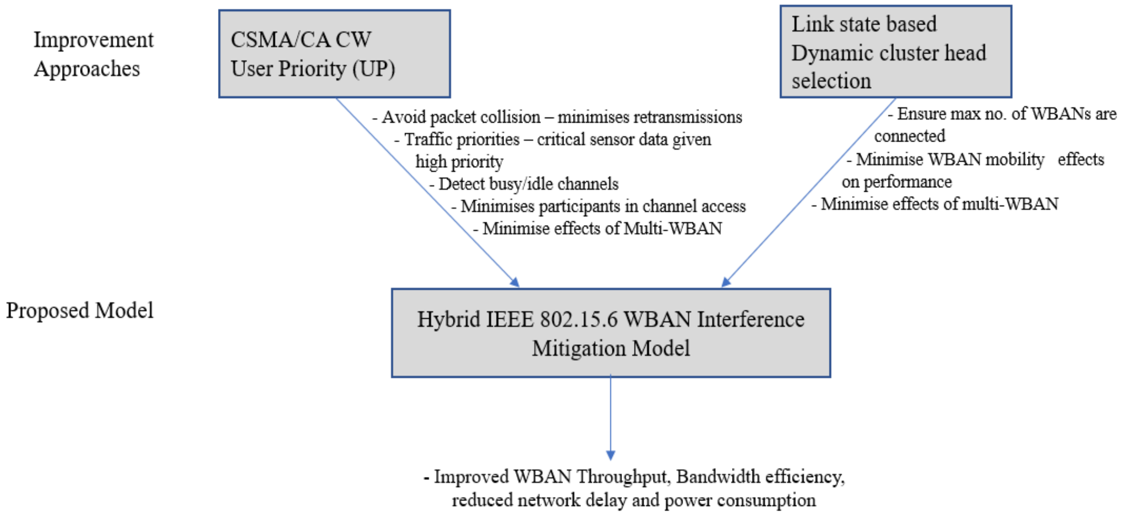

Figure 4.1: The conceptual model of the HIMM IEEE 802.15.6 WBAN model

Sections 4.3.1 and 4.3.2 discusses the two adopted mechanisms in detail. These are the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) Contention Window (CW) and User Priority (UP) approach and the dynamic cluster head selection approach respectively.

4.3.1 CSMA/CA Contention Window and User Priority Based Strategy

In this approach coexistence. This is an access method in which a network contention protocol listens to a transmission channel. In this research scenario of multi-WBAN, the nodes are many, even above 100, hence different channels cannot be used for different nodes. This leads to the option of sharing the channel. The WBAN interference happens, the collaborative carrier sense multiple access with collision avoidance (CSMA/CA) based strategy is adopted to address the WBAN when multiple nodes transmit to the coordinator node at the same time. To avoid interference among WBANs, CSMA/CA is implemented at the coordinator level; while for communications within each WBAN, Contention window (CW) and priority are used. The coexisting WBANs greatly improve performance and lower interference when the interfering nodes work in a collaboration to avoid channel interference by minimizing incidents of packet collision in the transmission channel. This include the combination of different techniques including the CSMA/CA's Contention Window (CW) technique (Shakir et al, 2016) and assigning the sensor nodes different priorities for channel access.

The second proposed approach of the CSMA/CA is the adaptation of eight user priorities (UP) mappings in traffic prioritization. In the IEEE 802.15.6 standard, the nodes have equal user priorities (UP). This research adopts eight (8) types of priority mappings as indicated in table 4.1. These CSMA/CA CW and user priority approached were initially adapted by Shakir *et al* (2016) and Ansar *et al* (2018) as a IEEE.802.15.6 as interference mitigation improvements to base model. The higher the user priority value the critical the traffic is. The user priority (UP) has a defined contention windows size, defined as ranging from CW_{min} (the minimum contention window size) and CW_{max} (the maximum contention window size) parameters. CW_{min} is the initial random backoff wait time (window) for retry of a transmission while CW_{max} is Maximum Contention Window and it is the upper limit (in milliseconds) for the doubling of the random backoff value. These CW_{min} and CW_{max} are shown in table 4.2.

The smaller the CW value, the easier the nodes accesses the channel for transmission, consequently the bigger the UP the higher the transmission priority for that specific WBAN sensor node. This means a sensor node with highest UP of seven has the highest priority for channel access and that the traffic in this node has the smallest value of CW as the nodes with lesser CW accesses the channel earliest while node with highest CW accesses last.

The benefits of the proposed use of CSMA/CA Contention Window (CW) and Priority queues are.

(a) By using priority schedules, we can allocate the emergency critical sensor node data the highest priority and the rest of data lower priorities accordingly.
(b) This scheme avoids packet collision hence minimising the number of retransmissions by means of Contention Window. Under the CW, the model detects a busy or idle channel. When the transmission channel is idle, its counter is reduced to minimum (CW_{min}) according to the traffic priority CW_{min} value but when the channel is busy, no packet is transmitted and the counter increments (doubles back off counter) until CW_{max} and the next channel is scanned for availability. By reducing the interference level the CSMA approach enable a WBAN to enjoy a high throughput by giving many WBANs a chances in channel access in multi-WBAN scenario.
(c) Further, the priority queues introduced in the proposed scheme minimizes the number of participants in contention of channel access. Hence, the probability of collision amongst the nodes is diminished. Each node in a WBAN is given a priority value with which it uses to access a channel. High priority node traffic is always given priority for channel access.

In the CSMA/CA access mechanism of the proposed model, the node sets (initializes) its backoff counter to a random integer (a value between one and a contention window (CW) depending on the user priority (UP)) that is uniformly distributed over the interval [1, Contention Window (CW)], where CW∈(CW_{min}, CW_{max}). CW_{min} is the minimum size of the contention window while CW_{max} is the maximum size of the contention window and are selected according to the user priority as given in Table 4.1 and Table 4.2. The CW_{min} would denote that the transmission channel is free hence decrements the back off by one while CW_{max} would signify the channel is busy therefore locks its backoff counter until the channel is idle. The high-priority traffic will have a small contention window compared to that of low-priority traffic, which increases the probability of accessing the channel to report emergency events.

In CSMA/CA the node detects the channel for idleness, if the channel is idle, then the node will broadcast the data through the channel and if the channel is busy, the node will wait for a random time and will try again (Ullah *et al*, 2009). In the IEEE 802.15.6 based CSMA/CA Protocol, in which the node sets a back off counter between 1 and contention window size. If the channel is idle, the node will decrement the back off counter by one for each idle CSMA slot. When the back off counter becomes zero, the node will transmit the data or frame. If the channel is found busy, the node will lock its back off counter until the channel becomes idle. Here in (Ullah *et al*, 2012), another counter which counts the number of failures is presented. Two cases are presented here, the first one in which the number of failures is odd, then Contention Window (CW) size will remain unchanged and if the number of failures is even, then CW size will be doubled. After successful data transmission, CW is set to initial CW.

The CW varies depending on the user priority and it varies from CW_{max} to CW_{min}. Then the counter decremented constantly till a CSMA slot is equal to the physical CSMA Slot Length (pCSMASlotLength). When the counter reaches CWmin the data is transmitted. In case the counter reaches CW_{max} (higher priority) the CW will be doubled and the channel will be busy.

Where;

pCSMASlotLength = pCCATime + pCSMAMACPHYTime (Ho, J. M., 2012)

where each is defined as;

pCCATime = 63 / Symbol Rate

pCSMAMACPHYTime = 40 μs

pCCA refers to physical Clear Channel Assessment

4.3.1.1 Traffic Prioritization

The table 4.1 shows the eight (8) types of priority mapping which are used in the new model and are proposed by IEEE 802.15.6. This research adopted the same eight priority classes, namely 0,1, 2, 3, 4,5,6 and 7 for WBANs. These UPs are able to provide sufficient performance differentiation at a lower cost for manufacturers of IEEE 802.15.6-compliant hardware and software. The priority values are determined based on the designation of the traffic payloads contained on the frame.

Table 4.1: User Priority (UP) Frame Types

User Priority (UP)	Traffic designation	Frame type
0	Background and Best effort	Data
1	Best effort	Data
2	Excellent effort	Data or management
3	Controlled load	Data or management
4	Video	
5	Voice	
6	Medical data or network control	
7	Emergency and High-priority medical data	

The adopted CWmin and CWmax parameters for each proposed user priority are as shown in table 4.2.

Table 4.2: User Priority (UP) CW_{Min} and Max parameters

UP	Traffic Type	CWmin	CWmax
0	Background and Best effort	16	64
1	Best effort	16	32
2	Excellent effort	8	32
3	Controlled load	8	16
4	Video	4	16
5	Voice	4	8
6	Medical data or network control	2	8
7	Emergency and High-priority medical data	1	4

$CW \in (C_{min}, C_{max})$:

C_{min} and C_{max} being the lower and upper limits of the CW respectively.

It should be noted that nodes with lesser CW accesses the channel earliest while node with highest CW accesses last.

The CW value is determined in the following way:

- $CW = CW_{min}[UP]$, if the station has never had an opportunity to transmit, and also when it has completed its last frame transmission with success i.e. it has requested and received the acknowledgement (Ack) in the last contented allocation (Node Succeeded).

- The CW remains unchanged if the station has not requested acknowledgement for the last frame sent at the end of the last contended allocation, and if the station has failed to complete the transmission, i.e. when it has requested acknowledgement of the successful receipt of the last transmitted frame during the contended allocation and has not received such an acknowledgement (Node Fail) in m number of consecutive attempts, where m is an odd number.

- CW= 2*CW, if the station has failed to complete the transmission in n number of consecutive attempts, where n is an even number.
- CW=CW_{max}[UP], if the CW value, obtained by doubling the CW, exceeds CW_{max} [UP].

4.3.2 The WBAN Dynamic Cluster Head Selection Based Strategy

A cluster head can be described as the central node in a WBAN which collects sensor data from all the WBAN nodes and communicates to the outside world such the health monitoring systems or a remote doctor. This central node is vital in the reliability and overall performance of the WBAN as it is expected to communicate with all the sensor nodes as well as to the outside world.

As discussed in problem statement in chapter 1 and in the WBAN mobility in section 2.7 of chapter 2, human beings generally change their postures often and as the human body moves (group mobility), the wireless connectivity amongst the nodes also varies. In this situation, the data cluster head has to be changed and adjusted as distance between sensor nodes varies. Another thing, which is very important for cluster head is its accessibility by all neighboring nodes. This would ensure that each node sends its data to the cluster head, which will ultimately increase the reliability of WBAN. For this reason, an easily accessible cluster head for data packets is very important for wireless body area network. As we know that in WBAN, distances and connectivity between different nodes vary according to the posture, as shown in Figure 4.2 and Figure 4.3. Using fixed cluster head has no significance because other nodes may or may not access that particular node. So, it is required to use cluster head which keeps changing throughout network lifetime. Routing table is commonly used to select a random cluster head for data packets. In most situations, the cluster head or central node selected will most likely be the node rotating around the center of the body including the heart, chest, wrist, shoulders etc. as it is the front side of a human with higher concentration of the sensor nodes.

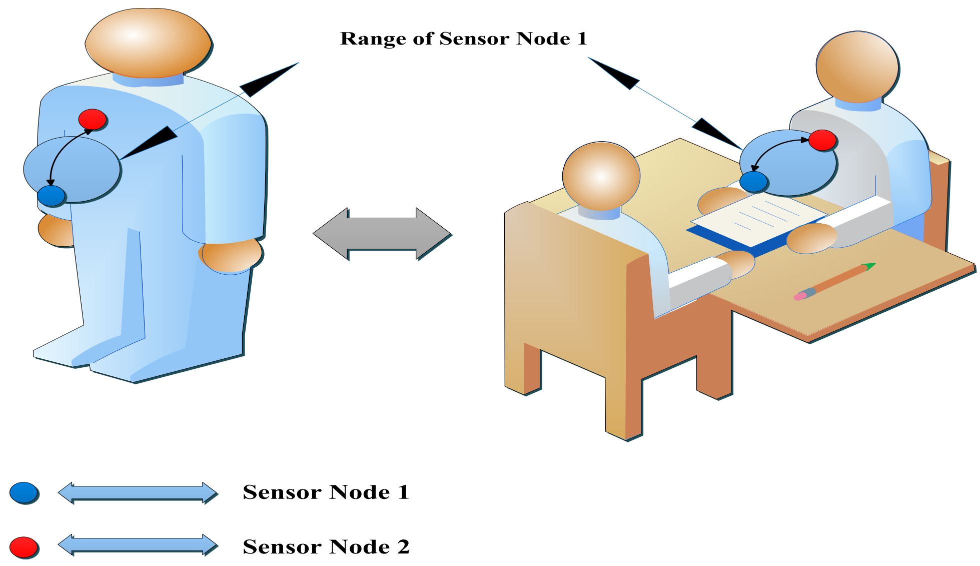

Figure 4.2. Changing of Sensor Nodes with postural changes

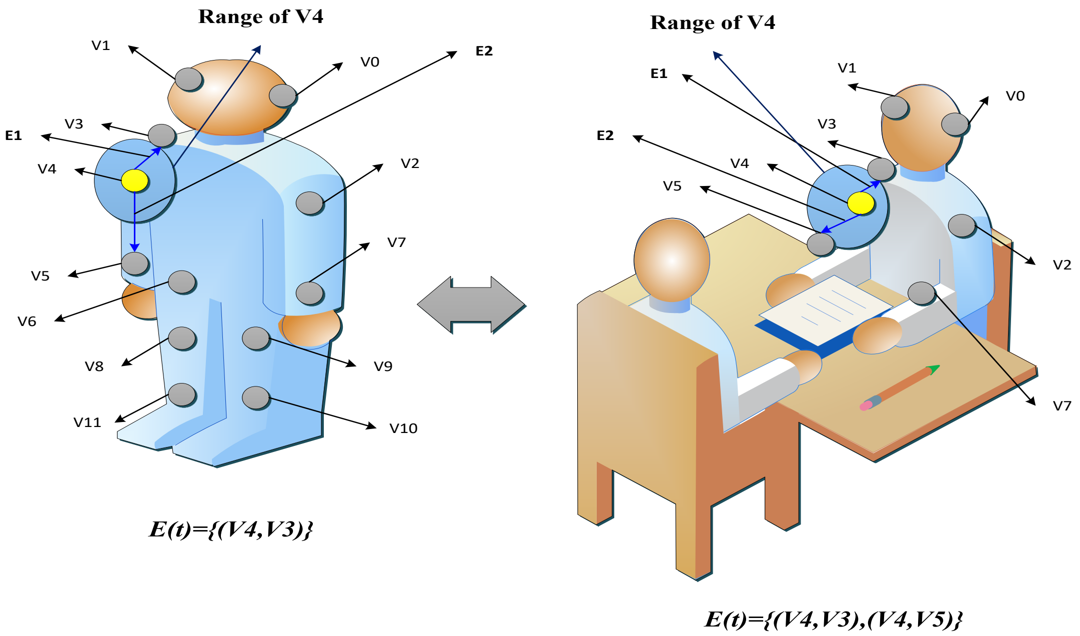

Figure 4.3. Variation in number of connections with postural changes

4.3.2.1 The legacy Link-state routing in networking devices

Link state routing is a family of legacy routing protocols used in routers. It was developed as an advancement from the distance vector routing (EIGRPs and RIPs) and was used as a distributed algorithm to compute their routing tables. Ideally under link-state, the router nodes build a link-state routing table (inform of a link-state packet) which is a table containing the active neighbor connections of a specific node. The link-state devices (devices supporting link-state tables) exchange messages (known hello messages) to allow each router node to learn the entire network topology. Based on this learned topology, each router is then able to compute its routing table by using a shortest path computation and create a Link State Packet (LSP), which is a packet which contains names (for example network addresses) and cost to each of its neighbours. This LSP is transmitted to all other routers, who each update their own records.

In this legacy routing, LSPs are generated and distributed when:

i. A time passes
ii. New neighbours connect to the router
iii. The link cost of a neighbour has changed
iv. A link to a neighbour has failed (link failure)
v. A neighbour has failed (node failure)

Therefore, the concept of link-state routing is that every node constructs a map of the connectivity to the network, in the form of a graph, showing which nodes are connected to which other nodes. It was built around a well-known algorithm from graph theory, E. W. Dijkstra's shortest path algorithm.

When a link-state node power up, it first discovers to which nodes it is directly connected. For this, each router node sends a HELLO message every *N* seconds on all of its interfaces. This message contains the nodes address. Each node has a unique address. As its neighboring nodes also send HELLO messages, the node automatically discovers to which neighbors it is connected. These HELLO messages are only sent to neighbors who are directly connected to a node, and a node never forwards the HELLO messages that they receive. HELLO messages are also used to detect link and nodes failures. A link is considered to have failed if no HELLO message has been received from the neighboring router for a period of $k\ x\ N$ seconds.

When changes occur on the table of the connected nodes on the device, the device sends update information to its connected nodes. Only devices running the routing algorithm listen to these updates. Updates are sent to a multicast address.

4.3.2.2 Adapting the Link-state in multi-WBAN cluster head selection

Link state routing has been very successfully in the world of router devices, evidenced by the wide adaptation of the Open Shortest Path First (OSPF) routing protocol in both enterprise environments and internet service providers (ISPs). This is mainly due to its adaptive or dynamic nature to adjust paths to destinations.

In the previous chapters, we have seen that, because of its application nature, the IEEE 802.15.6 WBAN was meant to be a reliable, efficient and energy efficient standard for the medical applications. Through the literature review, we have also seen the challenges of the WBAN still exist especially in the Multi-WBAN mobility nature of the medical application and the application of link-state routing in the selection of a cluster-head based on the number of connections for each node at every given time can increase the WBAN efficiency and reliability. As shown in Figure 4.3 on the variation on the number of connections with postura; chnages, each node has a certain number of neighboring nodes in which it can successfully connect to and making sure the node with the highest number of neighbors in its LSP is very important as it assures the best possible performance of the WBAN.

4.3.2.3 The Cluster Head Selection based on Link-state

In this research, a dynamic cluster head selection scheme for wireless body area networks has been adopted, in which case the cluster head is selected on the basis of link state. This scheme is an enhancement to the IEEE 802.15.6 based CSMA/CA protocol.

Link state table is a very important feature of our model. This link-state table (LST), just as seen in legacy routing, contains information about number of connections that each node holds. This table is maintained at each node. The complete procedure for updating this table and selecting dynamic cluster head on the basis of the LST is illustrated through Figure 4.4. According to Figure 4.4 on the example given on cluster head selection in the HIMM scheme, each WBAN sensor node broadcast a control packet, upon the reception of control packets from other nodes, each node will acknowledge the sender that the control packet has been received. The node will then form a link state table from the acknowledgement responses received. Among the sensor nodes in this WBAN, the node with the highest members in its LST is chosen as the cluster head. Random HELLO packets are randomly send by the nodes to check the life of the existing nodes (in the LST) as well as any other node which may have become available to the node.

A simple example for cluster head selection in the proposed model is given in Figure 4.4. According to Figure 4.4, at time t_{k+1}, node 5 will become cluster head node because of holding maximum number of connections. At t_{k+21}, node 3, will become cluster head.

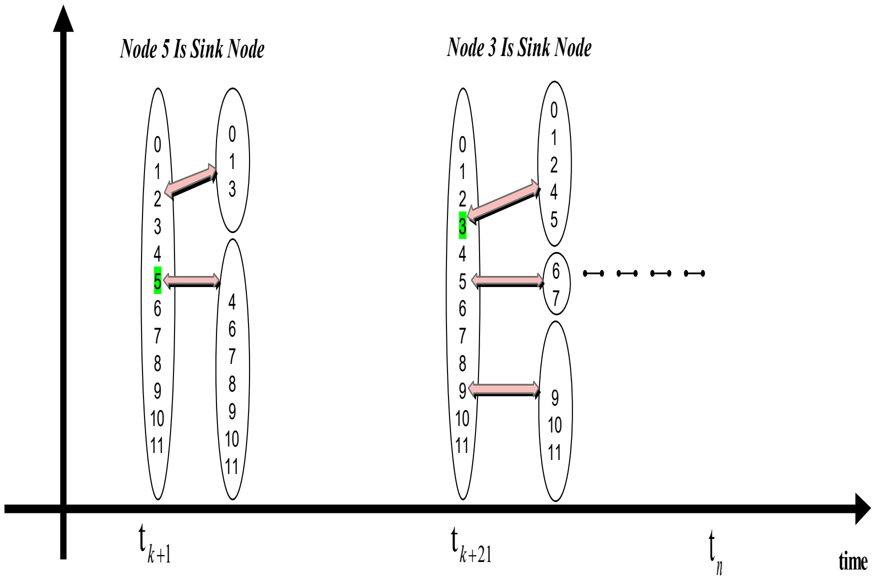

Figure 4.4. Example of cluster head selection in the HIMM Model

4.4 The HIMM Model Flow Chart

The HIMM model is presented in Figure 4.5. According to flow chart, after initializing important parameters like CW_{min} count, backoff_count, channel idleness is checked, if idle, then backoff_count will be decremented until it becomes zero. Consequently, each node will broadcast control packet, upon the reception of control packets from other nodes, each node will acknowledge the sender that the control packet has been received. Link State Table (LST) will be updated (Incrementing No. of Links) after reception of acknowledgement otherwise it will remain unchanged. The node having maximum value in LST shows that it has maximum number of connections as compared to other nodes for current posture. So, there will be a competition between all sensors nodes to become "Cluster Head" on the basis of value stored in their LST. Node with maximum value in LST will become cluster head for other nodes. Power of those nodes which are not directly connected to the cluster head, will be increased, so that, each node can send its data to the cluster head. After that, data will be transmitted, if transmission is not successful, then number of failures will be counted, if odd, then contention Window size will remain same otherwise it will be doubled.

The reason is that even number of failures would confirm that there is a problem in contention window size, which stops transmission.

The flow chart in Figure 4.5 details the HIMM model as discussed in this chapter. It details the activities from the time a traffic is received on a WBAN node.

In this Figure, the following abrevaitions, symbols and terms have been used. They are defined or explained as follows:

a) CW refers to the term contention windows as explained in section 4.3 on CSMA/CA Contention window with user priority approach. CWmin and CWmax symbolised minim contention window and maximum contention window respectively
b) Backoff_Count means the number of times the backoff mechanisms is called. When a channel found to be idle (not transmitting), the backoff count decreaments by one until it reaches zero when that channel tranmits packet. When the channel is found busy, the backoff count is increamented until the count reaches maximum (CWmax) when the channel sensing is abardoned for some random duration before it is sensed again for availability. Backoff Count is abbreaviated by BC where BC=BC+1 is backoff increament (after busy channel is detected) while BC=BC-1 is count decreament (after idle channel is detected).
c) An idle channel is a channel which is not in transmission mode
d) Abreciation C_n is used to mean the sensor node count number in a WBAN. If a node six (6) can successfully connect to six (4) neighbouring sensor nodes within a WBAN, $C_n = C_6$ and it is a set of those nodes. E.g. $C_6 \in \{4\}$.
e) Abreviation F in equation f=f+1 is a letter representing failure hence f=f+1 in an increamental count of the number of packet transmission failures. When the number of packet transmission failures are even, the contention window if doubled and repeated until CWmax. If failures are even, it symbolised the transmission was successful, and the contention window is reset to CWmin ready for more data transmission.

f) The ACK is an acronym for Acknowledge or Acknowledgement. It is a term used in telecommunication (WSN included) to refer to a confirmation of receipt of transmission packet by the receiver. When data is transmitted between two nodes or systems, the recipient acknowledges that it received the data by sending an ACK packet. If a station receives a corrupted packet, it returns a NAK (negative acknowledgment) to the sender.

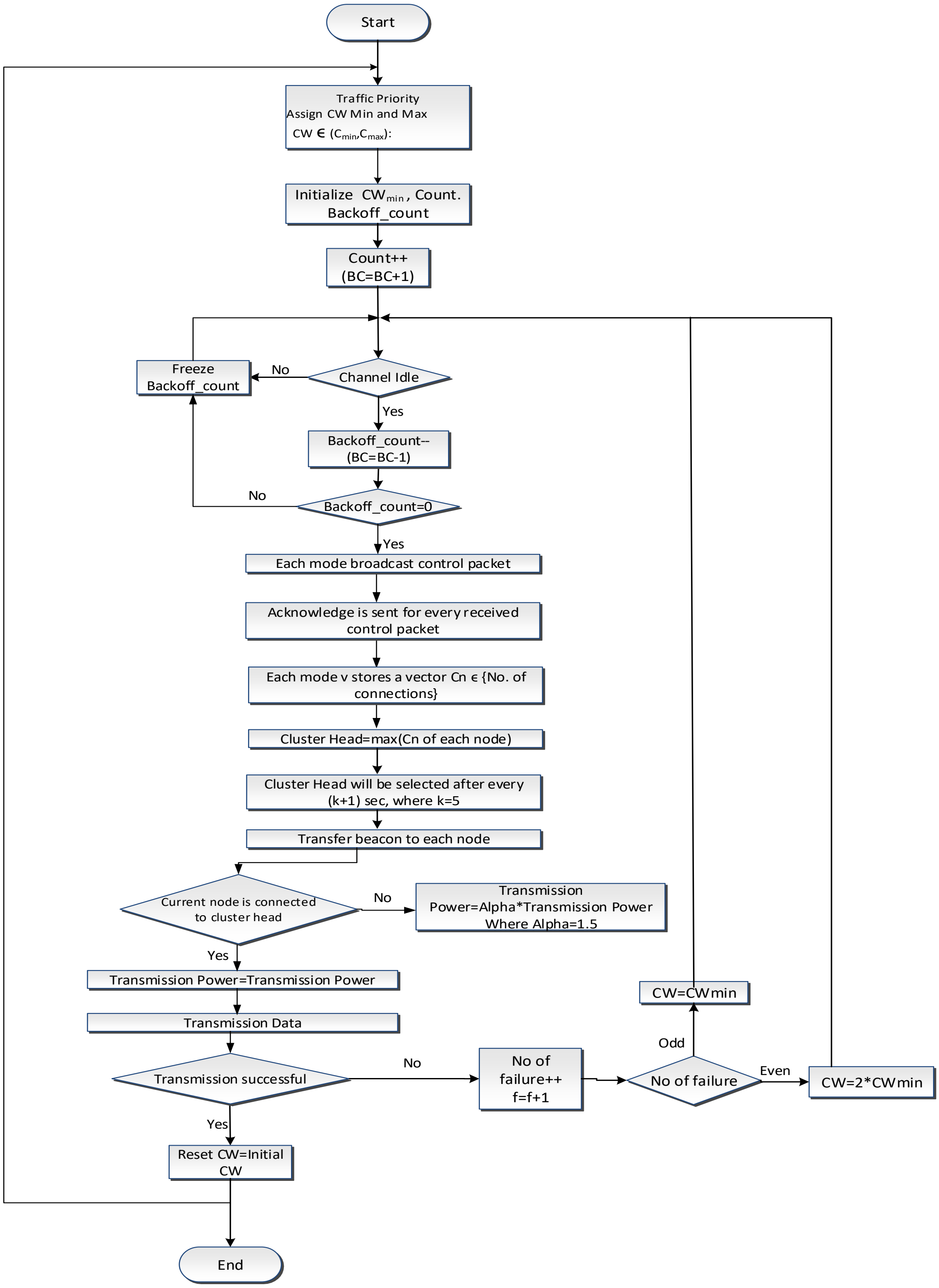

Figure 4.5: HIMM Model Flowchart

4.4.1 The Flow Chart Description

- The first step is the START or receiving of data
- The node is assigned CW (CW_{min}, CW_{max}) set and priority
- The CW_{min} and backoff counter are initialized.
- For every count increment, the channel is checked for availability. If the channel is found idle, the count is decremented (this is repeated until count is zero (0)) otherwise the count is incremented until CW_{max}.
- In the case that the channel is found idle (and count decremented to 0), each node broadcasts a control packet to all nodes. ACK is send for every received packet.
- Based on the ACK received, the node (v) stores the connections on a vector Cn which is a set of active connections per node.
- Based on the number of connections received per node, the node with the highest number of connections resumes the cluster-head role.
- For the nodes which are unreachable (did not send an ACK), the transmission power is doubled. Data is now transmitted via the new cluster head.
- If the transmission of data is successful, the CW is reset and more data is received for transmission.
- If the transmission is not successful, and the number of failures are even, the CW is doubled (2 x CW_{min}) otherwise if odd, the CW is initialised to CW_{min} and the counter is incremented and the channel checked for availability.

4.4.2 The Flow Chart Pseudo Code for the HIMM Model

The pseudo code below reflects the HIMM model as detailed in the flowchart in Figure 4.5. The flow of information in the pseudo code is as explained in the flow chart description in section 4.4.1. The detailed implementation of each section of the new model is expressed in section 4.5.

```
START
Initialization (CW is CWmin, CWmax)
Backoff_Count:
Count:
Increment count (Count = Count +1);
While count is less or equal to maximum count (While Count <= max);
    If channel idle
        Decrement backoff count (Backoff_Count = Backoff_Count -1)
    Else
        Increament count (Count = Count +1)
    If Backoff_Count is equal to zero
        Broadcast control packet:
        If control packet received
        Send Acknowledgement:
        No of connection save in vector:
        Cluster Head is node with max No. of connected nodes (Cluster Head = max number of connections)
        Compete after every (k+1)s for Cluster Head
        Broadcast beacon packet:
    If node not connected to Cluster Head
        Transmission power= alpha*Transmission power
    Else
        Transmission power = Transmission power
        Transmit data:
    Else
```

```
        Increament count (Count = Count +1);
    If transmission success
        Initialize contention window (Contention Window = initial CW)
        End, reset process
    Else Number of Failures = Number of Failures +1:
    If Number of Failures divided by 2 is zero:
        Double the Contention Window (Contention Window = 2 * CWmin)
        Increament count (Count = Count +1)
    Else
    Reset Contention Window to Minimum (Contention Window = CWmin)
    Increament count (Count = Count +1)

    END
```

4.5 The Implementation of the HIMM Model.

As discussed in the methodology, the flow chart in Figure 4.5 is implemented in Omnet++ simulation tool. In this section, the different sections of the new HIMM model relevant in relation to the model improvements are discussed. These included the CSMA/CA Contention Window with user priority which is implemented in the MAC layer of the multi WBAN, the dynamic cluster head selection of the multi-WBAN based on the link state table which is implemented in the network layer of the multi WBAN and lastly the MoBAN mobility model which is a core factor in this research. The rest of the standard codes are as attached in the appendix.

4.5.1 CSMA/CA Contention Window and User Priority

The implementation of the CSMA/CA CW with user priority involved the implementation of the MAC layer of the WBAN. This included the channel modeling, physical layer, the MAC layer, the battery module, the network IP and the mobility module. The mobility model used for performance evaluation of the CSMA/CA CW is discussed in sections 3.7 and 3.8 of the methodology.

The new HIMM Model improvement is mainly introduced in the MAC layer module while the rest of the modules are adopted as recommended by the WBAN standard.

The Contention Window (CW) is introduced as shown in Table 4.3. Out of the seven nodes, each is assigned a contention window which translated to priority of the node. The node with the smallest contention window is regarded as the node with highest preference in accessing the communication channel. This means that from Table 4.3, node 3 (contention window 2) has the highest preference while node 5 has the lowest preference (contention window 64).

Table 4.3: Contention Window Assignment per node

Node	Contention Window
0	32
1	8
2	16
3	2
4	4
5	64
6	16

One of the sections of the new HIMM model CSMA/CA Contention Window with Priority queues approach is the initialization of the counter for transmission failures. In this initialization, if the number of transmission failures are odd, the CW is initialized, and the count is increamented, otherwise if number of transmission failures are even, the Contention Window is double:

```
Initialise Count (C):
Increament Count (Count = Count ++)
        If channel idle
```

```
                Broadcast control packet
                If transmission success
                        Assign CW as minimum CW (CW=initial CW)
                        Restart process
                Else No of failure (NF) = NF++ (transmission failure i.e. no ack)
                        If number of failures divided by 2 ( NF/2 ) is zero
                        CW=2*CWmin
        Else Count = Count ++
```

Where;
Count+++ means count increament
Initial CW refers to initial contention window
NF refers to Number of failures
CWmin is the Minimum contention window size

Back off counter initialization is another function in the simulation of the CSMA/CA MAC layer. After data transmission and acknowledgement is received, the channel becomes free. The communication channel is often and after a random period of time checked for availability. When the channel is found to be in idle state or not transmitting, the count is decremented by value one (1). This decreament continues until value zero (Backoff_Count=0) after which the channel is assigned data to send. The initialization pseudo code is as shown:

```
CSMA Mac Layer
Decreament back off count (Backoff_Count --)
If decreamented till zero (Backoff_Count = 0)
        Transmit
Else
        Repeat
```

```
                    Decreament back off count (Backoff_Count --)
```

Where;
Backoff_Count-- represents the backoff counter counter decrement

4.5.2 Dynamic cluster head selection based on Link-state

The dynamic cluster head model is implemented in the network layer of the HIMM model (simplenetworklayer) Omnet++ class as shown in this section.

In this class, the simple network layer of the WBAN provides a simple routing (next hop) and message forwarding. At first there is a small "saying hello", a phase where the several network layers saying hello to each other and creating their routing table. After that phase the non-switch instances start to babbling randomly to other instances without caring if they hear them.

“Hello” Packet generation:

```
Broadcast HelloWorld
    Event Broadcasting HelloWorld.
    Set Destination Address (DestAddr – Broadcast)
    Set Source Address (SrcAddr)
    Set Sequence Number (runningSeqNumber++)
    Set Time to Live (Ttl) (maxTtl)
Forward Packet (DestAddr, SrcAddr, SeqNum, Ttl)
Decreament Time to Live (Ttl--)
sendDown(fwd)
```

This Hello Packet generation pseudo code represents how the Hello packet is generated for enabling dynamic discovery of neighbors and to maintain neighbor relationships. The “hello” packet is broadcasted to all neighboring nodes and once the neighbor node responds (with an acknowledgement ACK packet), the neighbor sensor node is added to the neighbor list table. In this pseudo code, the source or originating node address (src address), the time to live (TTL) are noted. TTL value tells a sensor node whether or not the packet has been in the network too long and should be discarded.

Receive Hello Packet and process it:

```
Handle HelloWorld
Received Packet (netwpkt_ptr_t)
    Get the source IP address from the packet (getSrcAddr)
        Check Src IP in routing table
        If exists, delete hello packet
        Else Save src IP
            Update routing table
```

Once the Hello Packet has been generated and send out, the neighbor nodes receive this packet (Received Packet) and checks the source IP address and if its in the routing table (Check Src IP in routing table). If it is not in the receipient routing table, it is added and saved. Alternatively, if the source IP address is in the routing table, the Hello packet is discarded (delete hello packet).

Function for receiving an acknowledgement from a node and adding the node to the LST table:

```
Handle IncomingAck packet

        Received Packet (netwpkt_ptr_t)
            Check source IP address from the packet (getSrcAddr)
                Check Src IP in routing table
                If exists, delete hello packet
                Else Save src IP
                    Update routing table with address of the
            previous hop
```

In pseudo code shows the action once the source node (node sending the Hello packet) receives an acknowledgment (Ack) packet from a neighboring sensor node. An Ack packet means the neighbor node can communicate with the source node. Once the Ack is received, it checks the source IP address (getSrcAddr) and further checks if that node (node sending the Ack packet) IP is in the source node routing table. If the source IP address is part of existing neighbor list of the sensor node, the Hello packet is deleted, otherwise the source IP is added to the routing table list.

4.6 Summary

In summary, this chapter presented the main contribution of this research study. The new Hybrid WBAN Interference Mitigation Model (HIMM Model) and the approaches to the improvements as the contributing factor in this research are discussed. First, the conceptual model model for the HIMM model presented and discussed. The new HIMM model implementation of the two approaches, the CSMA/CA Contention Window (CW) with User Priority (UP based approach and the dynamic cluster head using Link-State approach have been discussed in detail, including the model flow chart and pseudo codes.

The next chapter presents a performance evaluation of these two approaches in this research.

CHAPTER FIVE

RESULTS AND ANALYSIS

5.1 Introduction

In chapter four, the new HIMM Model improvements were introduced while in chapter 3, the research methodology was presented. In this chapter, the performance of the existing base IEEE 802.15.6 model and the under varying WBAN density and WBAN mobility is presented. Then the HIMM model in comparison to the existing IEEE 802.15.6 WBAN and the CSMA/CA with contention window model by Ansar *et al* (2018) is discussed and evaluated. The analysis of the simulation results is presented. On the HIMM model, we perform the performance evaluation in two approaches based on the two mechanisms introduced in our improved hybrid IEEE 802.15.6 interference mitigation model.

The performance of HIMM WBAN model which has been based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Contention Window (CW) approach and User Priority queues approach is evaluated. Using Omnet++ simulation, a comparison to the IEEE 802.15.6 based WBAN protocol is performed under the standing, walking sitting and Lying postural mobility scenarios using bandwidth efficiency, network throughput and network delay as main performance metrics.

5.2 Performance Evaluation the Current Model

In this section, the effects of mobility and WBAN density on the performance of the IEEE 802.15.6 WBAN standard is evaluated. Using Omnet++ simulation tool a simulation experiment under the MoBAN mobility while varying the number of WBAN to simulate a scenario of a changing WBAN density concentrations is carried out. Using bandwidth efficiency, network throughput and network delay performance metrics, we compared the results from single (1) WBAN, Nine (9) WBAN, Eighteen (18) WBAN and Twenty-Five (25) simulation scenarios.

5.2.1 The Performance Evaluation Simulation

There have been hardly accurate performance evaluation of IEEE 802.15.6 standard technology and many challenges and limitations have been experienced. In the recent past, Cavallari *et al*. (2014), Rahman *et al*. (2015), Wong *et al*. (2012) and Lee *et al*. (2013) claimed to be the IEEE 802.15.6 compliant radio transceivers, however, they are still limited due to a number of reasons. Firstly, the utilisation of low frequency bands which does not often satisfy most of the applications data rates requirement. Secondly, only transmitter is available without fully IEEE 802.15.6 standard compliant (Alam and Hamida, 2017). Finally works such as Cavallari *et al*. (2014) shows interesting experimental results using platform implementing the IEEE 802.15.6 CSMA/CA protocol. However, to best of our knowledge, IEEE 802.15.6 compliance radio transceivers are still to come. In this research study, we try to bring the simulations scenario to reality and by considering the biomechanical mobility for on-body and group mobility. This helps provide dynamic mobility patterns which are necessary to mimic applications such as rescue and critical, emergency management, remote health monitoring as well as mobile health among others.

In this simulation, mobility multi-WBAN in four different scenarios namely standard in a single (1) WBAN, nine (9) WBAN, eighteen (18) WBAN and twenty-Five (25) WBAN is considered. We analyze the performance of the existing IEEE 802.15.6 in the four scenarios. Each of the WBAN has seven (7) source sensor nodes distributed in different parts of the body with a single coordinator node. This means that 1WBAN has 7 sensor nodes, 9 WBAN scenario had 63 sensor nodes, 18 WBAN had 126 nodes and 25 WBAN had 175 sensor nodes. Different WBAN postures in the MoBAN mobility model namely running, walking, standing, sitting and Lying-down are used to consider the WBAN mobility scenario as a result of human locomotion.

Tables 5.1 to 5.5 show the Omnet++ simulation setting of the different WBANs for the performance evaluation. The settings options show the posture specification used, the config file and the number of hosts. More detailed settings are attached in the appendix on the omnetpp.ini file. These settings confirm the uniformity in the performance evaluation as compared to the different Multi-WBAN as well as the new HIMM model. From the tables (Table 5.1 to 5.5) the following terms have been used;

a) Configuration name – Is the name used to identify the simulation run instances. For example, simulation for single WBAN is represented as H1, for nineWBAN as H9, for eighteen WBAN as H18 and twenty-five WBAN as H25. The performance in each WBAN setup is compared to determine the effects of increase in number of sensor nodes.
b) Number of WBAN – is the number of humans in each simulation run instance.
c) Number of hosts – This represent the number of sensor nodes in the simulation instance setup. The number of nodes per WBAN has been setup as seven (7) in this researcg study. This means that the single WBAN has seven (7) sensors, nine WBAN has sixty-three (63) sensor nodes, eighteen WBAN has one hundred and sixty-three (163) nodes while twenty-five WBAN has one hundred and seventy-five (175) sensor nodes.
d) The number of MoBAN is the number of mobility for wireless area sensor networks. The MoBAN mobility model as discussed in the literature review chapter and the HIMM proposed model model in chapter four. Each WBAN is represented by one MoBAN hence the number of WBAN represents the number of MoBAN models used.
e) The Coordinator Posture Spec and Coordinator config xml Files are as discussed in section 2.8 on the mobility modeling.

Table 5.1: Single WBAN Setup Parameters

Description	Value
Configuration name	H1
Description	1 Human
Number of WBAN	1
Number of hosts	7
Number is MoBAN	1
Slot Duration	0.0002s
Coordinator posture Spec File	postures3.xml
Coordinator config File	configMoBAN3.xml

Table 5.2: 9 WBAN Setup Parameters

Description	Value
Configuration name	H9
Description	9 Human
Number of WBAN	9
Number of hosts	63
Number is MoBAN	9
Slot Duration	0.0002s
Coordinator posture Spec File	postures3.xml
Coordinator config File	configMoBAN3.xml

Table 5.3: 18 WBAN Setup Parameters

Description	Value
Configuration name	H18
Description	18 Human
Number of WBAN	18
Number of hosts	126
Number is MoBAN	18
Slot Duration	0.0002s
Coordinator posture Spec File	postures3.xml
Coordinator config File	configMoBAN3.xml

Table 5.4: 25 WBAN Setup Parameters

Description	Value
Configuration name	H25
Description	25 Human
Number of WBAN	25
Number of hosts	175
Number is MoBAN	25
Slot Duration	0.0002s
Coordinator posture Spec File	postures3.xml
Coordinator config File	configMoBAN3.xml

Table 5.5: Channel Parameters Setup Parameters

Description	Value	Unit of Measure
pMax	100mW	Milliwatt
Sat	-90dBm	decibel-milliwatts
Alpha	3	-
Carrier Frequency	2.412e+9Hz	Hertz

The tables 5.6 to 5.9 represents the other standard simulation parameters adopted in this research. These are parameters which have been used in previous studies as recommended values while others have been used for the purpose of maintanbining similarity for the purpose of performance evaluation comparison with existing. These parameters have been grouped as channel parameters, Physical Layer parameters, MAC Layer parameters, Battery Module parameters and the mobility parameters.

The Channel Parameters Setup Parameters are presented in Table 5.5 and they represent the carrier frequency adopted (2.4GHz frequency), pMax representing the maximum total transmit power of the sensor node (calculated in dBm).

Table 5.6 shows the Physical Layer parameters used in the proposed model and in the performance evaluation of the existing mechanisms. The thermal noise (or Nyquist noise as also refered to) is the electrionic noise generated by the thermal agitation of the charge carriers inside an electrical conductor at equilibrium. This the most sources of noise in radio frequency (RF). The Time RX to TX is the time from receiver to transmitter, Time RX to Sleep is the time a node takes from the time it receives the last packet and the time the node goes to sleep mode as a result of idleness. The Time TX to RX is the reverse of Time RX to TX and is the time packet takes to travel from the transmitter to receiver. The Time TX to Sleep is the time the node takes from sleep mode to transmission time. The Time Sleep to RX is the time the node takes from sleep mode to receiving packets. Sensitivity is the ability of a receiver to pick up weak signals which get affected by channel attenuation. The Max TX Power is the maximum transmission power if the WBAN sensor node.

Table 5.6: Physical Layer parameters

Description	**Value**	**Unit of Measure**
Thermal Noise	-100	decibel-milliwatts (dBm)
Time RX to TX	0.00021	Second
Time RX to Sleep	0.000031	Second
Time TX to RX	0.00012	Second
Time TX to Sleep	0.000032	Second
Time Sleep to RX	0.000102	Second
Time Sleep to TX	0.000203	Second
Sensitivity	-87	decibel-milliwatts (dBm)
Max TX Power	100.0	Milliwatts (mW)

Table 5.7 lists the MAC Layer parameters of the used in this research study implementation and perfromance evaluation of the models. The Queue Length signifies the length of the length of the packet queues while Header Length is the length of the length header packet. The Difs is the distributed inter-frame spacing and is used with data and management frames. It is the time delay for which sender wait after completing it’s backoff, before sending RTS package. The max TxAttempts parameter is the maximum number of transmission attempts after a transmission failure. Payload size is the actual data transmission size.

Table 5.7: MAC Layer parameters

Description	Value	Unit of Measure
Queue Length	5	count
Header Length	56	bit
use MAC Acks	true	Boolean
slot Duration	0.00035	Second
Difs	0.0005	Second
max TxAttempts	5	count
default Channel	0	
Bitrate	187500	Bit per second (bps)
Transmit (Tx) Power	1	Milliwatts
Payload size (x)	3000	bytes

The Battery Module parameters in Table 5.8 shows the WBAN battery module parameters used. These are standard WBAN optimal parameters as defined in the WBAN base standard.

Table 5.8: Battery Module parameters

Description	Value	Unit of Measure
Battery nominal	1000	milliampere hour
Battery capacity	1000	milliampere hour
Battery voltage	3.3	volt
Battery resolution	0.1	Second
Battery publish Delta	1	
Battery publish Time	0s	Second
Battery num Devices	1	
Nic sleep Current	0.02	Milliampere
Nic rx Current	16.4	Milliampere
Nic decoding Current Delta	0	Milliampere
Nic tx Current	17	Milliampere
Nic setup Rx Current	8.2	Milliampere
Nic setup Tx Current	8.2	Milliampere
Nic rxTx Current	17	Milliampere
Nic txRx Current	17	Milliampere

The MoBAN mobility parameters are shown in Table 5.9. These parameters have been discussed in detail in the mobilty model discussion in literature review and the mobility modeling in chapter three.

Table 5.9: Mobility parameters

Description	Value
Use Mobility Pattern	yes
Mobility Model	MoBAN
Mobility Type	MoBANLocal
Mobility update Interval	0.5 s

On initialization of the parameters used, section 3.6 of the methodology details the notations and parameters which have been adopted in all the simulations of this research. These are confirmed in the below calculation of the network throughput, network delay and bandwidth efficiency. Detailed and extended configuration details are attached in the appendix.

Throughput calculation:

Preamble time (Tp) = $90/Rs$ (Rs is Preamble transmission symbol rate)
Phy header time ($Tphy$) = $31/Rhdr$

Clear Channel Assignment Time ($Tcca$) = $63/Rs$

Slot Length Time (Ts) = $Tcca + 0.00002$

Average backoff time = (initialCW * time) / 2

Data Transmission time (*Tdata*) = Tp + Tphy + ((((MHR + FTR) * n) + x) / bitrate)

Tdata is the time required to transmit the data

Immediate ack Time (*Tiack*) = Tp + Tphy + (((MHR + FTR) * n) / bitrate)

Minimum delay (*Delay*) = average_backoff_time + Tdata + Tiack + (2 * Tsifs) + (2 * pdelay)

The delay is the sum of all time which is required for a sensor node while transmitting data.

Tiack is the time required for acknowledgment

TSIFS is Short inter-frame space time in ms

MHR is MAC header in bytes

FTR is MAC footer

Rhdr is the data rate of the header

Tsifs is the interframe spacing time which is 2 times as we need two spacing time at start and end

Pdelay is the propagation delay and they are required two one is required for data and other for acknowledgement so 1+1=2Pdelay

Maximum throughput (*mthroughput*) = x / delay

BW efficiency (*bwefficiency)* = (mthroughput / bitrate) *100

5.2.2 The Performance Analysis

In this section, the results for the performance analysis of the IEEE 802.15.6 base standard in reference to WBAN interference under multi-WBAN and high mobility scenarios are presented. The performance metrics used included Bandwidth efficiency, network throughput and network delay.

5.2.2.1 Bandwidth Efficiency

Figure 5.1 shows the mean bandwidth efficiency of H1, H9, H18 and H25 WBANs scenarios against time. The graph shows that WBAN with single WBAN is more efficiency in terms of network bandwidth than the 9 human WBAN, 18 Human and 25 Human WBAN in that order. WBAN with 25 humans is the least efficient. The graph trend confirms that the during the initial periods, the WBAN perform optimally and as traffic continues to increase with time to reach the capacity optimum, the performance starts to optimize at a level. In Figure 5.2, we show the bandwidth efficiency (against number of WBAN) performance trend between 1WBAN and 25 WBAN. From the results, the results trend show that the percentage bandwidth efficiency is inversely proportional to the number of WBAN. This means that on higher multi-WBAN scenarios, there is decreased performance of the WBAN.

All the simulations start at time zero with zero bandwidth efficiency at time zero, as time goes the performance changes based on the number of WBAN. The performance of single WBAN shows an exponential behavior of the graph with the bandwidth effience increasing with time. This means that the single WBAN performance of high and even with time, the performance increases as the WBAN is not believed to have reached optimal for the provided time duration of the simulation.

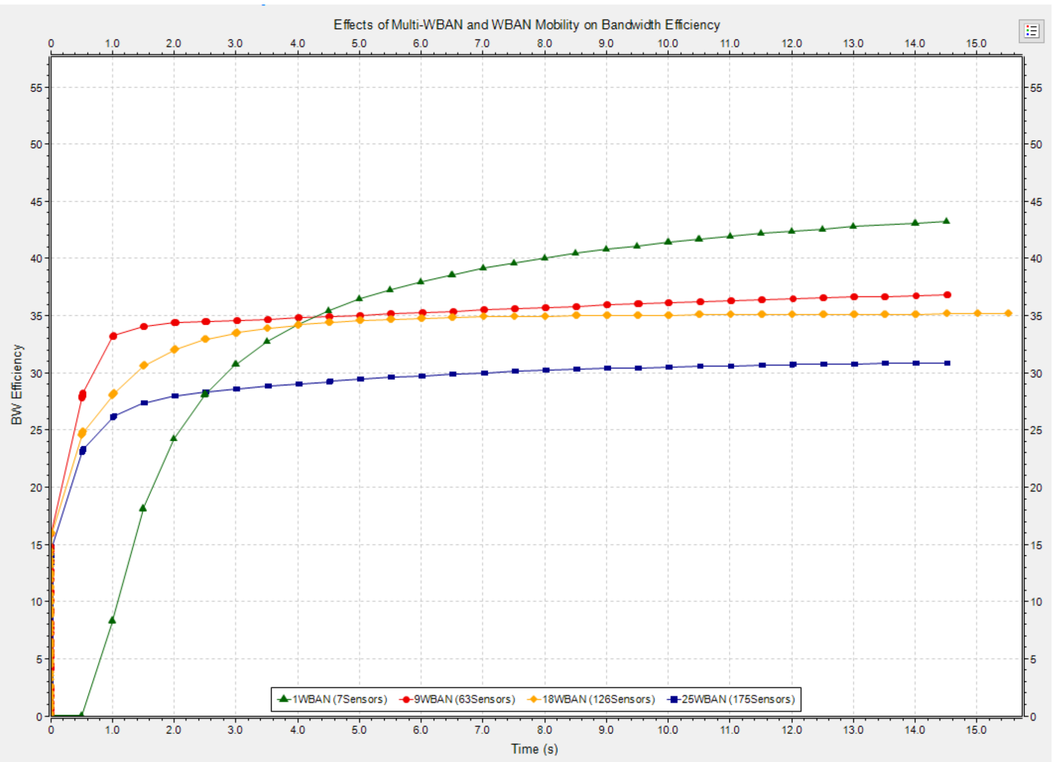

Figure 5.1: Bandwidth efficiency results of the existing IEEE 802.15.6 WBAN

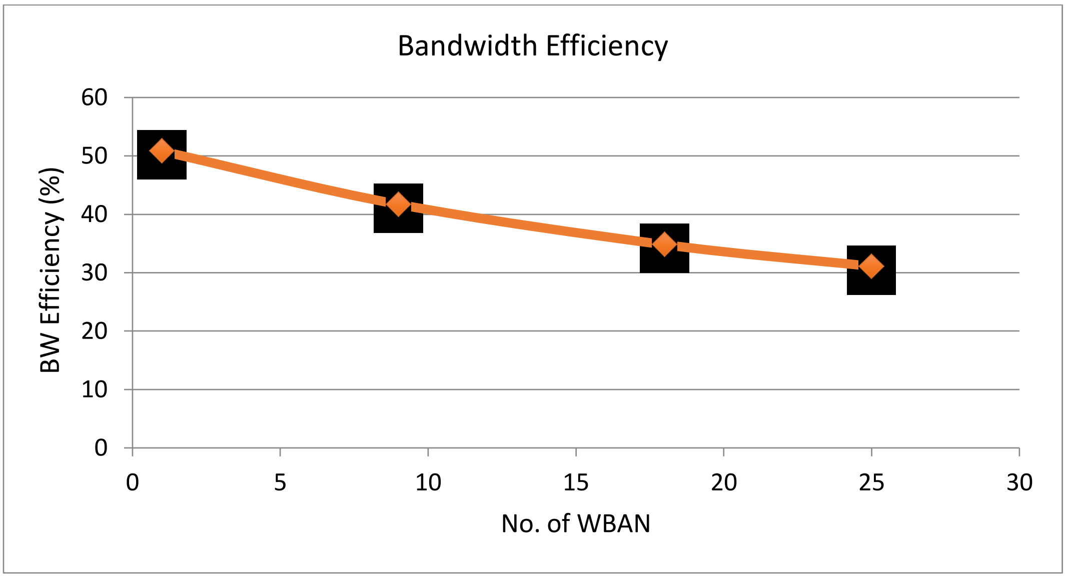

Figure 5.2: Bandwidth efficiency performance trend for the existing IEEE 802.15.6 WBAN

5.2.2.2 Network Throughput

In this simulation, WBAN throughput for 1, 9, 18 and 25 WBANs over a time duration is compared. The results in Figure 5.3 shows the performance of H1, H9, H18 and H25 against time. The results show that H1 (single WBAN) has higher network throughput than H9, H18 and H25 respectively. This can be explained by the fact the 1WBAN does not have a lot of interference as only seven (7) sensor nodes exist with the single WBAN. Since this experiment was simulated with mobility and multi-WBAN, the 9WBAN, 18WBAN and 25WBAN have 63 interfering sensor nodes, 126 interfering sensor nodes and 175 interfering sensor nodes respectively, meaning that their performance is expected to be much lower than 1WBAN, 9WBAN and 18WBAN in that order. This is seen from the results trend of Figure 5.4 which shows the throughput versus time trend. The results show that the network throughput performance decreases with the increase in the number of WBAN as the number of WBANs increase the interference levels increases affecting the WBAN performance.

From the graphs behavior, 1WBAN graphs starts from from time zero and the throughput increases steadly until it reaches an optimal performance of about 90Kbps where it almost stabilizes at this point as the best optimal throughput. For 9WBAN, the throughput also increases steadly until a saturation points of 75Kbps which is slightly lower than the 1WBAN optimal level. This is an expected performance as the higher the number of WBAN the lesser the expected throughput. This behavour is also observed in 18WBAN and 25WBAN. From this evaluation, we acertain that throughput increases in increased dynamic nature of a human.

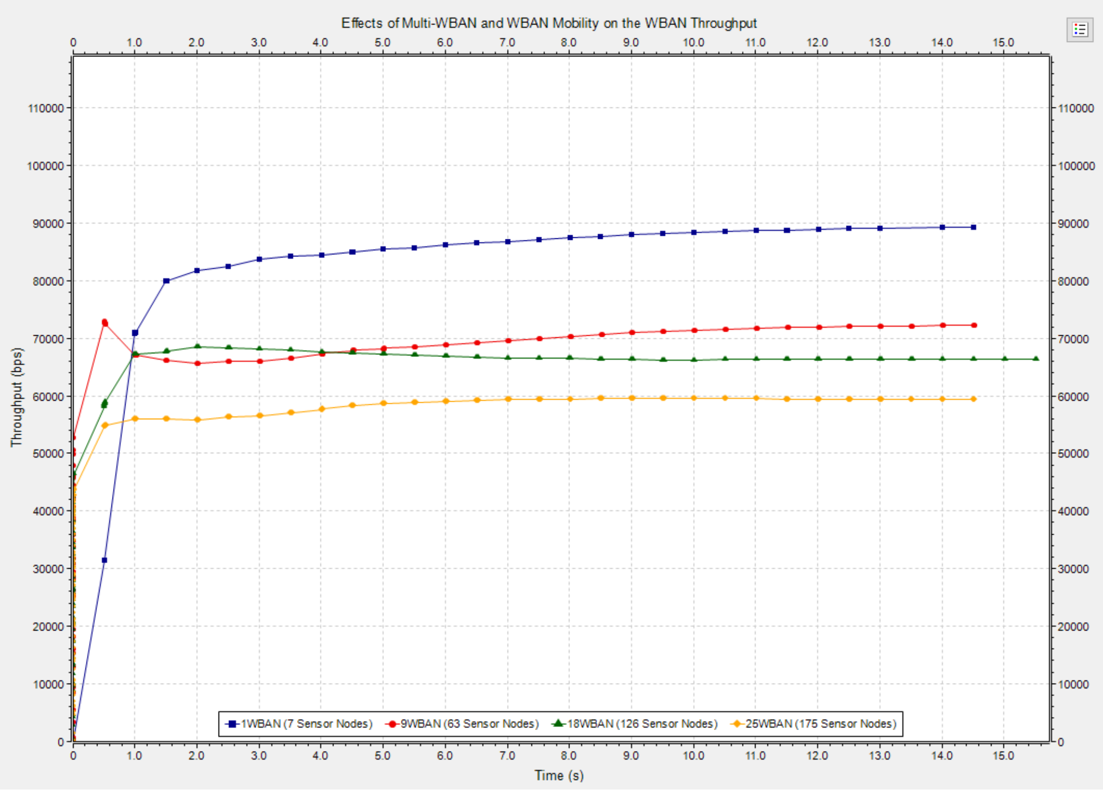

Figure 5.3. Throughput results of the IEEE 802.15.6 standard

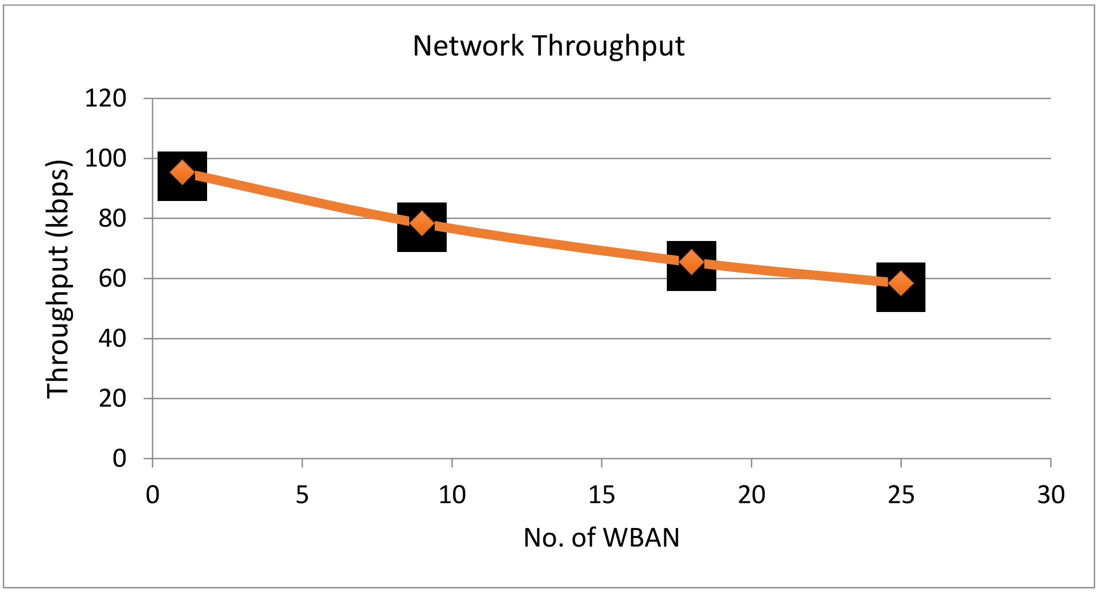

Figure 5.4. Throughput performance trend (against No. of WBAN) for IEEE 802.15.6 standard

5.2.2.3 Network Delay

In Figure 5.5, of network delay against time for the various number of multi-WBAN, we see that the higher the number of multi-WBAN the higher the delay. This confirms that the increase in the number of human body sensor around a WBAN directly affects its performance. Figure 5.6 shows the network delay versus Number of WBANs performance trend. The single WBAN shows 33.09ms, 9 WBAN shows 39.78ms, 18 WBAN show 47.13ms while 25WBAN has 52.58ms delay, indicating that the increase in WBAN is directly proportional to the increase in network delay. This indicates that an increase in WBAN in an environment decreases the performance of the WBAN in terms of delay. From the performance trend, the multi-WBAN performance degrades within a short time duration as compared to single WBAN. The single WBAN (1WBAN) because of the reduced interference levels (as expected), the delay levels are much lower and increased as number of WBAN increased.

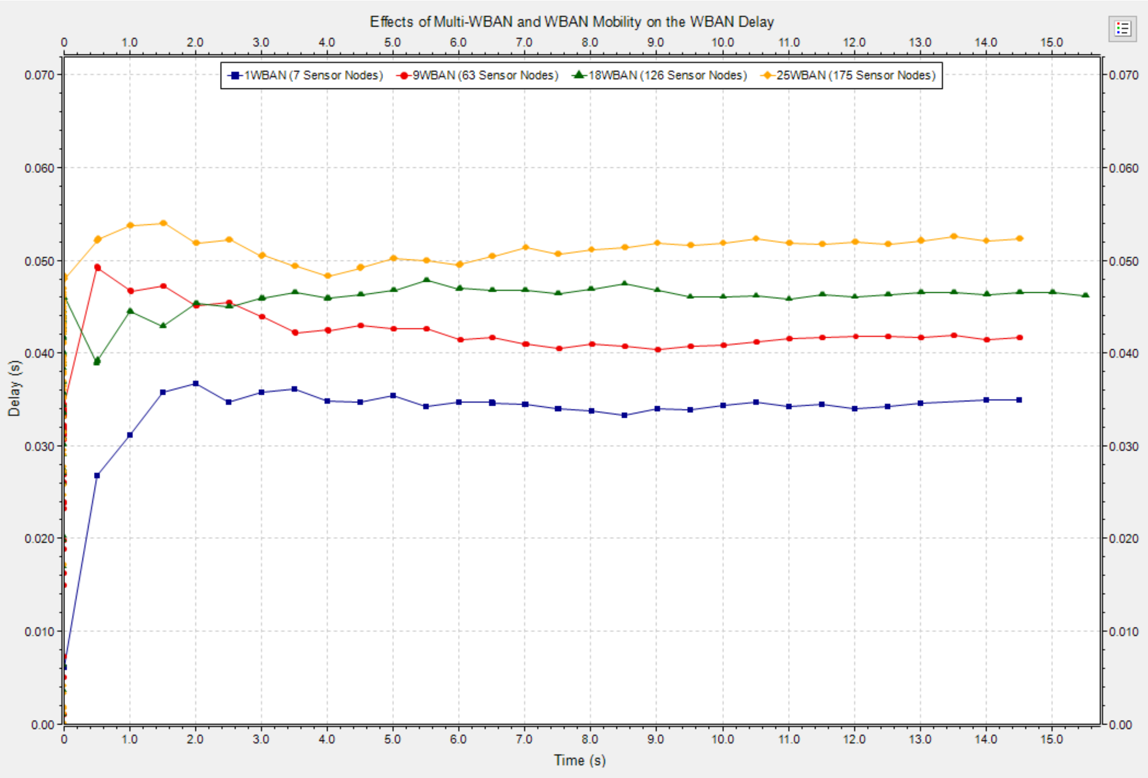

Figure 5.5. Network delay results of the base IEEE 802.15.6 standard for various WBAN

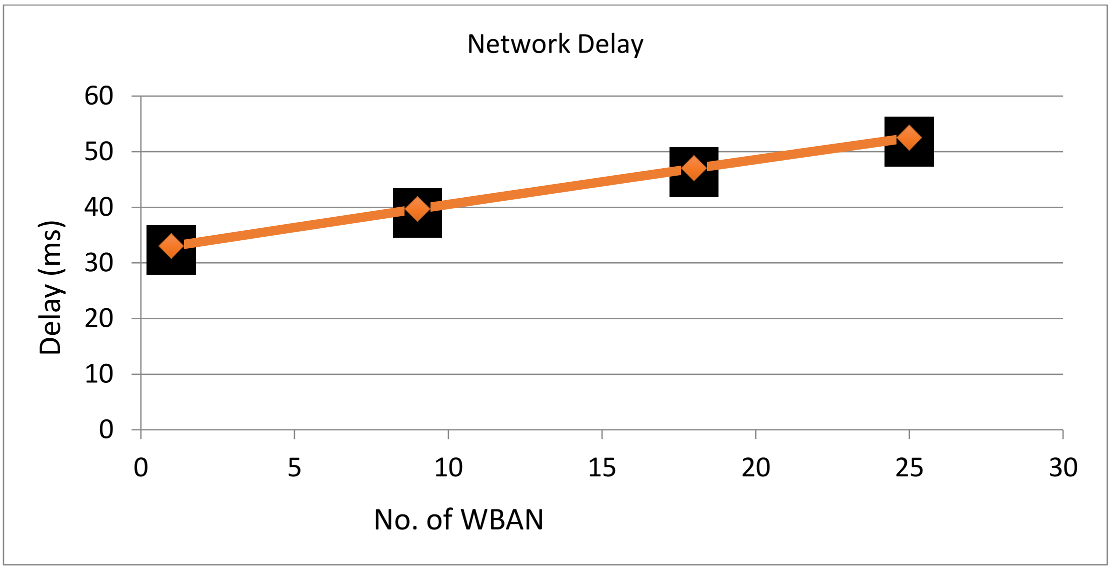

Figure 5.6. Network delay performance trend against No. of WBAN for the IEEE 802.15.6 standard

In the next sections, the performance of the two approaches which contribute the the new HIMM interference mitigation model is evaluated in respect to the base IEEE 802.15.6 WBAN standard and the recent CSMA/CA MAC protocol approach model presented by Ansar *et al*, 2018. Firstly, we evaluate the performance of the proposed CSMA/CA CW with Priority Queues approach under varying postural mobility scenarios of lying down, walking, standing and running and compare with the standard IEEE 802.15.6 WBAN using bandwidth efficiency, network throughput and network delay as main performance metrics. Secondly, we evaluate the performance of proposed dynamic cluster head selection approach for the wireless body area networks.

5.3 Performance Evaluation of the CSMA/CA CW and Priority Queues Approach

In this section, the performance of the HIMM WBAN interference mitigation model under varying postural mobility scenarios of lying down, walking, standing and running and compare with the standard IEEE 802.15.6 WBAN using bandwidth efficiency, network throughput and network delay as main performance metrics is presented. The uniqueness of this testing is that no previous research studies have evaluated multi-WBAN the under the different mobility scenarios of walking, lying down sitting and standing. In the experiment, we adopt the notation metrics discussed in section 3.6 for the bandwidth efficiency, network throughput and network delay.

Section 5.3.1 discusses the performance evaluation simulation, section 5.3.2 presents the results of the bandwidth efficiency, section 5.3.3 presents the throughput and section 5.3.4 presents the results of the network delay. We thereafter discuss the performance results in section 5.5.

5.3.1 The Performance Evaluation Simulation

In this section, the performance evaluation simulation setup is presented. Tables 5.10 to Table 5.15 shows the parameters adopted in the performance evaluation simulation study of the CSMA/CA with contention window and user priority queues. To ensure validity of the comparison, the simulation parameters have been maintained with the same parameters used in the performance evaluation simulation of the current model as observed in section 5.2.1. This is to ensure credible validation results. These existing model parameters are discussed in section 5.2.1. In this section, we as well detail the main parameters used.

Table 5.10 shows the Channel Setup Parameters adopted in the CSMA/CA Contention window approach. This is in similarity to Table 5.5 in the performance evaluation of the base IEEE 802.15.6 WBAN standard.

Table 5.10: CSMA/CA CW Approach Channel Setup Parameters

Description	Value	Units Measure
pMax	100	milliWatts
Sat	-90	decibel-milliwatts
Alpha	3	
Carrier Frequency	2.412e+9	Hertz

Table 5.11 presents the Physical Layer Setup Parameters adopted in the CSMA/CA Contention window approach. This is in similarity to Table 5.6 which shows used in the performance evaluation of the base IEEE 802.15.6 WBAN standard.

Table 5.11: CSMA/CA CW Approach Physical Layer parameters

Description	Value	Unit Measure
Thermal Noise	-100	decibel-milliwatts
Time RX to TX	0.00021	Second
Time RX to Sleep	0.000031	Second
Time TX to RX	0.00012	Second
Time TX to Sleep	0.000032	Second
Time Sleep to RX	0.000102	Second
Time Sleep to TX	0.000203	Second
Sensitivity	-87	decibel-milliwatts
Max TX Power	100.0	Milliwatts

Table 5.12: CSMA/CA CW Approach MAC Layer parameters

Description	Value	Unit Measure
Queue Length	5	Count
Header Length	56	bit
use MAC Acks	true	-
slot Duration	0.00035	Second
Difs	0.0005	Second
max TxAttempts	5	Count
default Channel	0	-
Bitrate	187500	Bit per second (bps)
Transmit (Tx) Power	1	Milliwatt (mW)
Payload size (x)	3000	Bytes

The battery module parameters shown in Table 5.13 as used in this simulation are maintained in uniformity to the base standard performance evaluation as presented in Table 5.8.

Table 5.13: CSMA/CA CW Approach Battery Module parameters

Description	Value	Unit Measure
Battery nominal	1000	milliampere hour (mAh)
Battery capacity	1000	milliampere hour (mAh)
Battery voltage	3.3	Volt
Battery resolution	0.1	Second
Battery publish Delta	1	Count
Battery publish Time	0	Second
Battery num Devices	1	Count
Nic sleep Current	0.02	Milliamp (mA)
Nic rx Current	16.4	Milliamp (mA)
Nic decoding Current Delta	0	Milliamp (mA)
Nic tx Current	17	Milliamp (mA)
Nic setup Rx Current	8.2	Milliamp (mA)
Nic setup Tx Current	8.2	Milliamp (mA)
Nic rxTx Current	17	Milliamp (mA)
Nic txRx Current	17	Milliamp (mA)

The MoBAN mobility model is adopted across the entire simulations in this research work. This is presented in Table 5.9 and Table 5.14. The parameters adopted are as recommended by the best practices of the model. The Network Layer parameters are as presented in Table 5.15.

Table 5.14: CSMA/CA CW Approach Mobility parameters

Description	**Value**
Use Mobility Pattern	yes
Mobility Model	MoBAN
Mobility Type	MoBANLocal
Mobility update Interval	0.5 s
Coordinator posture Spec File	postures1.xml
Coordinator config File	configMoBAN3.xml

Table 5.15: CSMA/CA CW Approach Network Layer parameters

Description	**Value**	**Unit Measure**
max Ttl	3	Count
bored Time	0.5	Second
Pass Time	35	Second

5.3.1.1 The HIMM Model CSMA/CA CW Model WBAN Specific Parameters

The Tables 5.16 to 5.19 show the modified HIMM CSMA/CA CW WBAN model specific parameters. The parameters inherit the paramters used in Tables 5.1 to 5.5 in the performance evaluation of the base IEEE 802.15.6 standard. From the Tables 5.16 to 5.19, the introduced new features of the proposed CSMA/CA Contention Window are the muti-WBAN represented by the varying number of sensor nodes per simulation. Also introduced in below specific parameters are the contention window parameters as proposed in chapter four. Each of the seven sensor nodes in each WBAN is assigned contention window values as below:

Node [0] contentionWindow = 4

Node [1] contentionWindow = 2

Node [2] contentionWindow = 4

Node [3] contentionWindow = 8

Node [4] contentionWindow = 8

Node [5] contentionWindow = 2

Node [6] contentionWindow = 16

For simulation purposes only, the configuration name for the adopted approach has been abbreviated as PH to refer to HIMM Model Humans, for example PH1 refers to HIMM Model single WBAN, PH9 refers to HIMM Model nine humans, PH18 refers to HIMM Model 18 humans and PH25 refers to HIMM Model 25 humans WBANs.

Table 5.16: CSMA/CA CW Model Specific Parameters – PH1 WBAN

Description	**Value**
Config name	PH1
Nodes	1
Description	Single Human
MAC slotDuration	0.0002s
postureSpecFile	postures3.xml
configFile	configMoBAN3.xml
Number of Hosts	7
Number of MoBAN	1
Nodes CW	node[0] contentionWindow = 4 node[1] contentionWindow = 2 node[2] contentionWindow = 4 node[3] contentionWindow = 8 node[4] contentionWindow = 8 node[5] contentionWindow = 2 node[6] contentionWindow = 16

Table 5.17: CSMA/CA CW Model Specific Parameters – PH9 WBAN

Description	Value
Config name	PH9
Nodes	9
Description	Nine Human
MAC slotDuration	0.0002s
postureSpecFile	postures3.xml
configFile	configMoBAN3.xml
Number of Hosts	63
Number of MoBAN	9
Nodes CW per WBAN (Nodes 0-62)	Node [0] contentionWindow = 4 Node [1] contentionWindow = 2 Node [2] contentionWindow = 4 Node [3] contentionWindow = 8 Node [4] contentionWindow = 8 Node [5] contentionWindow = 2 Node [6] contentionWindow = 16

Table 5.18: **CSMA/CA CW Model Specific Parameters – PH18 WBAN**

Description	Value
Config name	PH18
Nodes	18
Description	Eighteen Human
MAC slotDuration	0.0002s
postureSpecFile	postures3.xml
configFile	configMoBAN3.xml
Number of Hosts	125
Number of MoBAN	18
Nodes CW per WBAN (Nodes 0-124)	Node [0] contentionWindow = 4 Node [1] contentionWindow = 2 Node [2] contentionWindow = 4 Node [3] contentionWindow = 8 Node [4] contentionWindow = 8 Node [5] contentionWindow = 2 Node [6] contentionWindow = 16

Table 5.19: CSMA/CA CW Model Specific parameters - PH25 WBAN

Description	Value
Config name	PH25
Nodes	25
Description	Twenty-five Human
MAC slotDuration	0.0002s
postureSpecFile	postures3.xml
configFile	configMoBAN3.xml
Number of Hosts	175
Number of MoBAN	25
Nodes CW per WBAN (Nodes 0-174)	Node [0] contentionWindow = 4 Node [1] contentionWindow = 2 Node [2] contentionWindow = 4 Node [3] contentionWindow = 8 Node [4] contentionWindow = 8 Node [5] contentionWindow = 2 Node [6] contentionWindow = 16

Calculation of the network delay, throughput and the bandwidth efficiency of the simulation:

Preamble time (Tp) = 90/ Preamble transmission symbol rate (Rs);

Phy header time (Tphy) = 31/ data rate of the header(Rhdr);

Clear Channel Assignment Time (Tcca) = 63/ Preamble transmission symbol rate;

Slot Length Time (Ts) = Clear Channel Assignment Time + 0.00002;

Average backoff time (argbftime) = (initialCW*time)/2;

Where: time = (slots * slotDuration);

slots = intrand (initialCW + txAttempts) + 1.0 + dblrand();

Tdata = Tp + Tphy + ((((MHR + FTR) * n) + x) / bitrate);

Tiack = Tp + Tphy + (((MHR + FTR) * n)/bitrate);

Where:

Tdata is the time required to transmit the data and is expressed in kbit

MHR is the MAC header in bytes

FTR is the MAC footer

Tiack is the time required for acknowledgment

Delay:

Delay = argbftime + Tdata + Tiack + (2 * Tsifs) + (2 * pdelay);

Where:

Tsifs is the interframe spacing time which is 2 times as we need two spacing time at start and end

Pdelay is the propagation delay and they are required two one is required for data and other for acknowledgement so 1+1=2Pdelay

Maximum throughput (mthroughput):

mthroughput = x / delay; x = payload size

BW efficiency (bwefficiency):

bwefficiency = (mthroughput / bitrate) * 100;

Recording of the network delay, throughput and the bandwidth efficiency are done as scalar and vector quantities and the results can be displayed in either. The scalar results are one directional while the vector gives results in both magnitude and direction.

5.3.2 Bandwidth Efficiency

The performance of the new HIMM interference mitigation mechanism against the existing IEEE 802.15.6 base model and the recent Energy-Efficient and Priority-Based Enhanced IEEE802.15.6 CSMA/CA MAC Protocol by Ansar *et al*, 2018 in respect to the mean bandwidth efficiency under multi-WBAN in mobility is compared. Figures 5.7, 5.8, 5.9 shows the bandwidth efficiency results for 63WBAN sensor nodes, 126WBAN sensor nodes and 175WBAN sensor nodes respectively. For each of the WBAN scenarios, the results show that the new HIMM model has a significant improvement in bandwidth efficiency under the changing mobility scenarios of walking, lying down, sitting and standing postural mobilities with performances improvement from existing of 30% to as high as 58% depending on the number of sensor nodes. The results diagram shows the lowest performing (lowest level line graphs) as existing base standard and the Energy-Efficient and Priority-Based Enhanced IEEE802.15.6 CSMA/CA MAC Protocol model posting an improved performance (middle level graph) to the base standard but lower performance to the

HIMM mechanism. This shows improvement in the proposed mechanism.

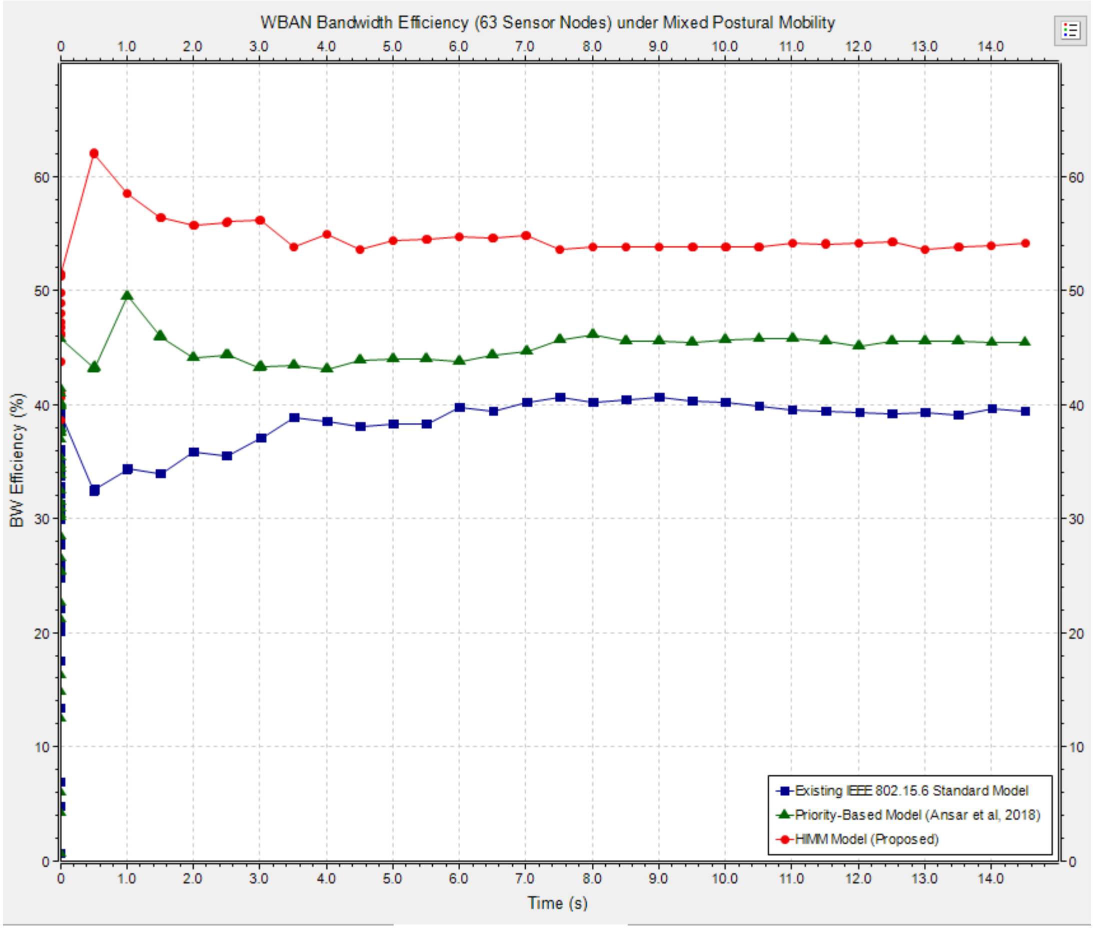

Figure 5.7. WBAN Bandwidth efficiency for HIMM Model and existing models for 63 nodes

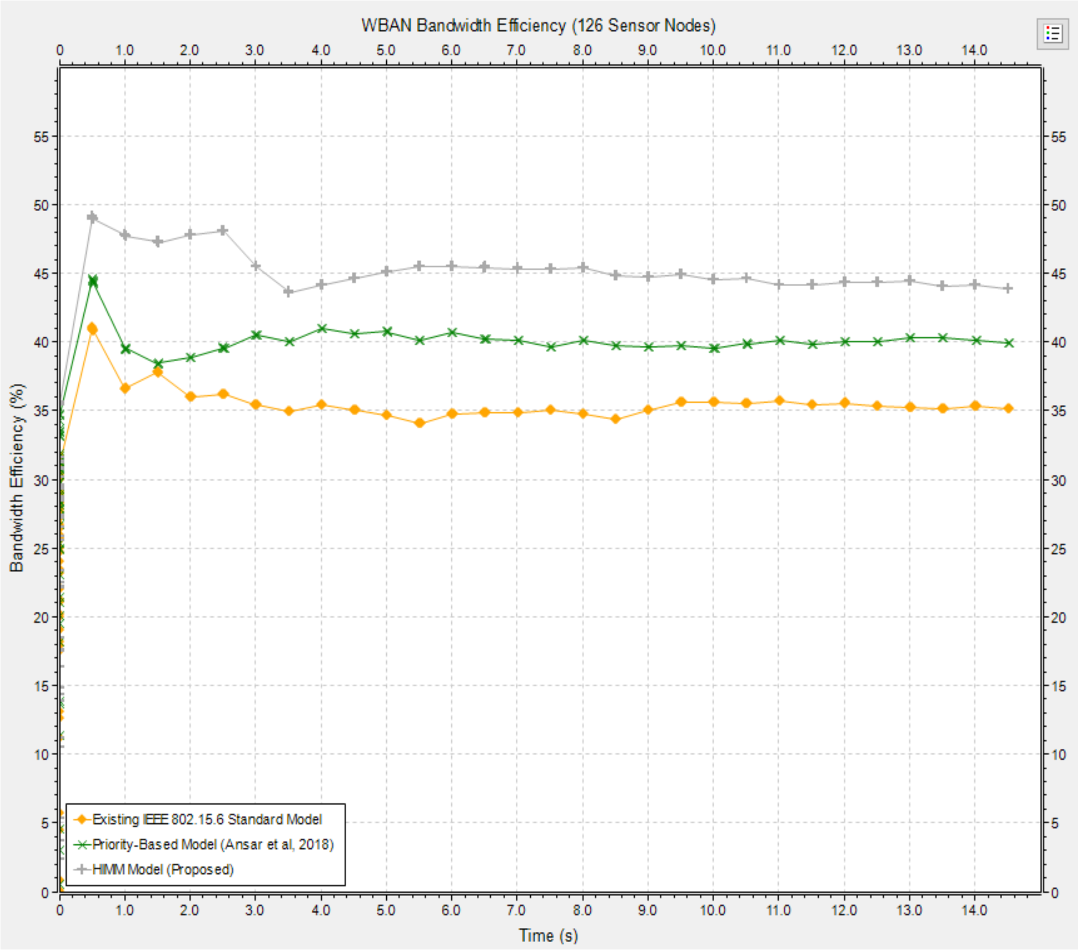

Figure 5.8. WBAN Bandwidth efficiency for HIMM Model and existing models for 126 nodes

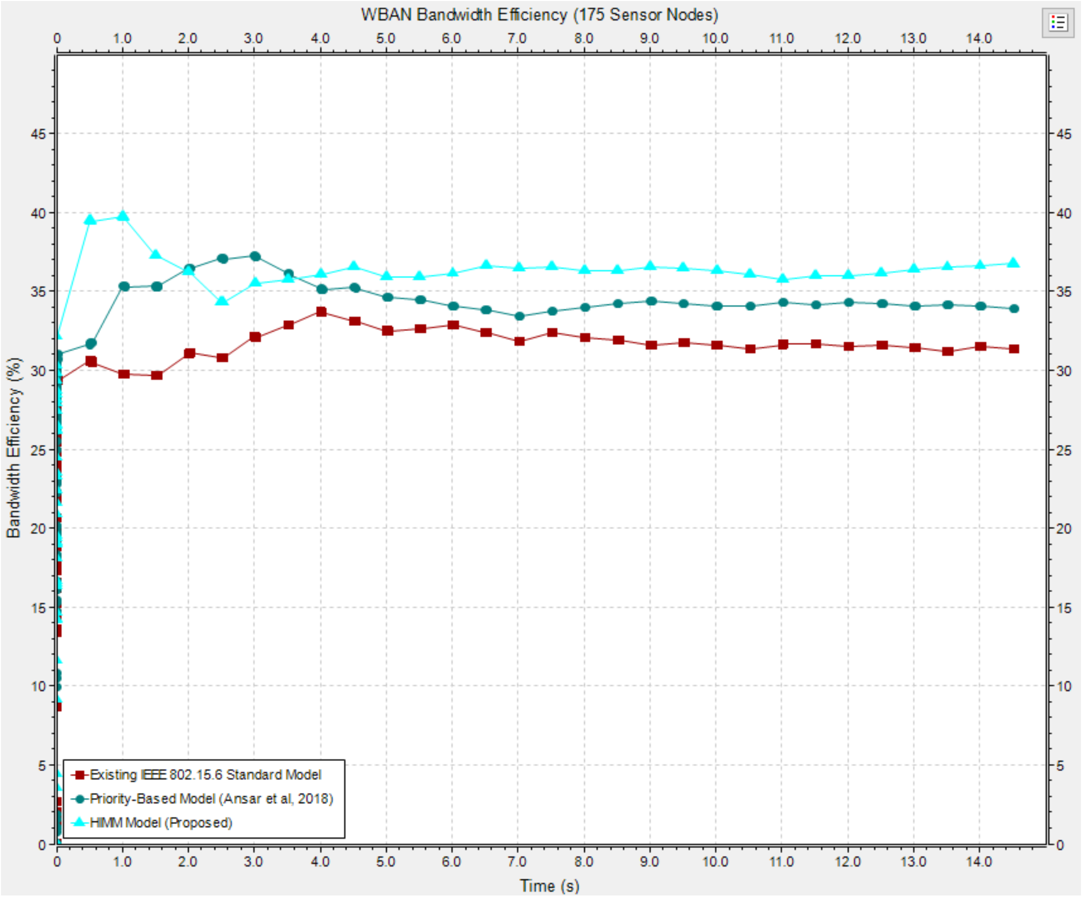

Figure 5.9. WBAN Bandwidth efficiency for HIMM Model and existing models for 175 nodes

5.3.3 Network Throughput

Figures 5.10, 5.11, 5.12 shows the performance of the existing base IEEE 802.15.6 WBAN model, the Energy-Efficient and Priority-Based Enhanced IEEE 802.15.6 CSMA/CA MAC Protocol model by Ansar *et al*, 2018, and the proposed HIMM WBAN interference mitigation model against time for the network throughput for 63 nodes, 126 nodes and 175nodes multi-WBAN scenarios. The upper line in the graphs indicating the proposed model confirms an improvement in throughput of the proposed by a significant level in mobility scenarios. The results show increased network throughput in the proposed model for multi-WBAN with mobility scenarios from average of 80Kbps to 110Kbps, depending on the number of multi-WBAN nodes.

This is because in WBAN, throughput reduces du to reduced traffic collisons which is experienced in this study.

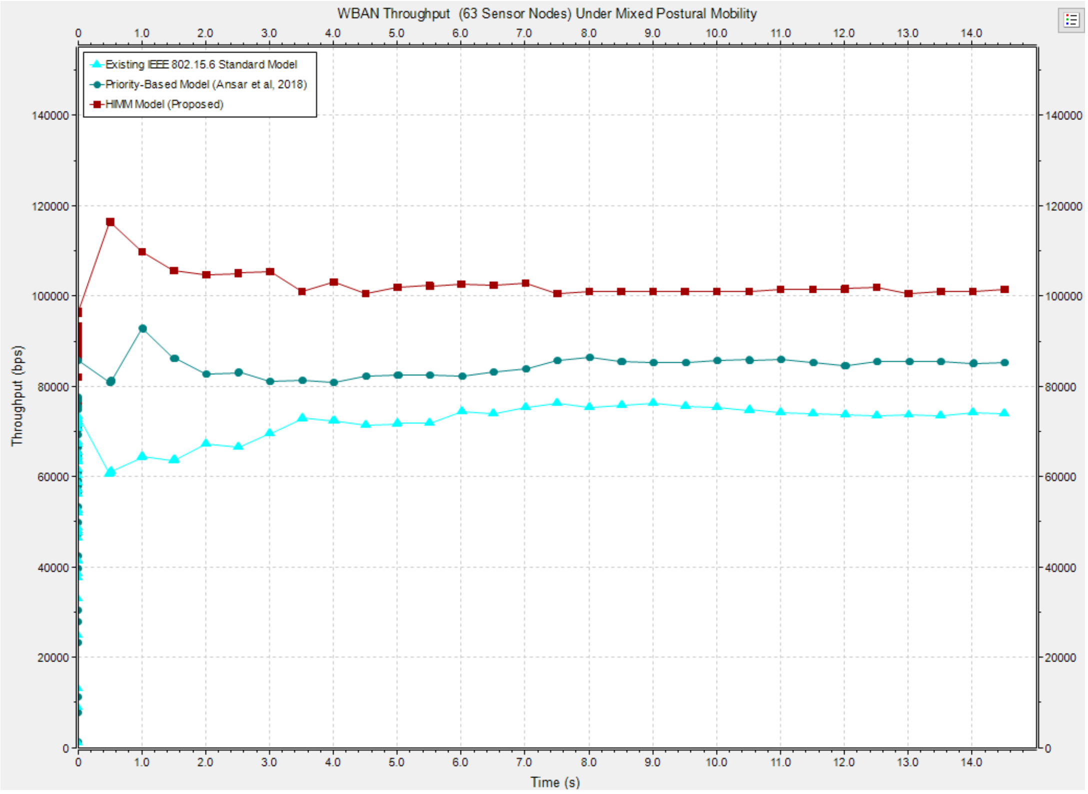

Figure 5.10. Results of throughput for HIMM Model and existing models for 63nodes

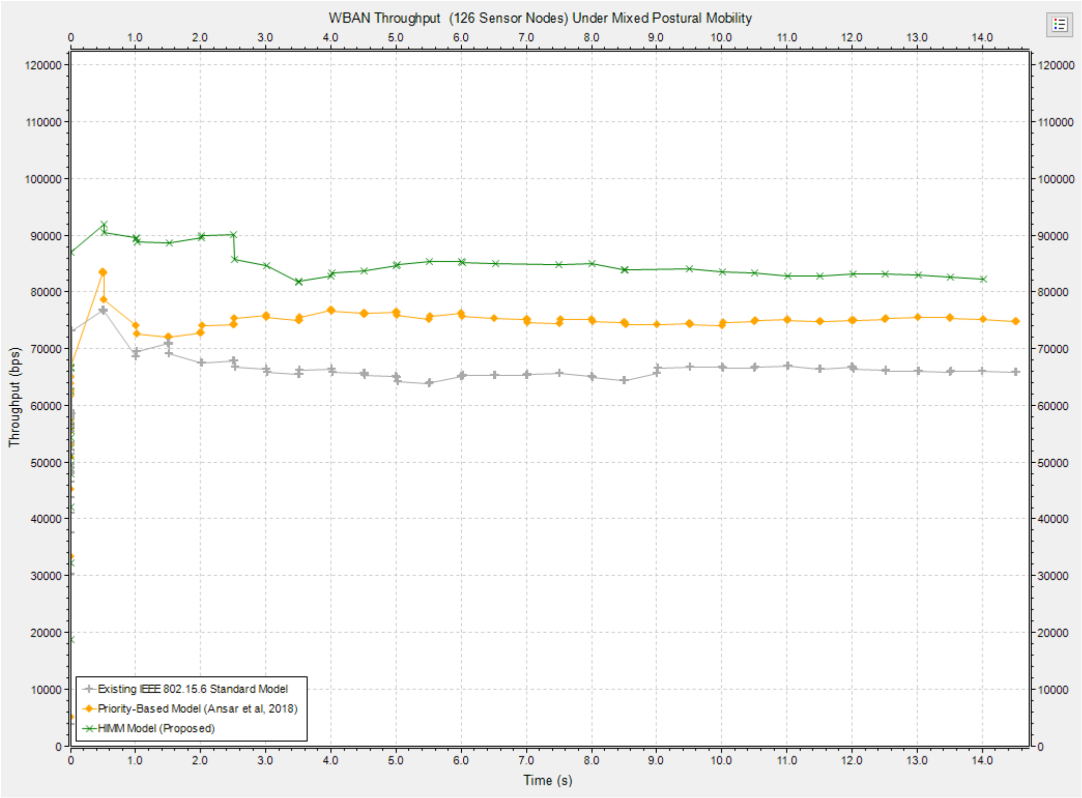

Figure 5.11. Results of network throughput for HIMM Model and existing models for 126 nodes

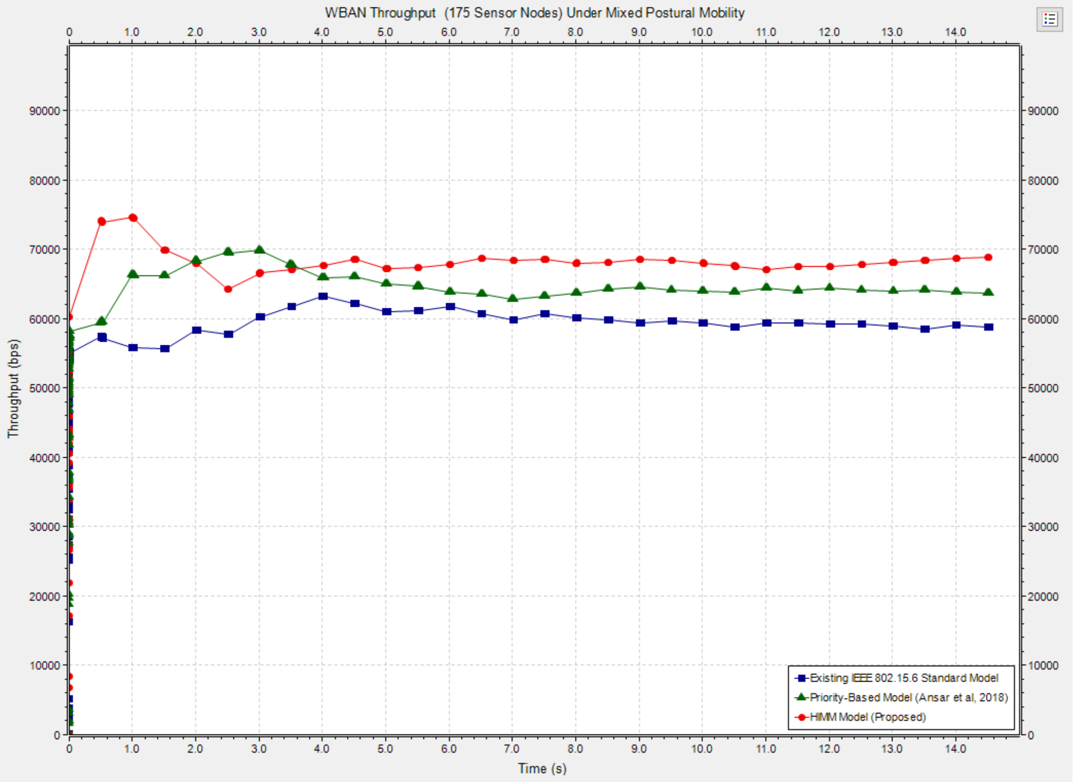

Figure 5.12. Results of throughput for HIMM Model and existing models for 175 nodes.

5.3.4 Network Delay

Network delay is an important factor in the performance of WBAN because of the nature of the applicability of the WBAN. In this research simulation results, the network delay performance is demonstrated in Figures 5.13, 5.14, and 5.15 in which the delay is shown against time for the various number of multi-WBAN sensor nodes under postural mobility. The new HIMM interference mitigation mechanism showed improved performance in all multi-WBAN scenarios as compared to the existing and current interference mitigation models. A decrese is recorded on network delay in the HIMM interference mitigation model for all the multi-WBAN scenarios compared to both the existing IEEE 802.15.6 WBAN base standard and the Energy-Efficient and Priority-Based Enhanced IEEE 802.15.6 CSMA/CA MAC Protocol model. This indicates a magnificent improvement in the WBAN in terms of delay performance.

This a clear demonstration of the improvement and contribution of the proposed model to the technology. The delay first increased gradually as the interference builds up with time. The delay majorly comes as a result of congestion in the transmission channel as a result of different sensor nodes trying to access the channel at the same time. This leads to retransmissions and hence increased delay.

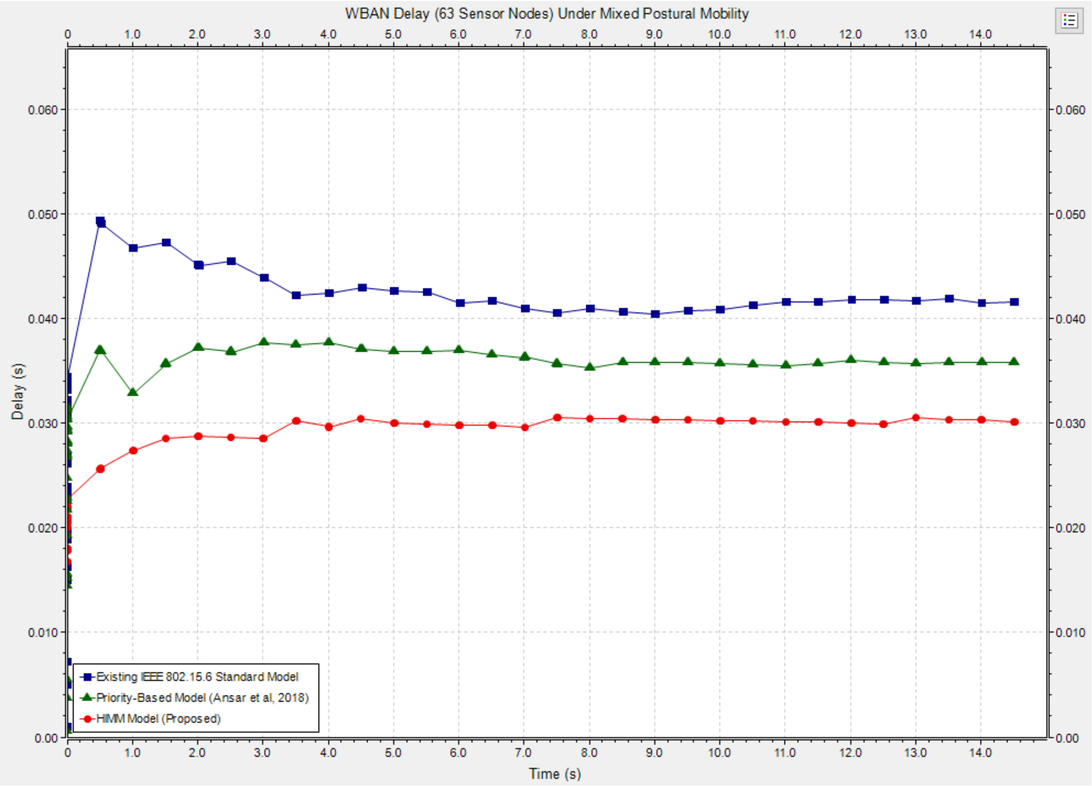

Figure 5.13. Network delay performance for HIMM Model and existing models under 63 nodes

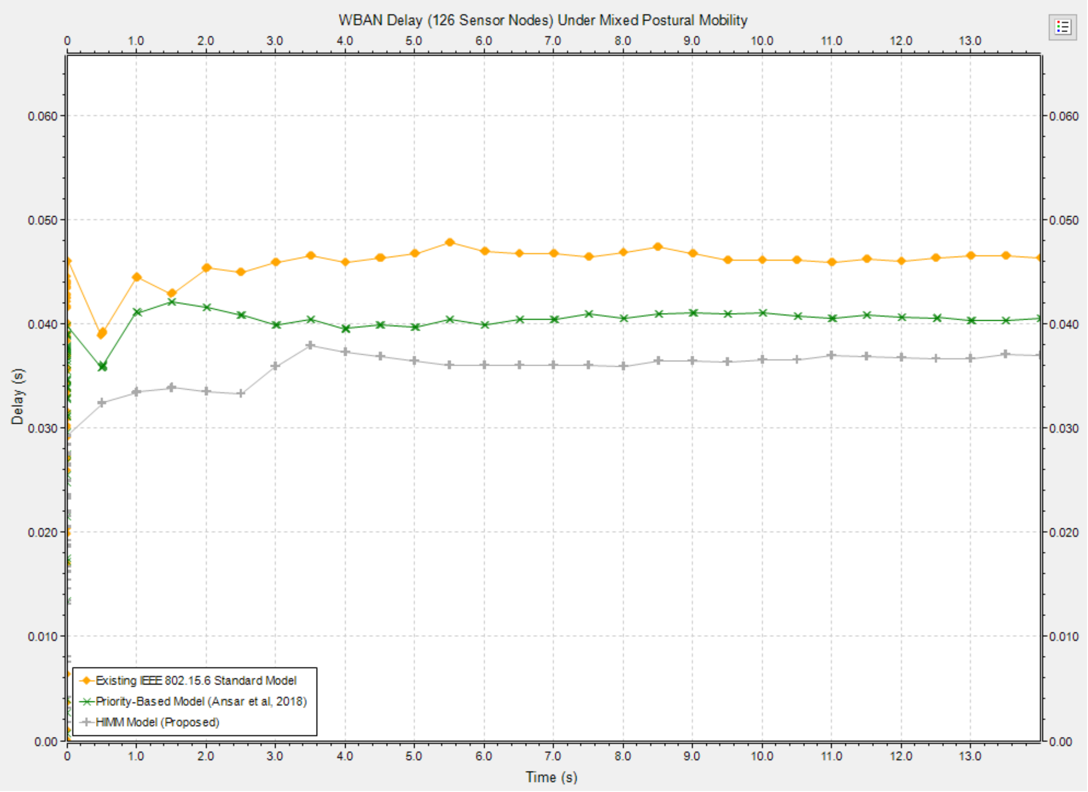

Figure 5.14. Network delay performance for HIMM Model and existing models under 126 nodes

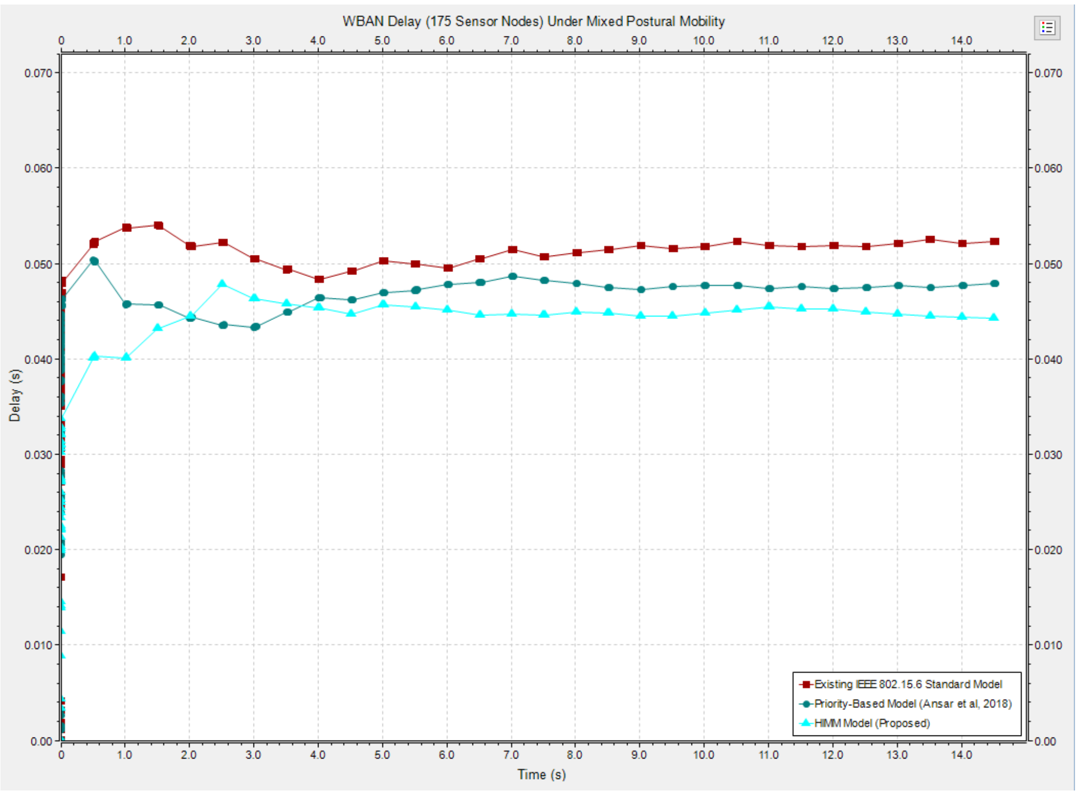

Figure 5.15. Network delay performance for HIMM Model and existing models under 175 nodes

5.4 Performance Evaluation of the Dynamic Cluster Head Selection Model Approach

In section 4.5, we presented a new dynamic cluster head selection approach for the wireless body area networks. The main idea to introduce this approach in the HIMM Model was to make WBAN more reliable and energy efficient by having idea of acknowledgement and dynamic cluster head selection in CSMA/CA protocol of the WBAN. This was in comparison to other methods which have been in use including Random cluster head, fixed cluster head at Head position, Foot position and at the belly, as the common positions of cluster node in WBAN.

In this evaluation, as discussed in the methodology, Omnet++ simulation with Mixim framework was used to do the performance evaluation of WBAN cluster head positions random cluster head, fixed cluster head at head position, foot position, at the belly and the proposed dynamic cluster head.

In this dynamic cluster head selection performance evaluation, we as well adopt the performance notations and parameters as discussed in section 3.6 for the bandwidth efficiency, network throughput and network delay.

The rest of the sections are as follows; section 5.4.1 discusses the simulation and parameters, section 5.4.2 shows the network delay results, section 5.4.3 presents the network throughput results while section 5.4.4 presents the bandwidth efficiency. The results discussion are presented in section 5.5.

5.4.1 The Performance Evaluation Simulation

The specific parameters of the HIMM Model are discussed in section 4.7.2 of the Dynamic cluster head selection scheme. In this section, the general parameters as used on this simulation for the comparison with the current and the previous simulations carried out in this research study are shown. As discussed in the simulation parameters of performance evaluation of the IEEE 802.15.6 base standard and the Energy-Efficient and Priority-Based Enhanced IEEE 802.15.6 CSMA/CA MAC Protocol model by Ansar *et al*, 2018, the general parameters and most of the specific parameters have been maintained for evaluation purpose. This means the Tables 5.20 to Table 5.24 parameters share similarity to paramters used in the IEEE 802.15.6 CSMA/CA contention window with user priority queues (Table 5.10 to Table 5.15) and the base standard IEEE 802.15.6 WBAN performance evaluation (Table 5.1 to Table 5.9).

Table 5.20: The HIMM Model Dynamic cluster head approach Channel Parameters

Description	Value	Unit of measure
pMax	100	Milliwatt
Sat	-90	decibel-milliwatts (dBM)
Alpha	3	
Carrier Frequency	2.412e+9	Hertz (Hz)

Table 5.21: The HIMM Model Dynamic cluster head approach Physical Layer parameters

Description	Value	Unit of measure
Thermal Noise	-100	decibel-milliwatts (dBm)
Time RX to TX	0.00021	Second
Time RX to Sleep	0.000031	Second
Time TX to RX	0.00012	Second
Time TX to Sleep	0.000032	Second
Time Sleep to RX	0.000102	Second
Time Sleep to TX	0.000203	Second
Sensitivity	-87	decibel-milliwatts (dBm)
Max TX Power	100.0	Milliwatt (mW)

Table 5.22: The HIMM Model dynamic cluster head approach MAC Layer parameters

Description	Value	Unit of measure
Queue Length	5	
Header Length	56	bit
use MAC Acks	true	
slot Duration	0.00035	Second
Difs	0.0005	Second
max TxAttempts	5	
default Channel	0	
Bitrate	187500	Bit per second (bps)
Transmit (Tx) Power	1	Milliwatt
Payload size (x)	3000	

Table 5.23: The HIMM Model dynamic cluster head approach Battery Module parameters

Description	Value	Unit of Measure
Battery nominal	1000	milliampere hour (mAh)
Battery capacity	1000	milliamperehour (mAh)
Battery voltage	3.3	Volt
Battery resolution	0.1	Second
Battery publish Delta	1	
Battery publish Time	0	Second
Battery num Devices	1	
Nic sleep Current	0.02	milliampere (mA)
Nic rx Current	16.4	milliampere (mA)
Nic decoding Current Delta	0mA	milliampere (mA)
Nic tx Current	17mA	milliampere (mA)
Nic setup Rx Current	8.2mA	milliampere (mA)
Nic setup Tx Current	8.2mA	milliampere (mA)
Nic rxTx Current	17mA	milliampere (mA)
Nic txRx Current	17mA	milliampere (mA)

Table 5.24: The HIMM Model Dynamic cluster head approach Mobility parameters

Description	Value
Use Mobility Pattern	yes
Mobility Model	MoBAN
Mobility Type	MoBANLocal
Mobility update Interval	0.5 s
Coordinator posture Spec File	postures1.xml
Coordinator config File	configMoBAN2.xml

Table 5.25: The HIMM Model dynamic cluster head approach Network Layer parameters

Description	Value
max Ttl	3
bored Time	0.5
Pass Time	35

5.4.2 Network Delay

Figure 5.16 presents delay against time comparison between fixed cluster head at head position, foot position, at the belly and the HIMM Model dynamic cluster head. In these results, lowest delay is achieved in Dynamic cluster head selection scheme with priority.

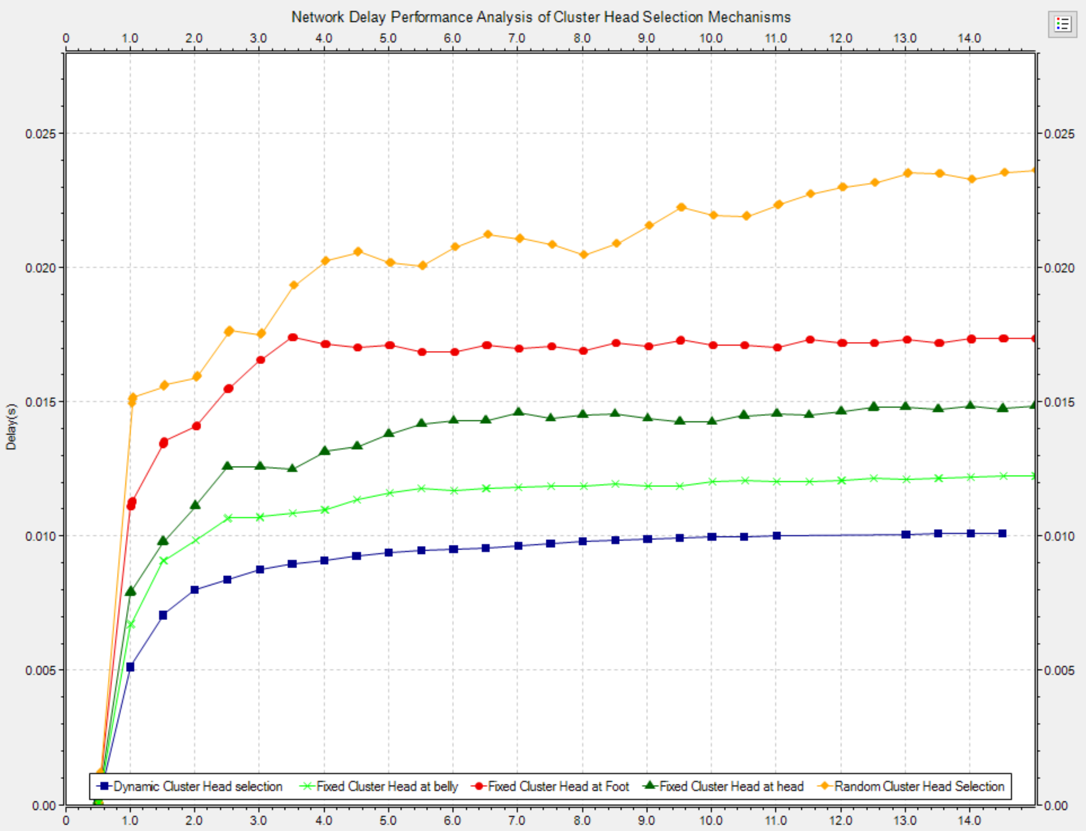

Figure 5.16. Network Delay performance of the Different WBAN Cluster Head selection

The Figure 5.17 presents the delay as a function data rate. The delay declines as a function of data rate. The dynamic cluster head outperforms all other cluster head selection schemes by the virtue of collision avoidance in each UP. Average number of backoffs are reduced in hybrid node prioritization scheme.

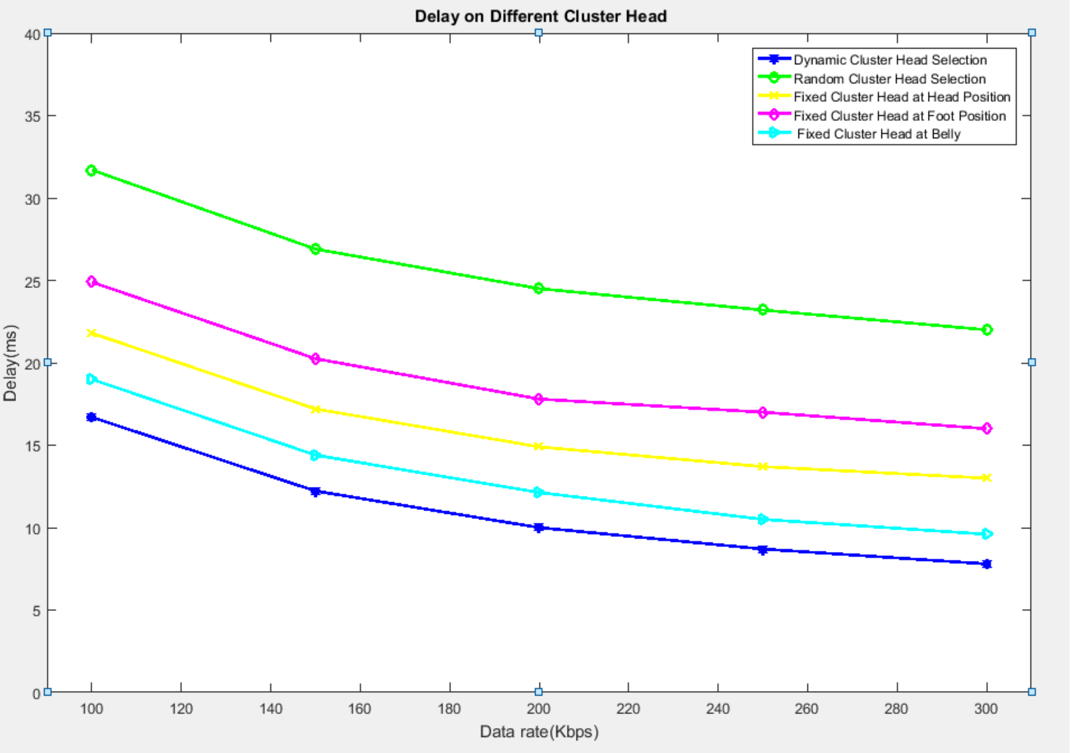

Figure 5.17: Effects of data rate on WBAN delay on Different Cluster Head

5.4.3 Network Throughput

Figure 5.18 shows throughput performance comparison between fixed cluster head at foot position, head position and at belly position, random cluster head selection scheme and the proposed dynamic cluster head selection scheme with priority for WBAN network. As depicted from results, higher throughput is achieved in proposed dynamic cluster head selection scheme. This is because the dynamic cluster head ensures that the sensor node with connections to the rest of sensor nodes in the WBAN assumes the cluster head hence the increased network throughput. The rest of fixed position or random cluster head selection method do not maximize on the number of nodes which are connected at a given time hence the reason for lower throughput.

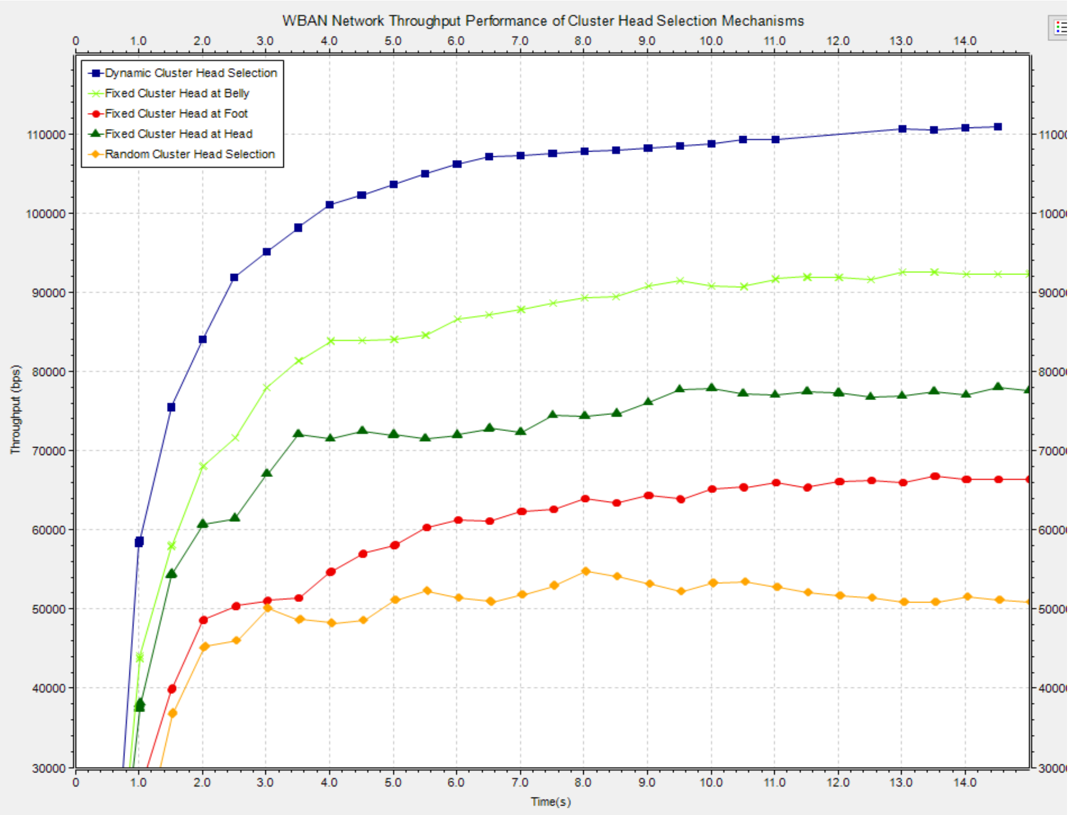

Figure 5.18. WBAN Network Throughput performance of the Different WBAN Cluster Head selection

5.4.4 Bandwidth Efficiency

Figure 5.19 presents bandwidth efficiency versus time comparison between fixed cluster head, random cluster head selection scheme and dynamic cluster head selection scheme with priority for WBAN. As seen from results, higher bandwidth efficiency is achieved in dynamic cluster head selection scheme with priority. The bandwidth efficiency is directly proportional to the throughput hence the reason for the directly proportional performance. As well bandwidth efficiency is inversely proportional to delay. The lower the network delay the higher the bandwidth efficiency as seen in the performance evaluation formulas discussed in section 5.2.1. The efficiency increases gradually till a steady state in which it normalizes due to maximum optimization of the WBAN. The Figure 5.20 presents the bandwidth efficiency as a function data rate. Bandwidth efficiency is inversely proportional to data rate. Dynamic cluster head selection scheme is most bandwidth efficient amongst all other cluster head selection schemes as shown in the Figure 5.20.

The bandwidth efficiency curves are very important to observe the saturation tendency for different times and data rates. The bandwidth efficiency is used to determine the spectral utilization of the 1EEE 802.15.6 CSMA/CA. It is the ratio of maximum throughput to the data rate.

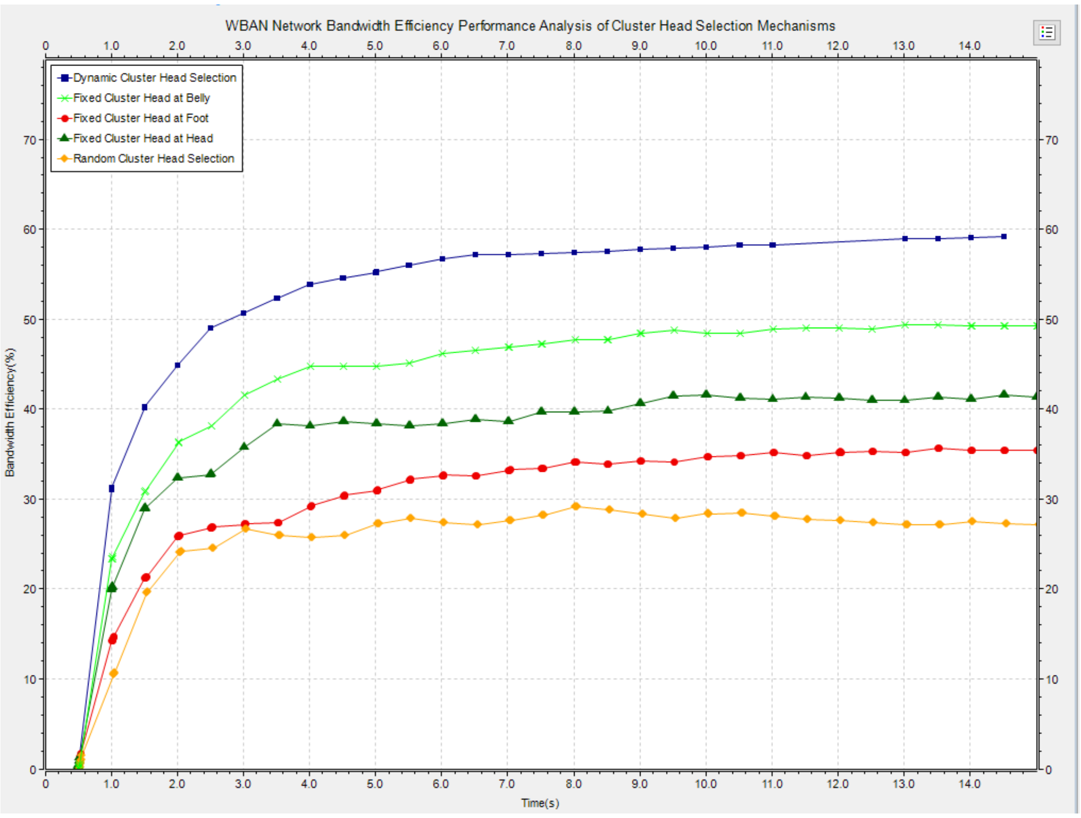

Figure 5.19. WBAN Network Bandwidth Efficiency on Different Cluster Head

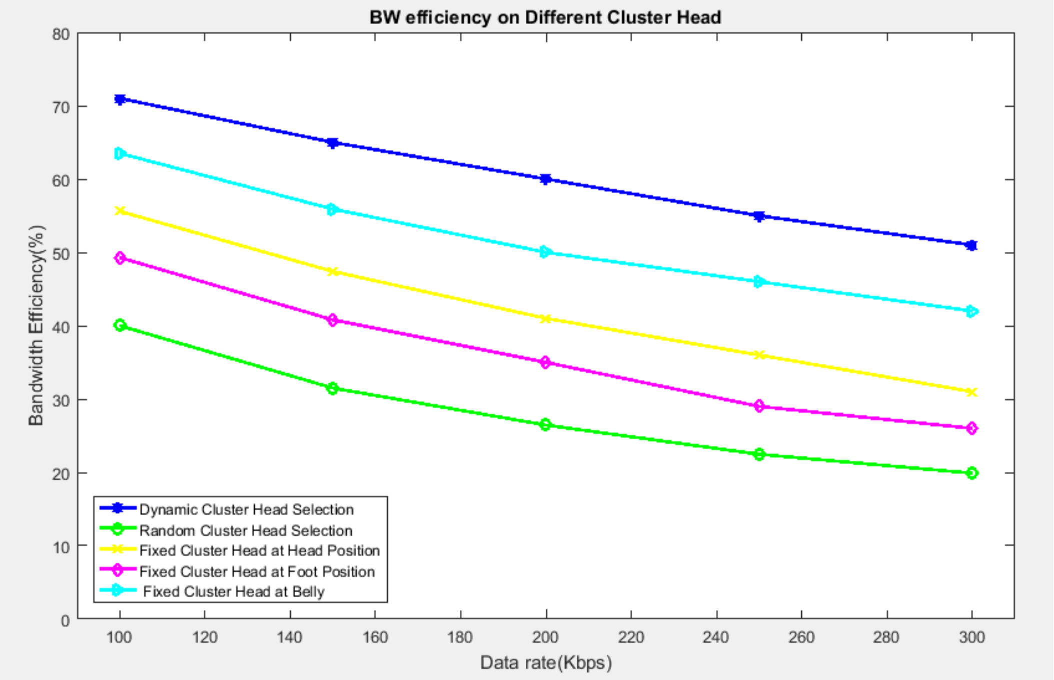

Figure 5.20. Effects of data rate on WBAN Bandwidth Efficiency on Different Cluster Head

5.5 Discussion of Results

In the first experiment in section 5.2, performance evaluation of the current IEEE 802.15.6 WBAN was carried out. It should be noted that the performance of WBAN is very crucial to achieve the intended purpose of the body area sensor networks which is critical and lifesaving Medicare eHealth monitoring. The application of these WBAN is very challenging in the environments which exhibit interference due to multi-WBAN with high mobility. The results have indicated that there is degradation of WBAN performance in respect to bandwidth efficiency, network throughput and delay as seen in Figures 5.1, 5.2 and 5.3 respectively. The results have shown that bandwidth efficiency decreases with increase in number of interfering WBAN, network throughput decreases with increase in WBAN while network delay decreases with increase in WBAN. This can be attributed to intra-WBAN, inter- WBAN and co-channel interference among the neighbour WBANs or sensor nodes as well as from other technologies operating in the same frequency band. In conclusion, there is a considerable effect on performance of WBAN due to increase in number of WBAN in a fixed environment.

The performance evaluation has shown that there is reduced performance of WBAN while the standard minimum throughput should be 10kbps with a maximum of 10Mbps while error rate should be less than 10% (meaning that the efficiency should be high) hence the need for improvement.

In the second simulation experiment in section 5.3 on the performance evaluation of the CSMA/CA with Contention Window and priority queues proposed approach, the results recorded significant improvement in bandwidth efficiency, network throughput and network delay in the proposed model in comparison to the current IEEE 802.15.6 model and the recent Energy-Efficient and Priority-Based Enhanced IEEE 802.15.6 CSMA/CA MAC Protocol model. This proves that the proposed model makes significant contribution to WBAN technology. As seen from the diagram, the lying down outperforms all the other postural positions. This can be attributed to minimal mobility in a lying down position. Walking registers the lowest performance of the postural modes due to expected increase in WBAN interference. On the comparison between the proposed and current model, the improvement in the proposed is significant on the performance metrics of WBAN bandwidth efficiency, network throughput and network delay, as shown in Figures 5.7 to 5.15. The bandwidth efficiency, improvement from an average 38% to 58% was achieved for 63 sensor nodes, 35% to 47% for 126 WBAN sensor nodes and 32% to 37% in 175 WBAN sensor node scenarios, as shown in Figures 5.7, 5.8 and 5.9 respectively. The network throughput improvement from 78Kbps to 110Kbps for 63 sensor nodes, 63Kbps to 83Kbps for 126 WBAN sensor nodes and from 58Kbps to 70Kbps for 175 sensor nodes WBAN scenario as shown in performance graphs 5.10, 5.11 and 5.12 respectively. This WBAN throughput reduces due to reduced packet collisions, reduced packet retransmisions and most importantly because of maintaining the maximum number of connections within a WBAN. This makes the applications that require high throughput such as ECG sensors achieve best performance. The network delay reduction was significant contribution as 63 sensor nodes WBAN scenario recording reduction of delay from average of 45ms to 37ms. The 126 sensor nodes scenario from average of 45ms to 34ms and from 51ms to 45ms for 175 WBAN scenario as shown in figures 5.13, 5.14 and 5.15 respectively. This performance trend also confirms the increased performance degradation with increase in interfering WBAN in mobility scenario. This performance is attributed to the point that CSMA/CA can lead improved WBAN performance because it aids in the WBAN to channel interference avoidance by minimising occurrences of packet collision in the transmission channel. The introduced idea of Contention Window (CW) technique and assigning the sensor nodes different priorities for channel access also improves the WBAN performance because the different nodes or traffic transmit at different time schedules hence minimising any probability of data collision and retransmission. The delay also comes as a result of congestion in the transmission channel as a result of different sensor nodes trying to access the channel at the same time. This leads to retransmissions and hence increased delay. As the a WBAN delay majorly comes as a result of congestion in the transmission channel due to different sensor nodes trying to access the channel at the same time. This leads to retransmissions and hence the increased delay. The reduction in delay means that the energy consumption is reduced as well.

We therefore conclude that CSMA/CA Contention Window (CW) technique with User Priority brings a positive contribution to the WBAN performance.

The third simulation experiment in section 5.4 focused on the performance evaluation of the proposed cluster head selection using link state. As the cluster head node has maximum number of connections available in dynamic cluster head selection scheme, it is easier for other nodes to access the cluster head, which results in better performance. Adding priority further enhances its performance. While in random cluster head selection scheme, destination node may or may not have enough number of connections to accommodate nodes, which results in more delay, more power consumption and lower throughput. From the results in Figures 5.16, 5.17, 5.18, 5.19 and 5.20 for network delay, throughput and bandwidth efficiency, the dynamic cluster head selection scheme shows significant improvement in results as compared to all other mechanisms with random cluster head selection schemes performing the worst. The network delay showed dynamic cluster head perform at average of 15ms compared to others performing at high delays with random cluster head at head position performing worst at average of 35ms. The network throughput for dynamic head selection performed the best at average of 110kbps while the random cluster head at head position performing worst at average of 50kbps. In the bandwidth efficiency, the dynamic cluster head performed at average of 60% while the least performing random cluster head selection at foot performed at average of 29%. This can be attributed to the reason that the randomly selected cluster head is not easily accessible as compared to the fixed cluster heads for current posture. Another important thing which is depicted from these results is that dynamic cluster head selection scheme with priority show steady behaviour after first few seconds, because at that time, network has adopted a cluster head, which gives ultimate performance. This behaviour is lacking in random cluster head selection scheme. The network delay, throughput and bandwidth efficiency performances are directly proportional to each other as they are all interrelated.

CHAPTER SIX

CONCLUSION AND FUTURE WORK

6.1 Conclusion

The WBAN effectiveness is very important in the adaptation and success of remote medical monitoring for ubiquitous and affordable healthcare. The standard minimum performance throughput is indicated to be 10kbps with a maximum of 10Mbps while error rate should be less than 10% (meaning that the efficiency should be high) hence the need for continuous improvement of the WBAN technologies performance especially in high WBAN interference operating environments. Basing on the results from the different mobility scenarios, the new HIMM model outperformed the existing IEEE 802.15.6 based WBAN technology in the reference areas of network delay, bandwidth efficiency and network throughput.

The inappropriate cluster head scheme is one of the major factors of data loss in WBAN and the dynamic cluster head selection scheme presented in this research is based upon dynamic cluster head selection using link state technology which helps in reduction of network delay, mean power consumption and increasing network throughput. In this scheme, cluster head for data packet is adaptive to the variation in number of connections that each node holds. The number of connections for every node is present in link state table. This means that the WBAN always has the most possible connections at any given time hence improved performance and reliability.

Therefore, we conclude that a hybrid WBAN interference mitigation model (HIMM Model) consisting of both the CSMA/CA contention window (CW) with user priority (UP) as well as dynamic cluster head selection interference mitigation approaches leads to significant contribution to the performance of WBAN technology as it outperforms the current IEEE 802.15.6 based CSMA/CA technology in all major aspects of performance.

6.2 How the Research Objectives have been achieved

As discussed in chapter one, the general objective of this thesis was to develop an interference mitigation mechanism that seeks to ensure effective and reliable communication within and between multiple WBANs.

In specific, the first objective was to determine the effects of increased mobility, WBANs density and interfering networks to WBAN. This objective was achieved through simulation study on the performance evaluation of the current WBAN as presented in section 5.2. The simulation detailed how increase in WBAN from one (1) to nine (9) to eighteen (18) and to twenty-five (25) affected the performance of WBAN while simulating mobility scenario of WBAN using MoBAN mobility model. The results affirmed or ascertained our notion that high mobility and increase in WBAN interference degrades WBAN performance.

In the second objective of the study on analysis and identification of collaborative approaches or mechanisms can be applied to the IEEE 802.15.6 WBAN to achieve interference mitigation, this was approached through the two new mechanisms presented, namely CSMA/CA with Contention Window and User Priority approach and the Cluster Head selection based on Link State table model. These two approaches formed the now new HIMM Model presented in this research. The HIMM abbreviating "Hybrid Interference Mitigation Model" which was then presented in objective three and discussed in chapter four.

The third objective was to develop or design a HIMM WBAN hybrid model and then in objective four evaluate it in relation the current model. The HIMM hybrid model was developed as discussed in chapter three and four where the new model methodology is clearly outlined and designed. The modeling and simulation notations and parameters for the new HIMM model are also presented. Chapter four detailed the two approaches and how they contribute to the HIMM model. The two mechanisms CSMA/CA with Contention Window and User Priority approach and the Cluster Head selection based on Link State approach are then evaluated as detailed in chapter five with their results showing significant WBAN technology achievement in the HIMM model.

6.3 Research Contribution

The thesis proposes an improved wireless body area network (WBAN) interference mitigation model of mechanisms which aids in the improved performance reliability of the wireless body area networks. Through the literature review in chapter two, various state of the art existing mechanisms was presented, including the base IEEE 802.15.6 WBAN standard. A summary of these mechanisms was presented highlighting the research gap which formed the basis of this research work.

Firstly, the performance of wireless body area network under multi-WBAN and wireless body area network mobility scenarios was investigated. The results confirmed degraded WBAN performance in bandwidth efficiency, network throughput and network delay.

Secondly, a new model, namely, a hybrid wireless body area network interference mitigation model (abbreviated as HIMM Model) was presented in the fourth chapter. The new model was based on two approaches; the collaborative approach carrier sense multiple access with collision avoidance (CSMA/CA) with Contention Window (CW) with User Priority (UP) and a dynamic cluster head selection (DCHS) based on Link-state (LS) approach. The CSMA/CA based strategy was adopted to address the WBAN coexistence as CSMA/CA is an access method in which a network contention protocol listens to a transmission channel where there are many nodes competing for channel access while the Contention Window and user priorities (UP) mappings was adopted to address the traffic management and prioritization problem to differentiate critical traffic from ordinary or non-critical traffic. The advantages of the adopting this method was discussed. The dynamic cluster head selection based on Link-state approach was adopted to increase the reliability of the WBAN by ensuring that the WBAN has the maximum number of connection to the nodes as much as possible at every one time. The performance evaluation of the hybrid model confirmed that the new model outperformed the existing the base IEEE 802.15.6 WBAN model. This new hybrid model (HIMM Model) is the main contribution of this research and an addition in the body of knowledge on wireless body area sensor networks.

6.4 Research Limitations

Like any other research work, this research had some limitations as it is impossible to factor every aspect at once.

Firstly, this research covered only interference mitigation schemes for IEEE 802.15.6 WBANs technology in medical application scenario.

Secondly, it considered mobility and high WBAN density environment. It did not consider static scenarios and less density scenarios which have already been considered by previous research work.

Thirdly, the research was specific to narrow band frequency band. It did not consider interference in MICS, WMTS and UWB licensed frequency bands for the different specific countries.

Lastly, the research did not cover in-body WBANs. In-body WBANs have challenges which are specific to the nature of their use. Instead the research concentrates on on-body WBANs.

6.5 Future Research

In this thesis, we looked at the WBAN interference mitigation in high mobility and dense or Multi-WBAN scenarios in WBAN. Although this research has contributed to the WBAN research by increasing its adoptability and reliability, a lot of issues and challenges still exist. Firstly, this research majored on the on-body wireless body area networks. Although this scenario depicts the real-life scenario, the future work on the effects of body fluids and WBAN would be important to consider for the probability of sensor nodes embedded in-body occurrence. This is because the in-body wireless body area networks sensor nodes and their effects on the human body conditions cannot be entirely ignored.

Secondly, monitoring and evaluating of humans, especially the elderly is a not a simple task because of the complexity as a result of their daily activities. Some of the human activities in real life scenarios are so vigorous and undermines the performance of the wireless body sensor networks, making them less effective. Simulation experiments simulate a regular pattern which may not be a 100% ideal scenario in some human scenarios. In future, such ranging scenarios would be good to consider.

Thirdly, this research did not address the known wireless body sensor open issue of power consumption or energy saving. Power saving is a critical requirement of wireless body area networks and a continous research is needed to advance this requirement. This research would greatly improve the proposed HIMM model in this research. This would be an important improvement of the new model.

Fourthly, the security of the healthcare systems, including the monitoring system is critical and may involve the different components of the wireless body area sensor networks such as the sensors themselves, data collection process, and the communication and transmission of that sensor data. This is an important aspect which calls for continuous research initiatives. Further, mobility nature of the wireless body area networks is a challenge in reference to security.

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APPENDICES

Appendix I: Performance Evaluation of Current WBAN Model

(i) The Omnet ini File configuration

```
cmdenv-config-name = perftest
cmdenv-express-mode = true
network = CSMAMacExampleNetwork
**.vector-recording = true
**.scalar-recording = true

##################################################################
#                      Simulation parameters                     #
##################################################################
record-eventlog = false
tkenv-default-config =
*.**.coreDebug = false
*.playgroundSizeX = 3000m
*.playgroundSizeY = 3500m
*.playgroundSizeZ = 800m
**.constraintAreaMinX = 0m
**.constraintAreaMinY = 0m
**.constraintAreaMinZ = 0m
**.constraintAreaMaxX = 600m
**.constraintAreaMaxY = 400m
**.constraintAreaMaxZ = 300m

*.numHosts = 250

##################################################################
#                         channel parameters                     #
##################################################################
*.connectionManager.sendDirect = true
*.connectionManager.pMax = 100mW
*.connectionManager.sat = -90dBm
*.connectionManager.alpha = 3
*.connectionManager.carrierFrequency = 2.412e+9Hz

##################################################################
#          Host specific parameters                              #
##################################################################
*.node[*].nic.connectionManagerName = "connectionManager"

################# PhyLayer parameters ######################
```

```
*.node[*].nic.phy.usePropagationDelay = false
*.node[*].nic.phy.thermalNoise = -100dBm
*.node[*].nic.phy.useThermalNoise = true

*.node[*].nic.phy.analogueModels = xmldoc("config.xml")
*.node[*].nic.phy.decider = xmldoc("config.xml")

*.node[*].nic.phy.timeRXToTX = 0.00021s
*.node[*].nic.phy.timeRXToSleep = 0.000031s

*.node[*].nic.phy.timeTXToRX = 0.00012s
*.node[*].nic.phy.timeTXToSleep = 0.000032s

*.node[*].nic.phy.timeSleepToRX = 0.000102s
*.node[*].nic.phy.timeSleepToTX = 0.000203s

*.node[*].nic.phy.sensitivity = -87dBm
*.node[*].nic.phy.maxTXPower = 100.0mW

################ MAC layer parameters ####################

*.node[*].nic.mac.queueLength = 5
*.node[*].nic.mac.headerLength = 56bit
**.node[*].nic.mac.useMACAcks = true
*.node[*].nic.mac.slotDuration = 0.00035s
*.node[*].nic.mac.difs = 0.0005s
*.node[*].nic.mac.maxTxAttempts = 5
*.node[*].nic.mac.defaultChannel = 0
*.node[*].nic.mac.bitrate =187500bps
*.node[*].nic.mac.txPower = 1mW  # [mW]
*.node[*].nic.mac.x=3000

################ Battery Module parameters ####################

**.battery.nominal = 1000mAh
**.battery.capacity = 1000mAh
**.battery.voltage = 3.3V
**.battery.resolution = 0.1s
**.battery.publishDelta = 1
**.battery.publishTime = 0s
**.battery.numDevices = 1
**.nic.sleepCurrent = 0.02mA
**.nic.rxCurrent = 16.4mA
**.nic.decodingCurrentDelta = 0mA
**.nic.txCurrent = 17mA
**.nic.setupRxCurrent = 8.2mA
```

```
**.nic.setupTxCurrent = 8.2mA
**.nic.rxTxCurrent = 17mA
**.nic.txRxCurrent = 17mA

################ NETWORK layer Parameters ########################

*.node[*].netwl.isSwitch = false
*.node[*].netwl.maxTtl = 3
*.node[*].netwl.boredTime = 0.5

################ Mobility Parameters ###############################

**.coordinator[*].useMobilityPattern = yes
**.coordinator[*].mobilityPatternFile = ""
**.mobilityType = "MoBANLocal"

**.mobility.updateInterval = 0.5 s

############################### NETWORK IP #######################

*.node[0].netwl.ip = 0
*.node[1].netwl.ip = 1
*.node[2].netwl.ip = 2
*.node[3].netwl.ip = 3
*.node[4].netwl.ip = 4
*.node[5].netwl.ip = 5
*.node[6].netwl.ip = 6
*.node[7].netwl.ip = 7
          .
          .
          .
          .
          .
          .
*.node[175].netwl.ip = 175

*.node[*].netwl.ip = 0
*.node[*].nic.id = 0

###################### 01 BAN #################################

[Config H1]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=1
description = "Single Human "
*.node[*].nic.mac.slotDuration = 0.0002s
```

```
**.coordinator[0].postureSpecFile = xmldoc("postures3.xml")
**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.node[*].mobility.coordinatorIndex = 0
*.numHosts = 7
**.numMoBAN = 1
sim-time-limit = 5000s

########################## 09 BAN #############################

[Config H9]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=9
description = "Nine Human "
*.node[*].nic.mac.slotDuration = 0.0002s

**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0

**.node[7].mobility.coordinatorIndex = 1
**.node[8].mobility.coordinatorIndex = 1
**.node[9].mobility.coordinatorIndex = 1
**.node[10].mobility.coordinatorIndex = 1
**.node[11].mobility.coordinatorIndex = 1
**.node[12].mobility.coordinatorIndex = 1
**.node[13].mobility.coordinatorIndex = 1

                .
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**.node[56].mobility.coordinatorIndex = 8
**.node[57].mobility.coordinatorIndex = 8
**.node[58].mobility.coordinatorIndex = 8
**.node[59].mobility.coordinatorIndex = 8
```

```
**.node[60].mobility.coordinatorIndex = 8
**.node[61].mobility.coordinatorIndex = 8
**.node[62].mobility.coordinatorIndex = 8

*.numHosts = 63
**.numMoBAN = 9
*.node[*].nic.mac.contentionWindow = 16
sim-time-limit = 5000s

############################## 18 BAN ##############################

[Config H18]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=18
description = "Eighteen Human "
*.node[*].nic.mac.slotDuration = 0.0002s

**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0

**.node[7].mobility.coordinatorIndex = 1
**.node[8].mobility.coordinatorIndex = 1
**.node[9].mobility.coordinatorIndex = 1
**.node[10].mobility.coordinatorIndex = 1
**.node[11].mobility.coordinatorIndex = 1
**.node[12].mobility.coordinatorIndex = 1
**.node[13].mobility.coordinatorIndex = 1

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**.node[119].mobility.coordinatorIndex = 17
**.node[120].mobility.coordinatorIndex = 17
**.node[121].mobility.coordinatorIndex = 17
```

```
**.node[122].mobility.coordinatorIndex = 17
**.node[123].mobility.coordinatorIndex = 17
**.node[124].mobility.coordinatorIndex = 17
**.node[125].mobility.coordinatorIndex = 17

*.numHosts = 126
**.numMoBAN = 18
sim-time-limit = 5000s

############################## 25 BAN ##############################

[Config H25]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=25
description = "twenty-five Human "
*.node[*].nic.mac.slotDuration = 0.0002s
**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0

**.node[7].mobility.coordinatorIndex = 1
**.node[8].mobility.coordinatorIndex = 1
**.node[9].mobility.coordinatorIndex = 1
**.node[10].mobility.coordinatorIndex = 1
**.node[11].mobility.coordinatorIndex = 1
**.node[12].mobility.coordinatorIndex = 1
**.node[13].mobility.coordinatorIndex = 1

               .
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**.node[168].mobility.coordinatorIndex = 24
**.node[169].mobility.coordinatorIndex = 24
**.node[170].mobility.coordinatorIndex = 24
**.node[171].mobility.coordinatorIndex = 24
```

```
**.node[172].mobility.coordinatorIndex = 24
**.node[173].mobility.coordinatorIndex = 24
**.node[174].mobility.coordinatorIndex = 24

*.numHosts = 175
**.numMoBAN = 25
sim-time-limit = 5000s
```

(ii) CSMA Mac Layer

```
#include "./CSMAMacLayer.h"

#include "FWMath.h"
#include "BaseConnectionManager.h"
#include "MacToPhyInterface.h"
#include "MacPkt_m.h"
#include "PhyUtils.h"

Define_Module( CSMAMacLayer )

/**
 * Initialize the of the omnetpp.ini variables in stage 1. In stage
 * two subscribe to the RadioState.
 */
void CSMAMacLayer::initialize(int stage)
{
   BaseMacLayer::initialize(stage);

   if (stage == 0) {

queueLength = hasPar("queueLength")     ? par("queueLength").longValue()     : 10;
slotDuration = hasPar("slotDuration")   ? par("slotDuration").doubleValue()  :
0.00035;
difs = hasPar("difs")                   ? par("difs").doubleValue()          : 0.0005;
maxTxAttempts = hasPar("maxTxAttempts") ? par("maxTxAttempts").longValue()
: 7;
bitrate = hasPar("bitrate")             ? par("bitrate").doubleValue()       : 187500;
txPower = hasPar("txPower")             ? par("txPower").doubleValue()       : 1;
initialCW = hasPar("contentionWindow")  ? par("contentionWindow").longValue():
16;

        /////////////////////////// vector////////
delay1 = registerSignal("delay1");
mthroughput1 = registerSignal("mthroughput1");
bwefficiency1 =registerSignal("bwefficiency1");
```

```
        ///////////////edit/////////////////
MHR =hasPar("Mheader")                ? par("Mheader").doubleValue() :56;
FTR = hasPar("Mfooter")              ? par("Mfooter").doubleValue() :16;
Rs = hasPar("sbrate")               ? par("sbrate").doubleValue()  :187500;
Rhdr = hasPar("phrate")               ? par("phrate").doubleValue()  :57500;
Tsifs = hasPar("tsifs")             ? par("Tsifs").doubleValue(): .00005;
Tmifs = hasPar("Tmifs")                ? par("Tmifs").doubleValue(): .00002;
pdelay = hasPar("pdelay")               ? par("pdelay").doubleValue(): .00000002;
x = hasPar("x")                        ? par("x").doubleValue(): 2000;

/////payload size

n = hasPar("n")                  ? par("n").doubleValue(): 1;
numMoBAN= hasPar("numMoBAN")          ? par("numMoBAN").doubleValue():
1;
numHosts = hasPar("numHosts")        ? par("numHosts").doubleValue(): 21;
CWmin = hasPar("minimumcontentionWindow") ?
par("minimumcontentionWindow").longValue(): 16;
CWmax = hasPar("maximumcontentionWindow") ?
par("maximumcontentionWindow").longValue(): 32;

backofcount = hasPar("backofcount")                 ?
par("backofcout").doubleValue(): 4;

        Pc = hasPar("Pz")                 ? par("Pz").doubleValue(): 3;
        Ptr = hasPar("Pt")                ? par("Pt").doubleValue(): 1.5;
        Prt = hasPar("Pr")                ? par("Pr").doubleValue(): 1.5;  /// mw
        Pidle = hasPar("Pidle")              ? par("Pidle").doubleValue(): 0.05;
        Ttr = hasPar("Ttr")                ? par("Ttr").doubleValue(): 0.00012; ///// s
        Trt = hasPar("Trt")                ? par("Trt").doubleValue(): 0.00021;
        T = hasPar("T")                 ? par("T").doubleValue(): 30;

        macState = RX;

       lastDataPktDestAddr = LAddress::L2BROADCAST;
       lastDataPktSrcAddr  = LAddress::L2BROADCAST;

        // initialize the timer
        backoffTimer = new cMessage("backoff");
        minorMsg = new cMessage("minClear");

        ////
       send_ack = new cMessage("send_ack");

        /////
```

```
    delayVec.setName("delay");
    bwefficiencyVec.setName("bwefficiency");
    mthroughputVec.setName("mthroughput");

    ///////// preamble time //////
    Tp = (0);

    //////// phy header time /////
    Tphy = (0);

    /////// slot length time /////
    Ts = (0);

    ////// CCA time //////
    Tcca = (0);

    /////// arg back off time ////

    argbftime = (0);
    ////// transimisin time of data ////
    Tdata = (0);

    ///// immediate ack time //////
    Tiack = (0);

    //// block ack time /////
    Tback = (0);

    //// minimum delay /////
    delay = 0;

    /// BW efficiency /////
    bwefficiency = 0;

    /// maximum throughput ////
    mthroughput = 0;

  }
  else if(stage == 1) {
    BaseConnectionManager* cc = getConnectionManager();

    if(cc->hasPar("pMax") && txPower > cc->par("pMax").doubleValue())
      opp_error("TranmitterPower can't be bigger than pMax in
ConnectionManager! "
           "Please adjust your omnetpp.ini file accordingly.");

    if(phy->getRadioState() != MiximRadio::RX) {
```

```
        opp_error("Initial radio state isn't RX but CSMAMacLayer"
                " assumes that the NIC starts in RX state.");
      }

      debugEV << "queueLength = " << queueLength
        //<< " busyRSSI = " << busyRSSI
        << " slotDuration = " << slotDuration
        << " difs = " << difs
        << " maxTxAttempts = " << maxTxAttempts
        << " bitrate = " << bitrate
        << " contentionWindow = " << initialCW << endl;

  }
}

CSMAMacLayer::~CSMAMacLayer() {
  cancelAndDelete(backoffTimer);
  cancelAndDelete(minorMsg);

  //////////// edit///////

  cancelAndDelete(send_ack);

  for(MacQueue::iterator it = macQueue.begin();
     it != macQueue.end(); ++it)
  {
     delete (*it);
  }
  macQueue.clear();
}

void CSMAMacLayer::finish() {

  recordScalar("mthroughput", mthroughput);
  recordScalar("delay", delay);
  recordScalar("bwefficiency", bwefficiency);


  BaseMacLayer::finish();
}

void CSMAMacLayer::throughputcal()
{

 CSMAMacLayer::payloadsize();
  Tp=90/Rs;
```

```
  Tphy=31/Rhdr;

  Tcca=63/Rs;

  Ts=Tcca+0.00002;

  double slots = intrand(initialCW + txAttempts) + 1.0 + dblrand();
  double time = (slots * slotDuration);

  //calc signal duration

  argbftime=(initialCW*time)/2;

  Tdata=Tp+Tphy+((((MHR+FTR)*n)+x)/bitrate);

  Tiack=Tp+Tphy+(((MHR+FTR)*n)/bitrate);

  ////////// minimum delay///////////////

  delay= argbftime+Tdata+Tiack+(2*Tsifs)+(2*pdelay);

  ///////////maximum throughput///////
  mthroughput = x/delay;

  /////// BW efficiency//////
  bwefficiency = (mthroughput/bitrate)*100;

}

void CSMAMacLayer::handleUpperMsg(cMessage *msg)
{
  cPacket* pkt = static_cast<cPacket*>(msg);

  delayVec.record(delay);
  bwefficiencyVec.record(bwefficiency);
  mthroughputVec.record(mthroughput);

  if (macQueue.size() <= queueLength)
  {
    macQueue.push_back(pkt);
    debugEV     << "packet putt in queue\n queue size:" << macQueue.size() << " macState:" << macState
        << " (RX=" << RX << ") is scheduled:" << backoffTimer->isScheduled() << endl;;
    if((macQueue.size() == 1) && (macState == RX) && !backoffTimer->isScheduled()) {
        scheduleBackoff();
```

```
        }
    }
    else {
        // queue is full, message has to be deleted
        EV << "New packet arrived, but queue is FULL, so new packet is deleted\n";
        macpkt_ptr_t mac = encapsMsg(pkt);
        mac->setName("MAC ERROR");
        mac->setKind(PACKET_DROPPED);

        CSMAMacLayer::counter();

        sendControlUp(mac);

    }
}

/**
 * Send one short preamble packet immediately.
 */

void CSMAMacLayer::sendMacAck()
{
        macpkt_ptr_t ack = new MacPkt();

        ack->setSrcAddr(myMacAddr);
        ack->setDestAddr(lastDataPktSrcAddr);
        ack->setKind(MAC_ACK);
        ack->setBitLength(headerLength);

        attachSignal(ack);

       sendControlDown(ack);

       nbTxAcks++;
    //endSimulation();
}

void CSMAMacLayer::sendMacAck1()
{
        macpkt_ptr_t ack = new MacPkt();

        ack->setSrcAddr(myMacAddr);
        ack->setDestAddr(lastDataPktSrcAddr);
        ack->setKind(MAC_ACK);
        ack->setBitLength(headerLength);

        attachSignal(ack);
```

```
      sendControlDown(ack);
      nbTxAcks++;
    //endSimulation();

}

void CSMAMacLayer::attachSignal(macpkt_ptr_t macPkt)
{
    //calc signal duration
    simtime_t duration = macPkt->getBitLength() / bitrate;

    //create and initialize control info with new signal
    setDownControlInfo(macPkt, createSignal(simTime(), duration, txPower,
bitrate));
}

/**
 * After the timer expires try to retransmit the message by calling
 * handleUpperMsg again.
 */

void CSMAMacLayer::handleSelfMsg(cMessage *msg)
{

    if (msg == backoffTimer) {
        debugEV << "backoffTimer ";

        if(macState == RX) {
            debugEV << " RX ";

            if(macQueue.size() != 0) {
                macState = CCA;

                if(phy->getRadioState() == MiximRadio::RX) {

                    if(phy->getChannelState().isIdle()) {
                        debugEV << " idle ";
                        scheduleAt(simTime()+difs, minorMsg);
                    }
                    else {
                        macState = RX;
                        debugEV << " busy ";
                        scheduleBackoff();
                    }
                }
            }
        }
```

```
        else {
            debugEV << "" << endl;
            debugEV << "state=" << macState << "(TX="<<TX<<",
CCA="<<CCA<<")\n";
            error("backoffTimer expired, MAC in wrong state");
        }
    }

    if (msg==minorMsg)
    {
        debugEV << " minorMsg ";

        //TODO: replace with channel sense request
        if((macState == CCA) && (phy->getRadioState() == MiximRadio::RX)) {

            if(phy->getChannelState().isIdle()) {
                debugEV << " idle -> to send ";
                macState = TX;
                phy->setRadioState(MiximRadio::TX);
            }
            else {
                debugEV << " busy -> backoff ";
                macState = RX;
                if(!backoffTimer->isScheduled())
                    scheduleBackoff();
            }
        }
        else {
            error("minClearTimer fired -- channel or mac in wrong state");
        }
    }

    debugEV << endl;
}


/**
 * Compare the address of this Host with the destination address in
 * frame. If they are equal or the frame is broadcast, we send this
 * frame to the upper layer. If not delete it.
 */

void CSMAMacLayer::handleLowerMsg(cMessage *msg)
{
    macpkt_ptr_t            mac  = static_cast<macpkt_ptr_t>(msg);
    const LAddress::L2Type& dest = mac->getDestAddr();
```

```
  if(dest == myMacAddr || LAddress::isL2Broadcast(dest))
  {
    debugEV << "sending pkt to upper...\n";
    sendUp(decapsMsg(mac));

   CSMAMacLayer::sendMacAck();
    CSMAMacLayer::throughputcal();
    emit(delay1, delay);
    emit(mthroughput1,mthroughput);
    emit(bwefficiency1,bwefficiency);

    if(mac->getKind()==MAC_ACK)
     nbRxAck++;
  }
  else {
    debugEV << "packet not for me, deleting...\n";
    delete mac;
  }
  if(!backoffTimer->isScheduled()) scheduleBackoff();

}

void CSMAMacLayer::handleLowerControl(cMessage *msg)
{
  if(msg->getKind() == MacToPhyInterface::TX_OVER) {
    debugEV << " transmission over" << endl;
    macState = RX;
    phy->setRadioState(MiximRadio::RX);
    txAttempts = 0;
    if(!backoffTimer->isScheduled()) scheduleBackoff();
  }
  else if(msg->getKind() == MacToPhyInterface::RADIO_SWITCHING_OVER) {
    if((macState == TX) && (phy->getRadioState() == MiximRadio::TX)) {
      debugEV << " radio switched to tx, sendDown packet" << endl;
      nbTxFrames++;


      sendDown(encapsMsg(macQueue.front()));
      macQueue.pop_front();
    }
  }
  else {
    EV << "control message with wrong kind -- deleting\n";
  }
  delete msg;
}
```

```
void CSMAMacLayer::scheduleBackoff()
{
  if(backoffTimer->isScheduled()) {
    std::cerr << " is scheduled: MAC state "
          << macState << " radio state : " << phy->getRadioState() << endl;
  }

  if(minorMsg->isScheduled()){
    cancelEvent( minorMsg );
    macState=RX;
  }


  if(txAttempts > maxTxAttempts) {
    debugEV << " drop packet " << endl;

    cMessage *mac = encapsMsg(macQueue.front());
    mac->setName("MAC ERROR");
    mac->setKind(PACKET_DROPPED);
    txAttempts = 0;


    //////// edit/////

    CSMAMacLayer::counter();

    macQueue.pop_front();
    sendControlUp(mac);

  }

  if(macQueue.size() != 0) {
    debugEV << " schedule backoff " << endl;

    double slots = intrand(initialCW + txAttempts) + 1.0 + dblrand();
    double time = slots * slotDuration;



    txAttempts++;
    debugEV << " attempts so far: " << txAttempts  << " " << endl;



    nbBackoffs = nbBackoffs + 1;
    backoffValues = backoffValues + time;
```

```
    scheduleAt(simTime() + time, backoffTimer);
  }

}

void CSMAMacLayer::counter()
{
  count++;
  if((count/2)!=0){
    initialCW=initialCW;
  }

  else{
    initialCW=2*initialCW;

  }

}


void CSMAMacLayer::backofcounter()
{
  backofcount--;
  if(backofcount==0)
  {
    CSMAMacLayer::handleSelfMsg(backoffTimer);
  }
  else
  {

    CSMAMacLayer::handleUpperMsg(backoffTimer);
    backofcount--;
  }
}


void CSMAMacLayer::payloadsize()
{

    x =x;

}


CSMAMacLayer::macpkt_ptr_t CSMAMacLayer::encapsMsg(cPacket *pkt)
```

```
{
   macpkt_ptr_t macPkt = BaseMacLayer::encapsMsg(pkt);

   //calc signal duration
   simtime_t duration = macPkt->getBitLength() / bitrate;

   if(duration > slotDuration) {
      EV << "Warning: Sending packet " << pkt
         << " - duration (" << duration
         << " ) is bigger than the slot duration (" << slotDuration
         <<")." << endl;
   }

   counter();
   //create signal
   setDownControlInfo(macPkt, createSignal(simTime(), duration, txPower,
bitrate));

   return macPkt;

}
```

Appendix II: CSMA/CA Contention Window with User Priority Approach

(i) The Omnet ini File configuration

```
[General]
cmdenv-config-name = perftest
cmdenv-express-mode = true
network = CSMAMacExampleNetwork
**.vector-recording = true
**.scalar-recording = true

##########################################################
#                    Simulation parameters                    #
##########################################################

record-eventlog = false
tkenv-default-config =
*.**.coreDebug = false
*.playgroundSizeX = 3000m
*.playgroundSizeY = 3500m
*.playgroundSizeZ = 800m
**.constraintAreaMinX = 0m
**.constraintAreaMinY = 0m
**.constraintAreaMinZ = 0m
**.constraintAreaMaxX = 600m
**.constraintAreaMaxY = 400m
**.constraintAreaMaxZ = 300m

*.numHosts = 250

#################### channel parameters ##################
*.connectionManager.sendDirect = true
*.connectionManager.pMax = 100mW
*.connectionManager.sat = -90dBm
*.connectionManager.alpha = 3
*.connectionManager.carrierFrequency = 2.412e+9Hz


################ PhyLayer parameters #####################

*.node[*].nic.phy.usePropagationDelay = false
*.node[*].nic.phy.thermalNoise = -100dBm
*.node[*].nic.phy.useThermalNoise = true

*.node[*].nic.phy.analogueModels = xmldoc("config.xml")
*.node[*].nic.phy.decider = xmldoc("config.xml")
```

```
*.node[*].nic.phy.timeRXToTX = 0.00021s
*.node[*].nic.phy.timeRXToSleep = 0.000031s

*.node[*].nic.phy.timeTXToRX = 0.00012s
*.node[*].nic.phy.timeTXToSleep = 0.000032s

*.node[*].nic.phy.timeSleepToRX = 0.000102s
*.node[*].nic.phy.timeSleepToTX = 0.000203s

*.node[*].nic.phy.sensitivity = -87dBm
*.node[*].nic.phy.maxTXPower = 100.0mW

################ MAC layer parameters ####################

*.node[*].nic.mac.queueLength = 5
*.node[*].nic.mac.headerLength = 56bit
**.node[*].nic.mac.useMACAcks = true
*.node[*].nic.mac.slotDuration = 0.00035s
*.node[*].nic.mac.difs = 0.0005s
*.node[*].nic.mac.maxTxAttempts = 5
*.node[*].nic.mac.defaultChannel = 0
*.node[*].nic.mac.bitrate =187500bps

*.node[*].nic.mac.txPower = 1mW  # [mW]
*.node[*].nic.mac.x=3000

################ Battery Module parameters ####################

**.battery.nominal = 1000mAh
**.battery.capacity = 1000mAh
**.battery.voltage = 3.3V
**.battery.resolution = 0.1s
**.battery.publishDelta = 1
**.battery.publishTime = 0s
**.battery.numDevices = 1
**.nic.sleepCurrent = 0.02mA
**.nic.rxCurrent = 16.4mA
**.nic.decodingCurrentDelta = 0mA
**.nic.txCurrent = 17mA
**.nic.setupRxCurrent = 8.2mA
**.nic.setupTxCurrent = 8.2mA
**.nic.rxTxCurrent = 17mA
**.nic.txRxCurrent = 17mA

################ NETW layer parameters ####################

*.node[*].netwl.isSwitch = false
```

```
*.node[*].netwl.maxTtl = 3
*.node[*].netwl.boredTime = 0.5

################ Mobility parameters #####################
**.coordinator[*].useMobilityPattern = false
**.coordinator[*].mobilityPatternFile = ""
**.mobilityType = "MoBANLocal"

**.mobility.updateInterval = 0.5 s

########################## NETWORK IP #########################

*.node[0].netwl.ip = 0
*.node[1].netwl.ip = 1
*.node[2].netwl.ip = 2
*.node[3].netwl.ip = 3
*.node[4].netwl.ip = 4
*.node[5].netwl.ip = 5
*.node[6].netwl.ip = 6
*.node[7].netwl.ip = 7
*.node[8].netwl.ip = 8
*.node[9].netwl.ip = 9
                    .
                    .
                    .
                    .
.*.node[175].netwl.ip = 175

*.node[*].netwl.ip = 0
*.node[*].nic.id = 0

######################### 01 BAN ###############################

[Config H1]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=1
description = "Single Human "
*.node[*].nic.mac.slotDuration = 0.0002s
**.coordinator[0].postureSpecFile = xmldoc("postures3.xml")
**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.node[*].mobility.coordinatorIndex = 0
*.numHosts = 7
**.numMoBAN = 1
sim-time-limit = 5000s

######################### 09 BAN #################################
```

```
[Config H9]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=9
description = "Nine Human "
*.node[*].nic.mac.slotDuration = 0.0002s

**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0


                    .
                    .
                    .
                    .
                    .
**.node[56].mobility.coordinatorIndex = 8
**.node[57].mobility.coordinatorIndex = 8
**.node[58].mobility.coordinatorIndex = 8
**.node[59].mobility.coordinatorIndex = 8
**.node[60].mobility.coordinatorIndex = 8
**.node[61].mobility.coordinatorIndex = 8
**.node[62].mobility.coordinatorIndex = 8

*.numHosts = 63
**.numMoBAN = 9
sim-time-limit = 5000s

######################### 18 BAN ##############################

[Config H18]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=18
description = "Eighteen Human "
*.node[*].nic.mac.slotDuration = 0.0002s

**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")
```

```
**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0

**.node[7].mobility.coordinatorIndex = 1
**.node[8].mobility.coordinatorIndex = 1
**.node[9].mobility.coordinatorIndex = 1
**.node[10].mobility.coordinatorIndex = 1
**.node[11].mobility.coordinatorIndex = 1
**.node[12].mobility.coordinatorIndex = 1
**.node[13].mobility.coordinatorIndex = 1


                .
                .
                .
                .
                .
**.node[119].mobility.coordinatorIndex = 17
**.node[120].mobility.coordinatorIndex = 17
**.node[121].mobility.coordinatorIndex = 17
**.node[122].mobility.coordinatorIndex = 17
**.node[123].mobility.coordinatorIndex = 17
**.node[124].mobility.coordinatorIndex = 17
**.node[125].mobility.coordinatorIndex = 17

*.numHosts = 126
**.numMoBAN = 18
sim-time-limit = 5000s

############################ 25 BAN ########################################

[Config H25]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=25
description = "twenty-five Human "
*.node[*].nic.mac.slotDuration = 0.0002s
**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
```

```
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0
                    .
                    .
                    .
                    .
                    .
**.node[168].mobility.coordinatorIndex = 24
**.node[169].mobility.coordinatorIndex = 24
**.node[170].mobility.coordinatorIndex = 24
**.node[171].mobility.coordinatorIndex = 24
**.node[172].mobility.coordinatorIndex = 24
**.node[173].mobility.coordinatorIndex = 24
**.node[174].mobility.coordinatorIndex = 24

*.numHosts = 175
**.numMoBAN = 25
sim-time-limit = 5000s


##################### Proposed HIMM Model ############################
#######################################################################

############################ 1 BAN ####################################

[Config PH1]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=1
description = "Single Human "
*.node[*].nic.mac.slotDuration = 0.0002s

**.coordinator[0].postureSpecFile = xmldoc("postures3.xml")
**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.node[*].mobility.coordinatorIndex = 0
*.numHosts = 7
**.numMoBAN = 1

*.node[0].nic.mac.contentionWindow = 4
*.node[1].nic.mac.contentionWindow = 2
*.node[2].nic.mac.contentionWindow = 4
*.node[3].nic.mac.contentionWindow = 8
*.node[4].nic.mac.contentionWindow = 8
*.node[5].nic.mac.contentionWindow = 2
```

```
*.node[6].nic.mac.contentionWindow = 16

sim-time-limit = 5000s


########################### 09 BAN ##################################

[Config PH9]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=9
description = "Nine Human"
*.node[*].nic.mac.slotDuration = 0.00015s

**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0


                    .
                    .
                    .
                    .
                    .
*.node[56].nic.mac.contentionWindow = 4
*.node[57].nic.mac.contentionWindow = 2
*.node[58].nic.mac.contentionWindow = 4
*.node[59].nic.mac.contentionWindow = 8
*.node[60].nic.mac.contentionWindow = 8
*.node[61].nic.mac.contentionWindow = 2
*.node[62].nic.mac.contentionWindow = 16

*.numHosts = 63
**.numMoBAN = 9

sim-time-limit = 5000s

############################### 18 BAN ##############################

 [Config PH18]
```

```
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=18
description = "Eighteen Human "
*.node[*].nic.mac.slotDuration = 0.00015s

**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0


                  .
                  .
                  .
                  .
                  .
**.node[119].mobility.coordinatorIndex = 17
**.node[120].mobility.coordinatorIndex = 17
**.node[121].mobility.coordinatorIndex = 17
**.node[122].mobility.coordinatorIndex = 17
**.node[123].mobility.coordinatorIndex = 17
**.node[124].mobility.coordinatorIndex = 17
**.node[125].mobility.coordinatorIndex = 17

*.node[0].nic.mac.contentionWindow = 4
*.node[1].nic.mac.contentionWindow = 2
*.node[2].nic.mac.contentionWindow = 4
*.node[3].nic.mac.contentionWindow = 8
*.node[4].nic.mac.contentionWindow = 8
*.node[5].nic.mac.contentionWindow = 2
*.node[6].nic.mac.contentionWindow = 16

*.node[7].nic.mac.contentionWindow = 4
*.node[8].nic.mac.contentionWindow = 2
*.node[9].nic.mac.contentionWindow = 4
*.node[10].nic.mac.contentionWindow = 8
*.node[11].nic.mac.contentionWindow = 8
*.node[12].nic.mac.contentionWindow = 2
*.node[13].nic.mac.contentionWindow = 16


                  .
```

```
                  .
                  .
                  .
.
*.node[119].nic.mac.contentionWindow = 4
*.node[120].nic.mac.contentionWindow = 2
*.node[121].nic.mac.contentionWindow = 4
*.node[122].nic.mac.contentionWindow = 8
*.node[123].nic.mac.contentionWindow = 8
*.node[124].nic.mac.contentionWindow = 2
*.node[125].nic.mac.contentionWindow = 16

*.numHosts = 126
**.numMoBAN = 18

sim-time-limit = 5000s



####################### 25 BAN ##############################

[Config PH25]
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.node[*].nic.mac.n=25
description = "twenty-five Human "
*.node[*].nic.mac.slotDuration = 0.0002s
**.coordinator[*].configFile = xmldoc("configMoBAN3.xml")
**.coordinator[*].postureSpecFile = xmldoc("postures3.xml")

**.node[0].mobility.coordinatorIndex = 0
**.node[1].mobility.coordinatorIndex = 0
**.node[2].mobility.coordinatorIndex = 0
**.node[3].mobility.coordinatorIndex = 0
**.node[4].mobility.coordinatorIndex = 0
**.node[5].mobility.coordinatorIndex = 0
**.node[6].mobility.coordinatorIndex = 0


                  .
                  .
                  .
                  .
                  .

**.node[168].mobility.coordinatorIndex = 24
**.node[169].mobility.coordinatorIndex = 24
**.node[170].mobility.coordinatorIndex = 24
```

```
**.node[171].mobility.coordinatorIndex = 24
**.node[172].mobility.coordinatorIndex = 24
**.node[173].mobility.coordinatorIndex = 24
**.node[174].mobility.coordinatorIndex = 24

*.node[0].nic.mac.contentionWindow = 4
*.node[1].nic.mac.contentionWindow = 2
*.node[2].nic.mac.contentionWindow = 4
*.node[3].nic.mac.contentionWindow = 8
*.node[4].nic.mac.contentionWindow = 8
*.node[5].nic.mac.contentionWindow = 2
*.node[6].nic.mac.contentionWindow = 16

                    .
                    .
                    .
                    .
                    .

*.node[168].nic.mac.contentionWindow = 4
*.node[169].nic.mac.contentionWindow = 2
*.node[170].nic.mac.contentionWindow = 4
*.node[171].nic.mac.contentionWindow = 8
*.node[172].nic.mac.contentionWindow = 8
*.node[173].nic.mac.contentionWindow = 2
*.node[174].nic.mac.contentionWindow = 16

*.numHosts = 175
**.numMoBAN = 25

sim-time-limit = 5000s
```

(ii) CSMA Mac Layer

* project1.cc

```
#include "./CSMAMacLayer.h"

#include "FWMath.h"
#include "BaseConnectionManager.h"
#include "MacToPhyInterface.h"
#include "MacPkt_m.h"
#include "PhyUtils.h"

Define_Module( CSMAMacLayer )

/**
 * Initialize the of the omnetpp.ini variables in stage 1. In stage
 * two subscribe to the RadioState.
 */
void CSMAMacLayer::initialize(int stage)
{
   BaseMacLayer::initialize(stage);

   if (stage == 0) {

 queueLength = hasPar("queueLength")     ? par("queueLength").longValue()     :10;
slotDuration = hasPar("slotDuration")   ? par("slotDuration").doubleValue()
:0.00035;
difs = hasPar("difs")                 ? par("difs").doubleValue()      : 0.0005;
maxTxAttempts = hasPar("maxTxAttempts") ? par("maxTxAttempts").longValue()
: 7;
bitrate = hasPar("bitrate")            ? par("bitrate").doubleValue()      : 187500;
txPower = hasPar("txPower")            ? par("txPower").doubleValue()      : 1;
initialCW = hasPar("contentionWindow")  ? par("contentionWindow").longValue():
16;


/////////////////////////// Vector Results ///////

        delay1 = registerSignal("delay1");

        mthroughput1 = registerSignal("mthroughput1");

        bwefficiency1 =registerSignal("bwefficiency1");


        ///////////////edit/////////////////
```

```
MHR =hasPar("Mheader")                    ? par("Mheader").doubleValue()    :56;
FTR = hasPar("Mfooter")                  ? par("Mfooter").doubleValue()   : 16;
Rs = hasPar("sbrate")                   ?par("sbrate").doubleValue()   : 187500;
Rhdr = hasPar("phrate")                   ? par("phrate").doubleValue()  : 57500;
Tsifs = hasPar("tsifs")                 ? par("Tsifs").doubleValue(): .00005;
Tmifs = hasPar("Tmifs")                    ? par("Tmifs").doubleValue(): .00002;
pdelay = hasPar("pdelay")                  ? par("pdelay").doubleValue(): .00000002;
x = hasPar("x")                  ? par("x").doubleValue(): 2000;

/////payload size

n = hasPar("n")                  ? par("n").doubleValue(): 1;
numMoBAN= hasPar("numMoBAN")                    ?
par("numMoBAN").doubleValue(): 1;
numHosts = hasPar("numHosts")                ? par("numHosts").doubleValue(): 21;
CWmin = hasPar("minimumcontentionWindow") ?
par("minimumcontentionWindow").longValue():16;
CWmax = hasPar("maximumcontentionWindow") ?
par("maximumcontentionWindow").longValue():32;

 backofcount = hasPar("backofcount")      ? par("backofcout").doubleValue(): 4;

      Pc = hasPar("Pz")                ? par("Pz").doubleValue(): 3;
      Ptr = hasPar("Pt")               ? par("Pt").doubleValue(): 1.5;
      Prt = hasPar("Pr")               ? par("Pr").doubleValue(): 1.5;  /// mw
      Pidle = hasPar("Pidle")                ? par("Pidle").doubleValue():0.05;
      Ttr = hasPar("Ttr")               ? par("Ttr").doubleValue(): 0.00012; ///// s
      Trt = hasPar("Trt")               ? par("Trt").doubleValue(): 0.00021;

      T = hasPar("T")                ? par("T").doubleValue(): 30;

      macState = RX;
     //macState=TX;

     lastDataPktDestAddr = LAddress::L2BROADCAST;
     lastDataPktSrcAddr  = LAddress::L2BROADCAST;

      // initialize the timer
      backoffTimer = new cMessage("backoff");
      minorMsg = new cMessage("minClear");

      ////

     send_ack = new cMessage("send_ack");

      /////
```

```
    delayVec.setName("delay");
    bwefficiencyVec.setName("bwefficiency");
    mthroughputVec.setName("mthroughput");

    ///////// preamble time //////
    Tp = (0);

    //////// phy header time /////
    Tphy = (0);

    /////// slot length time /////
    Ts = (0);

    ////// CCA time //////
    Tcca = (0);

    /////// arg back off time ////

    argbftime = (0);
    ////// transimisin time of data ////
    Tdata = (0);

    ///// immediate ack time //////
    Tiack = (0);

    //// block ack time /////
    Tback = (0);

    /////// power consumption ////

    //// minimum delay /////
    delay = 0;

    /// BW efficiency /////
    bwefficiency = 0;

    /// maximum throughput ////
    mthroughput = 0;

  }
  else if(stage == 1) {
    BaseConnectionManager* cc = getConnectionManager();

    if(cc->hasPar("pMax") && txPower > cc->par("pMax").doubleValue())
      opp_error("TranmitterPower can't be bigger than pMax in
ConnectionManager! "
           "Please adjust your omnetpp.ini file accordingly.");
```

```
    if(phy->getRadioState() != MiximRadio::RX) {
      opp_error("Initial radio state isn't RX but CSMAMacLayer"
            " assumes that the NIC starts in RX state.");
    }

    debugEV << "queueLength = " << queueLength
      << " slotDuration = " << slotDuration
      << " difs = " << difs
      << " maxTxAttempts = " << maxTxAttempts
      << " bitrate = " << bitrate
      << " contentionWindow = " << initialCW << endl;
  }
}

CSMAMacLayer::~CSMAMacLayer() {
  cancelAndDelete(backoffTimer);
  cancelAndDelete(minorMsg);

  //////////// edit///////

  cancelAndDelete(send_ack);

  for(MacQueue::iterator it = macQueue.begin();
    it != macQueue.end(); ++it)
  {
    delete (*it);
  }
  macQueue.clear();
}


void CSMAMacLayer::finish() {

  recordScalar("mthroughput", mthroughput);
  recordScalar("delay", delay);
  recordScalar("bwefficiency", bwefficiency);

  BaseMacLayer::finish();
}

void CSMAMacLayer::throughputcal()
{

  CSMAMacLayer::payloadsize();
  Tp=90/Rs;
```

```
    Tphy=31/Rhdr;

    Tcca=63/Rs;

    Ts=Tcca+0.00002;

    double slots = intrand(initialCW + txAttempts) + 1.0 + dblrand();
    double time = (slots * slotDuration);


    argbftime=(initialCW*time)/2;

    Tdata=Tp+Tphy+((((MHR+FTR)*n)+x)/bitrate);

    Tiack=Tp+Tphy+(((MHR+FTR)*n)/bitrate);

    ////////// minimum delay///////////////

    delay= argbftime+Tdata+Tiack+(2*Tsifs)+(2*pdelay);

    ///////////maximum throughput///////
    mthroughput = x/delay;

    /////// BW efficiency//////
    bwefficiency = (mthroughput/bitrate)*100;

}


void CSMAMacLayer::handleUpperMsg(cMessage *msg)
{
    cPacket* pkt = static_cast<cPacket*>(msg);

    delayVec.record(delay);
    bwefficiencyVec.record(bwefficiency);
    mthroughputVec.record(mthroughput);

    // message has to be queued if another message is waiting to be send
    // or if we are already trying to send another message

    if (macQueue.size() <= queueLength)
    {
       macQueue.push_back(pkt);
       debugEV     << "packet putt in queue\n  queue size:" << macQueue.size() << "
macState:" << macState
          << " (RX=" << RX << ") is scheduled:" << backoffTimer->isScheduled() <<
endl;;
```

```
    if((macQueue.size() == 1) && (macState == RX) && !backoffTimer-
>isScheduled()) {
      scheduleBackoff();
    }
  }
  else {
    // queue is full, message has to be deleted
    EV << "New packet arrived, but queue is FULL, so new packet is deleted\n";
    macpkt_ptr_t mac = encapsMsg(pkt);
    mac->setName("MAC ERROR");
    mac->setKind(PACKET_DROPPED);

    CSMAMacLayer::counter();

    sendControlUp(mac);

  }
}

/**
 * Send one short preamble packet immediately.
 */

void CSMAMacLayer::sendMacAck()
{
    macpkt_ptr_t ack = new MacPkt();

    ack->setSrcAddr(myMacAddr);
    ack->setDestAddr(lastDataPktSrcAddr);
    ack->setKind(MAC_ACK);
    ack->setBitLength(headerLength);

    attachSignal(ack);
    //sendDown(ack);
    sendControlDown(ack);
    nbTxAcks++;
  //endSimulation();

}

void CSMAMacLayer::sendMacAck1()
{
    macpkt_ptr_t ack = new MacPkt();

    ack->setSrcAddr(myMacAddr);
    ack->setDestAddr(lastDataPktSrcAddr);
    ack->setKind(MAC_ACK);
```

```
      ack->setBitLength(headerLength);

      attachSignal(ack);
     //sendDown(ack);
     sendControlDown(ack);
    // macQueue.pop_front();
     nbTxAcks++;
   //endSimulation();

}


void CSMAMacLayer::attachSignal(macpkt_ptr_t macPkt)
{
   //calc signal duration
   simtime_t duration = macPkt->getBitLength() / bitrate;

   //create and initialize control info with new signal
   setDownControlInfo(macPkt, createSignal(simTime(), duration, txPower,
bitrate));
}


/**
 * After the timer expires try to retransmit the message by calling
 * handleUpperMsg again.
 */

void CSMAMacLayer::handleSelfMsg(cMessage *msg)
{

   if (msg == backoffTimer) {
      debugEV << "backoffTimer ";

      if(macState == RX) {
         debugEV << " RX ";

         if(macQueue.size() != 0) {
            macState = CCA;

            if(phy->getRadioState() == MiximRadio::RX) {

               if(phy->getChannelState().isIdle()) {
                  debugEV << " idle ";
                  scheduleAt(simTime()+difs, minorMsg);
               }
               else {
```

```
                  macState = RX;
                  debugEV << " busy ";
                  scheduleBackoff();
               }
            }
         }
      }

      else {
         debugEV << "" << endl;
         debugEV << "state=" << macState << "(TX="<<TX<<",
CCA="<<CCA<<")\n";
         error("backoffTimer expired, MAC in wrong state");
      }
   }

   if (msg==minorMsg)
   {
      debugEV << " minorMsg ";

      // replace with channel sense request
      if((macState == CCA) && (phy->getRadioState() == MiximRadio::RX)) {

         if(phy->getChannelState().isIdle()) {
            debugEV << " idle -> to send ";
            macState = TX;
            phy->setRadioState(MiximRadio::TX);
         }
         else {
            debugEV << " busy -> backoff ";
            macState = RX;
            if(!backoffTimer->isScheduled())
               scheduleBackoff();
         }
      }
      else {
         error("minClearTimer fired -- channel or mac in wrong state");
      }
   }
   debugEV << endl;
}


void CSMAMacLayer::handleLowerMsg(cMessage *msg)
{
   macpkt_ptr_t           mac  = static_cast<macpkt_ptr_t>(msg);
   const LAddress::L2Type& dest = mac->getDestAddr();
```

```
   if(dest == myMacAddr || LAddress::isL2Broadcast(dest))
   {
      debugEV << "sending pkt to upper...\n";
      sendUp(decapsMsg(mac));

     CSMAMacLayer::sendMacAck();
      CSMAMacLayer::throughputcal();
      emit(delay1, delay);
      emit(mthroughput1,mthroughput);
      emit(bwefficiency1,bwefficiency);

      if(mac->getKind()==MAC_ACK)
        nbRxAck++;
   }
   else {
      debugEV << "packet not for me, deleting...\n";
      delete mac;
   }
   if(!backoffTimer->isScheduled()) scheduleBackoff();

}

void CSMAMacLayer::handleLowerControl(cMessage *msg)
{
   if(msg->getKind() == MacToPhyInterface::TX_OVER) {
      debugEV << " transmission over" << endl;
      macState = RX;
      phy->setRadioState(MiximRadio::RX);
      txAttempts = 0;
      if(!backoffTimer->isScheduled()) scheduleBackoff();
   }
   else if(msg->getKind() == MacToPhyInterface::RADIO_SWITCHING_OVER) {
      if((macState == TX) && (phy->getRadioState() == MiximRadio::TX)) {
         debugEV << " radio switched to tx, sendDown packet" << endl;
         nbTxFrames++;


         sendDown(encapsMsg(macQueue.front()));
         macQueue.pop_front();
      }
   }
   else {
      EV << "control message with wrong kind -- deleting\n";
   }
   delete msg;
}
```

```
void CSMAMacLayer::scheduleBackoff()
{
  if(backoffTimer->isScheduled()) {
    std::cerr << " is scheduled: MAC state "
          << macState << " radio state : " << phy->getRadioState() << endl;
  }

  if(minorMsg->isScheduled()){
    cancelEvent( minorMsg );
    macState=RX;
  }


  if(txAttempts > maxTxAttempts) {
    debugEV << " drop packet " << endl;

    cMessage *mac = encapsMsg(macQueue.front());
    mac->setName("MAC ERROR");
    mac->setKind(PACKET_DROPPED);
    txAttempts = 0;

    //////// edit/////

    CSMAMacLayer::counter();

    macQueue.pop_front();
    sendControlUp(mac);

  }

  if(macQueue.size() != 0) {
    debugEV << " schedule backoff " << endl;

    double slots = intrand(initialCW + txAttempts) + 1.0 + dblrand();
    double time = slots * slotDuration;

    txAttempts++;
    debugEV << " attempts so far: " << txAttempts  << " " << endl;

    nbBackoffs = nbBackoffs + 1;
    backoffValues = backoffValues + time;


    scheduleAt(simTime() + time, backoffTimer);
  }
}
```

```
void CSMAMacLayer::counter()
{
   count++;
  //CSMAMacLayer::identification();
   if((count/2)!=0){
      initialCW=initialCW;
   }

   else{
      initialCW=2*initialCW;
   }
}


void CSMAMacLayer::backofcounter()
{
   backofcount--;
   if(backofcount==0)
   {
      CSMAMacLayer::handleSelfMsg(backoffTimer);
   }
   else
   {

      CSMAMacLayer::handleUpperMsg(backoffTimer);
      backofcount--;
   }
}


void CSMAMacLayer::payloadsize()
{
      x =x;
}


CSMAMacLayer::macpkt_ptr_t CSMAMacLayer::encapsMsg(cPacket *pkt)
{
   macpkt_ptr_t macPkt = BaseMacLayer::encapsMsg(pkt);

   //calc signal duration
   simtime_t duration = macPkt->getBitLength() / bitrate;

  // emit(Delay_LPP, lifetime1);
   if(duration > slotDuration) {
      EV << "Warning: Sending packet " << pkt
```

```
         << " - duration (" << duration
         << " ) is bigger than the slot duration (" << slotDuration
         <<")." << endl;
   }

   counter();
   //create signal
   setDownControlInfo(macPkt, createSignal(simTime(), duration, txPower,
bitrate));

   return macPkt;

}
```

Appendix III: Dynamic Cluster Head Selection using Link State Approach

(i) The Network Layer

```
#ifndef SIMPLENETWLAYER_H_
#define SIMPLENETWLAYER_H_
#include <cassert>
#include <omnetpp.h>
#include <sstream>
#include "BaseModule.h"
#include "NetwPkt_m.h"#include "SimpleAddress.h"
#include "MacToNetwControlInfo.h"
#include "NetwToMacControlInfo.h"
#include "BaseMacLayer.h"
#include "FindModule.h"

/**
 * This is an implementation of a simple network layer
 * which provides some simple routing (next hop) and
 * message forwarding.
 *
 * This network layer isn't a real network layer its only purpose
 * is to provide some message sending for the CSMA-Mac layer.
 *
 * At first there is a small "saying hello"-phase where the
 * several network layers saying hello to each other and creating
 * their routing table.
 *
 * After that phase the non-switch instances start to babbling randomly
 * to other instances without caring if they here them.
 * The switch instances does only provide packet forwarding from there on.
 *
 * The several instances can babble directly to each other or over
 * a switch instance.
 *
 */


class SimpleNetwLayer : public BaseModule{
public:
        typedef NetwPkt    netwpkt_t;
        typedef netwpkt_t* netwpkt_ptr_t;
//--------members----------
private:
        /** Copy constructor is not allowed.
         */
        SimpleNetwLayer(const SimpleNetwLayer&);
```

```
        /** Assignment operator is not allowed.
         */
        SimpleNetwLayer& operator=(const SimpleNetwLayer&);

protected:
        bool isSwitch;
        /** time after when the module gets bored and starts jabbering. */
        simtime_t boredTime;
        simtime_t PassTime;
        int maxTtl;
        LAddress::L3Type ip;
        //LAddress::L3Type sink;
        int dataIn;
        int dataOut;
   int nbOfOnesinTSR_0;
   int nbOfOnesinTSR_1;
   int nbOfOnesinTSR_2;
   int nbOfOnesinTSR_3;
   int nbOfOnesinTSR_4;
   int nbOfOnesinTSR_5;
   int nbOfOnesinTSR_6;
   int nbOfOnesinTSR_7;
   int nbOfOnesinTSR_8;
   int nbOfOnesinTSR_9;
   int nbOfOnesinTSR_10;
   int nbOfOnesinTSR_11;
        cMessage* startJabberTimer;
        cMessage* startHelloWorldTimer;
        unsigned long runningSeqNumber;
        typedef std::map<LAddress::L3Type, LAddress::L2Type> RoutingTable;
        RoutingTable routingTable;
        enum NetwPktKind{
           START_HELLO_WORLD,
                HELLO_WORLD = 4200,
                JABBER,
                START_TO_JABBER,
                ACK
        };

//--------methods----------
protected:
        void scheduleJabbering
(){
                if(startJabberTimer->isScheduled()){
                        cancelEvent(startJabberTimer);
                }
```

```
            scheduleAt(simTime() + boredTime, startJabberTimer);
      }
  void scheduleHelloWorld(){
    if(startHelloWorldTimer->isScheduled()){
      cancelEvent(startHelloWorldTimer);
    }

    scheduleAt(simTime() + PassTime, startHelloWorldTimer);
  }
      void broadcastHelloWorld()
      {
            assert(!ev.isDisabled());
            ev << "Broadcasting hello world.\n";
            netwpkt_ptr_t helloWorld = new netwpkt_t("helloWorld",
HELLO_WORLD);
            helloWorld->setDestAddr(LAddress::L3BROADCAST);
            helloWorld->setSrcAddr(ip);
            helloWorld->setSeqNum(runningSeqNumber++);
            helloWorld->setTtl(maxTtl);
            NetwToMacControlInfo::setControlInfo(helloWorld,
LAddress::L2BROADCAST);
            const_cast<cModule*>(getNode())->bubble("Hello World!");
            sendDown(helloWorld);
            scheduleHelloWorld();
      }
      void sendDown(cPacket* pkt) {
            send(pkt, dataOut);
      }
      void forwardPacket(netwpkt_ptr_t pkt, const LAddress::L2Type&
nextHop){
            netwpkt_ptr_t fwd = new netwpkt_t(pkt->getName(), pkt-
>getKind());

            fwd->setDestAddr(pkt->getDestAddr());
            fwd->setSrcAddr(pkt->getSrcAddr());
            fwd->setSeqNum(pkt->getSeqNum());
            fwd->setTtl(pkt->getTtl() - 1);

            NetwToMacControlInfo::setControlInfo(fwd, nextHop);

            sendDown(fwd);
      }
      void handleHelloWorld(netwpkt_ptr_t pkt){

            //who said hello?
            const LAddress::L3Type& srcIP = pkt->getSrcAddr();
```

```
        //we already know ourself...
        if (srcIP == ip){
            delete pkt;
            return;
        }
        //do we already know him?
        if(routingTable.count(srcIP) == 0){
            //if not add him with the mac address of the previous hop
            MacToNetwControlInfo* cInfo =
static_cast<MacToNetwControlInfo*>(pkt->getControlInfo());

            const LAddress::L2Type& prevHop = cInfo-
>getLastHopMac();
            routingTable[srcIP] = prevHop;
            AckToSomeone(pkt);
            std::stringstream osBuff(std::stringstream::out);
            osBuff << "Got hello from " << srcIP;
            const_cast<cModule*>(getNode())-
>bubble(osBuff.str().c_str());
            ev << osBuff.str() << std::endl;
        }

        //if we are a switch and the time to live of the packet
        //hasn't exceeded yet forward it
        if(isSwitch){
            if(pkt->getTtl() > 0) {
                forwardPacket(pkt, LAddress::L2BROADCAST);
                std::stringstream osBuff(std::stringstream::out);
                osBuff << srcIP << " said hello!";
                const_cast<cModule*>(getNode())-
>bubble(osBuff.str().c_str());
                ev << osBuff.str() << std::endl;
            }
        } else {
            //otherwise reset the bored timer after when we will start
jabbering
            scheduleJabbering();
        }

        delete pkt;
    }
    void jabberToSomeone(){

        const LAddress::L3Type& dest= sink_decision();
        netwpkt_ptr_t jabber = new netwpkt_t("jabber", JABBER);
        jabber->setDestAddr(dest);
        jabber->setSrcAddr(ip);
```

```
            jabber->setSeqNum(runningSeqNumber++);
            jabber->setTtl(maxTtl);
            jabber->setKind(JABBER);
    NetwToMacControlInfo::setControlInfo(jabber,
    LAddress::L2Type(sink_decision()));
            std::stringstream osBuff(std::stringstream::out);
            osBuff << "Babbling with " << dest;
            const_cast<cModule*>(getNode())->bubble(osBuff.str().c_str());
            ev << osBuff.str() << std::endl;
            sendDown(jabber);
            scheduleJabbering();
        }
        void handleIncomingJabber(netwpkt_ptr_t pkt){
            if(isSwitch) {
                if(pkt->getDestAddr() != ip){
                    assert(pkt->getTtl() > 0);

                LAddress::L2Type nextHop = routingTable[pkt-
    >getDestAddr()];


                    forwardPacket(pkt, nextHop);
                } else {
                    std::stringstream osBuff(std::stringstream::out);
osBuff << pkt->getSrcAddr() << " babbles with me. But I'm a serious switch, I do not
babble...";
                    const_cast<cModule*>(getNode())-
    >bubble(osBuff.str().c_str());
                    ev << osBuff.str() << std::endl;
                    delete pkt;
                }
            } else {
                assert(pkt->getDestAddr() == ip);

                std::stringstream osBuff(std::stringstream::out);
                osBuff << "Got babbling from " << pkt->getSrcAddr();
                const_cast<cModule*>(getNode())-
    >bubble(osBuff.str().c_str());
                ev << osBuff.str() << std::endl;
            }

            delete pkt;
        }
        void AckToSomeone(netwpkt_ptr_t pkt){
          netwpkt_ptr_t ack = new netwpkt_t("ack", ACK);
          MacToNetwControlInfo* cInfo =
    static_cast<MacToNetwControlInfo*>(pkt->getControlInfo());
```

```
          const LAddress::L3Type& srcIP = pkt->getSrcAddr();
      const LAddress::L2Type& prevHop = cInfo->getLastHopMac();
          ack->setDestAddr(srcIP);
          ack->setSrcAddr(ip);
          ack->setSeqNum(runningSeqNumber++);
          ack->setTtl(maxTtl);
          NetwToMacControlInfo::setControlInfo(ack, prevHop);
          std::stringstream osBuff(std::stringstream::out);
          osBuff << "Sending Ack to " << srcIP;
          const_cast<cModule*>(getNode())->bubble(osBuff.str().c_str());
          ev << osBuff.str() << std::endl;
          sendDown(ack);
        }
        void handleIncomingAck(netwpkt_ptr_t pkt){
          const LAddress::L3Type& srcIP = pkt->getSrcAddr();
              if (srcIP == ip){
                delete pkt;
                return;
              }
              //do we already know him?
              if(routingTable.count(srcIP) == 0){
               //if not add him with the mac address of the previous hop
MacToNetwControlInfo* cInfo = static_cast<MacToNetwControlInfo*>(pkt-
>getControlInfo());
const LAddress::L2Type& prevHop = cInfo->getLastHopMac();
                routingTable[srcIP] = prevHop;
                entry();
                std::stringstream osBuff(std::stringstream::out);
                osBuff << "Got Ack from " << srcIP;
const_cast<cModule*>(getNode())->bubble(osBuff.str().c_str());
                ev << osBuff.str() << std::endl;
              }

              //if we are a switch and the time to live of the packet
              //hasn't exceeded yet forward it
              if(isSwitch){
                if(pkt->getTtl() > 0) {
                  forwardPacket(pkt, LAddress::L2BROADCAST);
                  std::stringstream osBuff(std::stringstream::out);
                  osBuff << srcIP << " sent Msg For Ack";
const_cast<cModule*>(getNode())->bubble(osBuff.str().c_str());
                  ev << osBuff.str() << std::endl;
                }
              } else {
                delete pkt;
              }
              delete pkt;
```

```
      }
      void entry()
{
  cModule* nic = getParentModule();
  if(nic->getIndex()==0)
  {
     entryInTSRForOne_0();
  }
  else if(nic->getIndex()==1)
  {
     entryInTSRForOne_1();
  }
  else if(nic->getIndex()==2)
  {
    entryInTSRForOne_2();
  }
  else if(nic->getIndex()==3)
  {
    entryInTSRForOne_3();
  }
  else if(nic->getIndex()==4)
  {
    entryInTSRForOne_4();
  }
  else if(nic->getIndex()==5)
  {
    entryInTSRForOne_5();
  }
  else if(nic->getIndex()==6)
  {
    entryInTSRForOne_6();
  }
  else if(nic->getIndex()==7)
  {
    entryInTSRForOne_7();
  }
  else if(nic->getIndex()==8)
  {
    entryInTSRForOne_8();
  }
  else if(nic->getIndex()==9)
  {
    entryInTSRForOne_9();
  }
  else if(nic->getIndex()==10)
  {
    entryInTSRForOne_10();
```

```
  }
  else
  {
    entryInTSRForOne_11();
  }
}
    void entryInTSRForOne_0()
    {
        nbOfOnesinTSR_0++;
    }
    void entryInTSRForOne_1()
    {
        nbOfOnesinTSR_1++;
    }
    void entryInTSRForOne_2()
    {
        nbOfOnesinTSR_2++;
    }
    void entryInTSRForOne_3()
    {
        nbOfOnesinTSR_3++;
    }
    void entryInTSRForOne_4()
    {
        nbOfOnesinTSR_4++;
    }

    void entryInTSRForOne_5()
    {
        nbOfOnesinTSR_5++;
    }
    void entryInTSRForOne_6()
    {
        nbOfOnesinTSR_6++;
    }
    void entryInTSRForOne_7()
    {
        nbOfOnesinTSR_7++;
    }
    void entryInTSRForOne_8()
    {
        nbOfOnesinTSR_8++;
    }
    void entryInTSRForOne_9()
    {
        nbOfOnesinTSR_9++;
    }
```

```
    void entryInTSRForOne_10()
    {
        nbOfOnesinTSR_10++;
    }
    void entryInTSRForOne_11()
    {
        nbOfOnesinTSR_11++;
    }
    const LAddress::L3Type sink_decision()
    {

if(nbOfOnesinTSR_0>=nbOfOnesinTSR_1&&nbOfOnesinTSR_0>=nbOfOnesinTS
R_2&&nbOfOnesinTSR_0>=nbOfOnesinTSR_3&&nbOfOnesinTSR_0>=nbOfOne
sinTSR_4&&nbOfOnesinTSR_0>=nbOfOnesinTSR_5&&nbOfOnesinTSR_0>=nb
OfOnesinTSR_6&&nbOfOnesinTSR_0>=nbOfOnesinTSR_7&&nbOfOnesinTSR_0
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_0>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_0>=nbOfOnesinTSR_10&&nbOfOnesinTSR_0>=nbOfOnesinTSR_11)
          {
            const LAddress::L3Type& sink=LAddress::L3N0;
            return sink;
          }
          else
if(nbOfOnesinTSR_1>=nbOfOnesinTSR_0&&nbOfOnesinTSR_1>=nbOfOnesinTS
R_2&&nbOfOnesinTSR_1>=nbOfOnesinTSR_3&&nbOfOnesinTSR_1>=nbOfOne
sinTSR_4&&nbOfOnesinTSR_1>=nbOfOnesinTSR_5&&nbOfOnesinTSR_1>=nb
OfOnesinTSR_6&&nbOfOnesinTSR_1>=nbOfOnesinTSR_7&&nbOfOnesinTSR_1
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_1>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_1>=nbOfOnesinTSR_10&&nbOfOnesinTSR_1>=nbOfOnesinTSR_11)
            {
             const LAddress::L3Type& sink=LAddress::L3N1;
             return sink;
            }
          else
if(nbOfOnesinTSR_2>=nbOfOnesinTSR_0&&nbOfOnesinTSR_2>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_2>=nbOfOnesinTSR_3&&nbOfOnesinTSR_2>=nbOfOne
sinTSR_4&&nbOfOnesinTSR_2>=nbOfOnesinTSR_5&&nbOfOnesinTSR_2>=nb
OfOnesinTSR_6&&nbOfOnesinTSR_2>=nbOfOnesinTSR_7&&nbOfOnesinTSR_2
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_2>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_2>=nbOfOnesinTSR_10&&nbOfOnesinTSR_2>=nbOfOnesinTSR_11)
            {
             const LAddress::L3Type& sink=LAddress::L3N2;
             return sink;
            }
          else
if(nbOfOnesinTSR_3>=nbOfOnesinTSR_0&&nbOfOnesinTSR_3>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_3>=nbOfOnesinTSR_2&&nbOfOnesinTSR_3>=nbOfOne
sinTSR_4&&nbOfOnesinTSR_3>=nbOfOnesinTSR_5&&nbOfOnesinTSR_3>=nb
```

```
OfOnesinTSR_6&&nbOfOnesinTSR_3>=nbOfOnesinTSR_7&&nbOfOnesinTSR_3
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_3>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_3>=nbOfOnesinTSR_10&&nbOfOnesinTSR_3>=nbOfOnesinTSR_11)
                {
                 const LAddress::L3Type& sink=LAddress::L3N3;
                 return sink;
                }
              else
if(nbOfOnesinTSR_4>=nbOfOnesinTSR_0&&nbOfOnesinTSR_4>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_4>=nbOfOnesinTSR_2&&nbOfOnesinTSR_4>=nbOfOne
sinTSR_3&&nbOfOnesinTSR_4>=nbOfOnesinTSR_5&&nbOfOnesinTSR_4>=nb
OfOnesinTSR_6&&nbOfOnesinTSR_4>=nbOfOnesinTSR_7&&nbOfOnesinTSR_4
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_4>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_4>=nbOfOnesinTSR_10&&nbOfOnesinTSR_4>=nbOfOnesinTSR_11)
                {
                 const LAddress::L3Type& sink=LAddress::L3N4;
                 return sink;
                }
              else
if(nbOfOnesinTSR_5>=nbOfOnesinTSR_0&&nbOfOnesinTSR_5>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_5>=nbOfOnesinTSR_2&&nbOfOnesinTSR_5>=nbOfOne
sinTSR_3&&nbOfOnesinTSR_5>=nbOfOnesinTSR_4&&nbOfOnesinTSR_5>=nb
OfOnesinTSR_6&&nbOfOnesinTSR_5>=nbOfOnesinTSR_7&&nbOfOnesinTSR_5
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_5>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_5>=nbOfOnesinTSR_10&&nbOfOnesinTSR_5>=nbOfOnesinTSR_11)
                {
                 const LAddress::L3Type& sink=LAddress::L3N5;
                 return sink;
                }
              else
if(nbOfOnesinTSR_6>=nbOfOnesinTSR_0&&nbOfOnesinTSR_6>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_6>=nbOfOnesinTSR_2&&nbOfOnesinTSR_6>=nbOfOne
sinTSR_3&&nbOfOnesinTSR_6>=nbOfOnesinTSR_4&&nbOfOnesinTSR_6>=nb
OfOnesinTSR_5&&nbOfOnesinTSR_6>=nbOfOnesinTSR_7&&nbOfOnesinTSR_6
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_6>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_6>=nbOfOnesinTSR_10&&nbOfOnesinTSR_6>=nbOfOnesinTSR_11)
                {
                 const LAddress::L3Type& sink=LAddress::L3N6;
                 return sink;
                }
              else
if(nbOfOnesinTSR_7>=nbOfOnesinTSR_0&&nbOfOnesinTSR_7>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_7>=nbOfOnesinTSR_2&&nbOfOnesinTSR_7>=nbOfOne
sinTSR_3&&nbOfOnesinTSR_7>=nbOfOnesinTSR_4&&nbOfOnesinTSR_7>=nb
OfOnesinTSR_5&&nbOfOnesinTSR_7>=nbOfOnesinTSR_6&&nbOfOnesinTSR_7
>=nbOfOnesinTSR_8&&nbOfOnesinTSR_7>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_7>=nbOfOnesinTSR_10&&nbOfOnesinTSR_7>=nbOfOnesinTSR_11)
```

```
                {
                const LAddress::L3Type& sink=LAddress::L3N7;
                return sink;
                }
            else
if(nbOfOnesinTSR_8>=nbOfOnesinTSR_0&&nbOfOnesinTSR_8>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_8>=nbOfOnesinTSR_2&&nbOfOnesinTSR_8>=nbOfOne
sinTSR_3&&nbOfOnesinTSR_8>=nbOfOnesinTSR_4&&nbOfOnesinTSR_8>=nb
OfOnesinTSR_5&&nbOfOnesinTSR_8>=nbOfOnesinTSR_6&&nbOfOnesinTSR_8
>=nbOfOnesinTSR_7&&nbOfOnesinTSR_8>=nbOfOnesinTSR_9&&nbOfOnesinT
SR_8>=nbOfOnesinTSR_10&&nbOfOnesinTSR_8>=nbOfOnesinTSR_11)
                {
                const LAddress::L3Type& sink=LAddress::L3N8;
                return sink;
                }
            else
if(nbOfOnesinTSR_9>=nbOfOnesinTSR_0&&nbOfOnesinTSR_9>=nbOfOnesinTS
R_1&&nbOfOnesinTSR_9>=nbOfOnesinTSR_2&&nbOfOnesinTSR_9>=nbOfOne
sinTSR_3&&nbOfOnesinTSR_9>=nbOfOnesinTSR_4&&nbOfOnesinTSR_9>=nb
OfOnesinTSR_5&&nbOfOnesinTSR_9>=nbOfOnesinTSR_6&&nbOfOnesinTSR_9
>=nbOfOnesinTSR_7&&nbOfOnesinTSR_9>=nbOfOnesinTSR_8&&nbOfOnesinT
SR_9>=nbOfOnesinTSR_10&&nbOfOnesinTSR_9>=nbOfOnesinTSR_11)
                {
                const LAddress::L3Type& sink=LAddress::L3N9;
                return sink;
                }
            else
if(nbOfOnesinTSR_10>=nbOfOnesinTSR_0&&nbOfOnesinTSR_10>=nbOfOnesin
TSR_1&&nbOfOnesinTSR_10>=nbOfOnesinTSR_2&&nbOfOnesinTSR_10>=nbO
fOnesinTSR_3&&nbOfOnesinTSR_10>=nbOfOnesinTSR_4&&nbOfOnesinTSR_1
0>=nbOfOnesinTSR_5&&nbOfOnesinTSR_10>=nbOfOnesinTSR_6&&nbOfOnesi
nTSR_10>=nbOfOnesinTSR_7&&nbOfOnesinTSR_10>=nbOfOnesinTSR_8&&nb
OfOnesinTSR_10>=nbOfOnesinTSR_9&&nbOfOnesinTSR_10>=nbOfOnesinTSR_
11)
                {
                const LAddress::L3Type& sink=LAddress::L3N10;
                return sink;
                }
            else
                {
                const LAddress::L3Type& sink=LAddress::L3N11;
                return sink;
                }
          }

public:
        SimpleNetwLayer()
```

```
            : BaseModule()
            , isSwitch(false)
            , boredTime()
      , PassTime()
            , maxTtl(0)
            , ip()
    //sink()
            , dataIn(-1)
            , dataOut(-1)
            , startJabberTimer(NULL)
    , startHelloWorldTimer(NULL)
            , runningSeqNumber(0)
            , routingTable()
      {}
      virtual ~SimpleNetwLayer() {
            cancelAndDelete(startJabberTimer);
            cancelAndDelete(startHelloWorldTimer);
      }
      virtual void initialize(int stage){

            if(stage == 0){
                  dataOut = findGate("lowerLayerOut");
                  dataIn = findGate("lowerLayerIn");

                  isSwitch = par("isSwitch").boolValue();

                  if(isSwitch) {
FindModule<>::findHost(this)-
>getDisplayString().setTagArg("i",0,"device/accesspoint");
                  }
                  ip = LAddress::L3Type(par("ip").longValue());
                  maxTtl = par("maxTtl").longValue();
                  boredTime = par("boredTime").doubleValue();
                  PassTime = par("PassTime").doubleValue();
                  nbOfOnesinTSR_0=0;
                  nbOfOnesinTSR_1=0;
                  nbOfOnesinTSR_2=0;
                  nbOfOnesinTSR_3=0;
                  nbOfOnesinTSR_4=0;
                  nbOfOnesinTSR_5=0;
                  nbOfOnesinTSR_6=0;
                  nbOfOnesinTSR_7=0;
                  nbOfOnesinTSR_8=0;
                  nbOfOnesinTSR_9=0;
                  nbOfOnesinTSR_10=0;
                  nbOfOnesinTSR_11=0;
            } else if(stage == 1) {
```

```
            startJabberTimer = new cMessage("jabber!",
START_TO_JABBER);
            startHelloWorldTimer = new cMessage("Hello
G!",START_HELLO_WORLD);
            broadcastHelloWorld();
        }
    }
    virtual void handleMessage(cMessage* msg){

        switch(msg->getKind()){
        case START_HELLO_WORLD:
          broadcastHelloWorld();
    break;
        case HELLO_WORLD:
            handleHelloWorld(static_cast<netwpkt_ptr_t>(msg));
            break;
        case START_TO_JABBER:
            jabberToSomeone();
            break;
        case JABBER:
            handleIncomingJabber(static_cast<netwpkt_ptr_t>(msg));
            break;
        case ACK:
          handleIncomingAck(static_cast<netwpkt_ptr_t>(msg));
          break;
        case BaseMacLayer::PACKET_DROPPED:
            ev << "Packet dropped by MAC layer." << endl;
            delete msg;
            break;
        default:
            error("unknown packet type of packet %s", msg->getName());
            break;
        }
    }
};

#endif /* SIMPLENETWLAYER_H_ */
```

(ii) The Omnet ini File configuration

```
[General]
cmdenv-config-name = perftest
cmdenv-express-mode = true
network = CSMAMacExampleNetwork
**.vector-recording = true
**.scalar-recording = true

##################################################################
#                       Simulation parameters                    #
##################################################################

record-eventlog = true
tkenv-default-config =
*.**.coreDebug = false
*.playgroundSizeX = 2000m
*.playgroundSizeY = 2000m
*.playgroundSizeZ = 400m
**.constraintAreaMinX = 0m
**.constraintAreaMinY = 0m
**.constraintAreaMinZ = 0m
**.constraintAreaMaxX = 600m
**.constraintAreaMaxY = 400m
**.constraintAreaMaxZ = 200m
*.numHosts = 12

##################################################################
#                            channel parameters                  #
##################################################################

*.connectionManager.sendDirect = true
*.connectionManager.pMax = 100mW
*.connectionManager.sat = -90dBm
*.connectionManager.alpha = 3
*.connectionManager.carrierFrequency = 2.412e+9Hz

##################################################################
#          Host specific parameters                              #
##################################################################

*.node[*].nic.connectionManagerName = "connectionManager"

################## PhyLayer parameters ########################

*.node[*].nic.phy.usePropagationDelay = false
*.node[*].nic.phy.thermalNoise = -100dBm
```

```
*.node[*].nic.phy.useThermalNoise = true
*.node[*].nic.phy.analogueModels = xmldoc("config.xml")
*.node[*].nic.phy.decider = xmldoc("config.xml")
*.node[*].nic.phy.timeRXToTX = 0.00021s
*.node[*].nic.phy.timeRXToSleep = 0.000031s
*.node[*].nic.phy.timeTXToRX = 0.00012s
*.node[*].nic.phy.timeTXToSleep = 0.000032s
*.node[*].nic.phy.timeSleepToRX = 0.000102s
*.node[*].nic.phy.timeSleepToTX = 0.000203s
*.node[*].nic.phy.sensitivity = -87dBm
*.node[*].nic.phy.maxTXPower = 100.0mW

################ MAC layer parameters ####################

*.node[*].nic.mac.queueLength = 5
*.node[*].nic.mac.headerLength = 56bit

**.node[*].nic.mac.useMACAcks = true

*.node[*].nic.mac.slotDuration = 0.00035s
*.node[*].nic.mac.difs = 0.0005s
*.node[*].nic.mac.maxTxAttempts = 10
*.node[*].nic.mac.defaultChannel = 0
*.node[*].nic.mac.bitrate =187500bps

*.node[*].nic.mac.contentionWindow = 16

*.node[0].nic.mac.txPower = 9mW  # [mW]
*.node[1].nic.mac.txPower = 8mW  # [mW]
*.node[2].nic.mac.txPower = 9mW  # [mW]
*.node[3].nic.mac.txPower = 7mW  # [mW]
*.node[4].nic.mac.txPower = 6mW  # [mW]
*.node[5].nic.mac.txPower = 8mW  # [mW]
*.node[6].nic.mac.txPower = 7mW  # [mW]
*.node[7].nic.mac.txPower = 9mW  # [mW]
*.node[8].nic.mac.txPower = 8mW  # [mW]
*.node[9].nic.mac.txPower = 7mW  # [mW]
*.node[10].nic.mac.txPower = 6mW  # [mW]
*.node[11].nic.mac.txPower = 6mW  # [mW]

############## EDIT #######################

*.node[*].nic.mac.x=2000

################ Battery Module parameters ####################

**.batteryStats.detail = true
```

```
**.batteryStats.timeSeries = false
**.battery.nominal = 1000mAh
**.battery.capacity = 1000mAh
**.battery.voltage = 3.3V
**.battery.resolution = 0.1s
**.battery.publishDelta = 1
**.battery.publishTime = 0s
**.battery.numDevices = 1
**.nic.sleepCurrent = 0.02mA
**.nic.rxCurrent = 16.4mA
**.nic.decodingCurrentDelta = 0mA
**.nic.txCurrent = 17mA
**.nic.setupRxCurrent = 8.2mA
**.nic.setupTxCurrent = 8.2mA
**.nic.rxTxCurrent = 17mA
**.nic.txRxCurrent = 17mA

################ NETW layer parameters ####################

*.node[*].netwl.isSwitch = false
*.node[*].netwl.maxTtl = 3
*.node[*].netwl.boredTime = 0.5
*.node[*].netwl.PassTime = 35 /////////

################ Mobility parameters #####################

**.coordinator[*].postureSpecFile = xmldoc("postures1.xml")
**.coordinator[*].configFile = xmldoc("configMoBAN2.xml")
**.coordinator[*].useMobilityPattern = false
**.coordinator[*].mobilityPatternFile = ""

**.mobilityType = "MoBANLocal"
**.node[*].mobility.coordinatorIndex = 0
**.mobility.updateInterval = 0.5 s
**.numMoBAN = 1

*.node[0].netwl.ip = 0
*.node[0].nic.id = 0

*.node[1].netwl.ip = 1
*.node[1].nic.id = 1
*.node[2].netwl.ip = 2
*.node[2].nic.id = 2
*.node[3].netwl.ip = 3
*.node[3].nic.id = 3
*.node[4].netwl.ip = 4
*.node[4].nic.id = 4
```

```
*.node[5].netwl.ip = 5
*.node[5].nic.id = 5
*.node[6].netwl.ip = 6
*.node[6].nic.id = 6
*.node[7].netwl.ip = 7
*.node[7].nic.id = 7
*.node[8].netwl.ip = 8
*.node[8].nic.id = 8
*.node[9].netwl.ip = 9
*.node[9].nic.id = 9
*.node[10].netwl.ip = 10
*.node[10].nic.id = 10
*.node[11].netwl.ip = 11
*.node[11].nic.id = 11

*.node[*].netwl.ip = 0
*.node[*].nic.id = 0

[Config perftest]
*.node[*].nic.mac.slotDuration = 0.0002s
*.node[*].nic.phy.usePropagationDelay = true
*.node[*].nic.phy.coreDebug = true
*.numHosts = 12
sim-time-limit = 5000s
```

Appendix IV: The MoBAN Mobility Model Framework

(i) Posture Specification File

Each posture can have a name that is used for showing in display during simulation, if the graphical display is used in simulation. Unique and subsequent ID numbers should also be given to the posture

```
<?xml version="1.0" encoding="UTF-8"?>
<root>
        <posture name="RUNNING" postureID="0" minSpeed="10"
maxSpeed="30">

                <nodeParameters positionX="300.0" positionY="220.0" positionZ=
"100.00" radius="5" speed="10" />
                <nodeParameters positionX="295.0" positionY="260.0" positionZ=
"70.000" radius="00" speed="00" />
                <nodeParameters positionX="330.0" positionY="260.0" positionZ=
"100.00" radius="10" speed="25" />
                <nodeParameters positionX="270.0" positionY="260.0" positionZ=
"100.00" radius="10" speed="25" />
                <nodeParameters positionX="300.0" positionY="280.0" positionZ=
"100.00" radius="00" speed="00" />
                <nodeParameters positionX="320.0" positionY="330.0" positionZ=
"100.00" radius="20" speed="20" />
                <nodeParameters positionX="280.0" positionY="330.0" positionZ=
"100.00" radius="20" speed="20" />


        </posture>

        <posture name="WALKING" postureID="1" minSpeed="20"
maxSpeed="100">


                <nodeParameters positionX="300.0" positionY="220.0" positionZ=
"100.00" radius="5" speed="10" />
                <nodeParameters positionX="295.0" positionY="260.0" positionZ=
"70.000" radius="00" speed="00" />
                <nodeParameters positionX="330.0" positionY="260.0" positionZ=
"100.00" radius="7.5" speed="15" />
                <nodeParameters positionX="270.0" positionY="260.0" positionZ=
"100.00" radius="7.5" speed="15" />
```

```
                <nodeParameters positionX="300.0" positionY="280.0" positionZ=
"100.00" radius="00" speed="00" />
                <nodeParameters positionX="320.0" positionY="330.0" positionZ=
"100.00" radius="15" speed="15" />
                <nodeParameters positionX="280.0" positionY="330.0" positionZ=
"100.00" radius="15" speed="15" />



        </posture>

        <posture name="STANDING" postureID="2" minSpeed="0"
maxSpeed="0">

                <nodeParameters positionX="300.0" positionY="220.0" positionZ=
"100.00" radius="5" speed="10" />
                <nodeParameters positionX="295.0" positionY="260.0" positionZ=
"70.000" radius="00" speed="00" />
                <nodeParameters positionX="330.0" positionY="260.0" positionZ=
"100.00" radius="02" speed="01" />
                <nodeParameters positionX="270.0" positionY="260.0" positionZ=
"100.00" radius="02" speed="01" />
                <nodeParameters positionX="300.0" positionY="280.0" positionZ=
"100.00" radius="00" speed="00" />
                <nodeParameters positionX="320.0" positionY="330.0" positionZ=
"100.00" radius="5" speed="05" />
                <nodeParameters positionX="280.0" positionY="330.0" positionZ=
"100.00" radius="5" speed="05" />



        </posture>

        <posture name="SITTING" postureID="3" minSpeed="0" maxSpeed="0">
                <nodeParameters positionX="300.0" positionY="290.0" positionZ=
"100.00" radius="5" speed="10" />
                <nodeParameters positionX="295.0" positionY="310.0" positionZ=
"70.000" radius="00" speed="00" />
                <nodeParameters positionX="330.0" positionY="330.0" positionZ=
"100.00" radius="02" speed="01" />
                <nodeParameters positionX="270.0" positionY="330.0" positionZ=
"100.00" radius="02" speed="01" />
                <nodeParameters positionX="300.0" positionY="330.0" positionZ=
"100.00" radius="00" speed="00" />
                <nodeParameters positionX="320.0" positionY="360.0" positionZ=
"100.00" radius="02" speed="03" />
```

```
                    <nodeParameters positionX="280.0" positionY="360.0" positionZ=
"100.00" radius="02" speed="03" />



          </posture>

          <posture name="LYING-DOWN" postureID="4" minSpeed="0"
maxSpeed="0">


                    <nodeParameters positionX="450.0" positionY="340.0" positionZ=
"100.00" radius="0" speed="0" />
                    <nodeParameters positionX="420.0" positionY="330.0" positionZ=
"70.000" radius="0" speed="0" />
                    <nodeParameters positionX="410.0" positionY="370.0" positionZ=
"100.00" radius="0" speed="0" />
                    <nodeParameters positionX="410.0" positionY="330.0" positionZ=
"100.00" radius="0" speed="0" />
                    <nodeParameters positionX="400.0" positionY="340.0" positionZ=
"100.00" radius="0" speed="0" />
                    <nodeParameters positionX="350.0" positionY="330.5" positionZ=
"100.00" radius="0" speed="0" />
                    <nodeParameters positionX="350.0" positionY="320.0" positionZ=
"100.00" radius="0" speed="0" />



          </posture>
</root>
```