Comparative Analysis of MAC protocols for Wireless Body Area Networks

Thesis submitted in partial fulfilment of the requirements for the award of degree of

Master of Engineering

in

Information Security

Submitted By

Jasleen Kaur

(801433013)

Under the supervision of:

Dr. Anil Kumar Verma

Associate Professor

COMPUTER SCIENCE AND ENGINEERING DEPARTMENT

THAPAR UNIVERSITY

PATIALA – 147004

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "*Comparative Analysis of MAC protocols for Wireless Body Area Networks*", in partial fulfilment of the requirements for the award of degree of Master of Engineering in *Information Security* submitted in Computer Science and Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of *Dr. Anil Kumar Verma* and refers other researcher's work which are duly listed in the reference section.

The matter presented in the thesis has not been submitted for award of any other degree of this or any other University.

Jasleen Kaur
Signature:

Jasleen Kaur

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Anil K. Verma

(Dr. Anil Kumar Verma)

Computer Science and Engineering

Thapar University

Countersigned by

(Dr. Maninder Singh)

Head

Computer Science and Engineering Department

Thapar University

Patiala

(Dr. S. S. Bhatia)

Dean (Academic Affairs)

Thapar University

Patiala

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Jasleen Kaur

(801433013)

ABSTRACT

Recent advancements to revolutionize health monitoring systems have enabled the development of wireless body area network (WBAN). Owing to the network specifications and stringent resource requirements including minimum energy consumption, low device complexity, and prolonged battery life, further led to the development of efficient medium access control (MAC) protocols.

In this thesis, two MAC protocols based on IEEE 802.15.4 (Zigbee MAC) and IEEE 802.15.6 (Baseline BAN MAC) standards were analysed using OMNET++ based Castalia-3.2 network simulator. The performance of the protocols was accessed and compared under similar environmental variations including temporal variations, power supply and type of channel access slots. The comparisons were done on the basis of three parameters: throughput, total energy consumption, and latency recorded during the transmission of data packets. The results have shown that Zigbee MAC protocol when subjected to no temporal variations and GTS mode is ON performs better than Baseline BAN MAC protocol. It is further observed that both the protocols perform best when -10dBm of power is supplied to the nodes. However, Zigbee MAC protocol performs best when random channel access is permitted along with GTS whereas efficient functioning of Baseline MAC protocol required a proper combination of scheduled and random access slots to access the channel.

Keywords: Wireless Body Area Network, Medium Access Control, IEEE 802.15.4, IEEE 802.15.6

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LIST OF ABBREVIATIONS

WBAN	Wireless Body Area Network
QoS	Quality of Service
WWAN	Wireless Wide Area Network
WMAN	Wireless Metropolitan Area Network
WLAN	Wireless Local Area Network
WPAN	Wireless Persona Area Network
BAN	Body Area Network
WLL	Wireless Local Loop
EEG	Electroencephalogram
ECG	Electrocardiogram
PHY	Physical layer
MAC	Medium Access Control
BER	Bit Error Code
CS	Compressed Sensing
PDA	Personal Digital Assistance
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
CDMA	Code Division Multiple Access
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
RFD	Reduced Functional Device
FFD	Full Functional Device
CAP	Contention Access Period

CFP	Contention Free Period
NB	Narrow Band
UWB	Ultra-Wide Band
HBC	Human Bond Communication
EAP	Exclusive Access Phase
RAP	Random Access Phase
MAP	Managed Access Phase
GTS	Guaranteed Time Slot

CHAPTER 1

INTRODUCTION

1.1 Motivation

Advancements in the area of wireless communications and health monitoring had triggered the development of low-power, intelligent, nano-and micro-devices which are used to monitor activities within the vicinity of human body. Moreover, recent technological upgrades gave rise to the development new research niche known as Wireless Body Area Network (WBAN) that aims to provide guidelines and communication specifications to develop design efficient wireless devices.

To monitor the activities of human body,the required frequencies should be in acquiescence with the communication standards and protection of the tissues and organs of the body. WBAN is anassemblage of invasive and non-invasive sensor devices which have prolonged battery life and operates on low power, thus holds promiseto obtain timely information regarding crucial body parameters and movements.

Although WBAN standards are designed for the purpose of medical applications but its applicability covers a broad range including gaming, authentication and security, education, entertainment, sports, training and military purposes.

1.2 State of the Art

Numerous health diagnosing technologies are being developed with the aim to revolutionize ubiquitous health monitoring systems. Various projects including MyHeart [1], WWBAN [2], WIMoCA [3], Bi-Fi [4], BASUMA [5], Human++ [6], HeartToGo [7], ABUADE [8], Omron [9], Vivago [10], Polar [11], etc. are being carried out in renowned institutions with the aim to provide better health facilities. These projects are targeted on the development of a number of health applications that can be employed for the diagnosis and prevention of acute diseases, measurement and processing of physiological signals, posture recognition and evaluation of emotional states, etc. These applications require a wide range of sensors to measure various physiological signals including blood pressure, heart rate, pulse, skin temperature, and respiration rate etc. The transmission of recorded signals need different communication standards including Wi-Fi, Bluetooth, Zigbee, GPRS, etc.

Although WBAN enable the advent of new applications, but few important issues regarding design and technical requirements of applications need immediate consideration. The diversity of envisioned applications required a set of specified quality of service (QoS) parameters including high data rate, energy efficiency, security and reliability of data which generates a need of designing new paradigms and protocols.

1.3 Thesis Outline

The thesis structure involve organization into 7 chapters including Introduction to WBAN, Emergence of WBAN, Literature Survey, Problem Statement and Objectives, Installation and Simulation involving Castalia-3.2 network simulator, Results and Discussion, Conclusion and Future Scope.

Chapter 1 gives the introduction of the work in terms of Motivation behind the pursuit of this thesis, succeeding with State of Art and the thesis outline. Chapter 2 provides the introduction to wireless networks and specifies the need for the development of Body Area Networks. Chapter 3 includes the survey of literature that includes details about WBAN, its communication architecture and requirements and lastly gives an overview of communication standards, IEEE 802.15.4 and IEEE 802.15.6. Chapter 4 describes the problem statement and objectives of the work. Chapter 5 lists the various tools and software involved to create a simulation environment Chapter 6 gives an analysis of performance of Zigbee MAC and Baseline MAC protocols on the basis of the obtained results and lastly Chapter 7 concludes the thesis with the description of future scope.

CHAPTER 2

EMERGENCE OF WBAN

2.1 Wireless Network

Recent technological advancements in the area of**wireless networks** has experienced remarkable growth. Further, it is known that communication inwireless network is administered with the help of radio signals that mediate establishment of a link among the nodes of a communication network.

The advantages ofusing wireless networks over wired connections are:

- Ease of network organisation and relatively low communicationcost.
- Easily upgradable and require low cost of maintenance.
- Its offers mobility and flexibility of communicating nodes.

2.2 Hierarchy of Wireless Networks

Wireless networks can be classifiedon the basis of geographical coverage area or on the basis of their generation. Classification into different types of network enables the development of guidelines and standards to meet the specific needs of a wireless network.

On the basis of geographical coverage, wireless networkscan be broadly classified as:

- Wireless Wide Area Networks (WWANs)
- Wireless Metropolitan Area Networks (WMANs)
- Wireless Local Area Networks (WLANs)
- Wireless Personal Area Networks (WPANs)

2.2.1 Wireless Wide Area Networks

WWANsare wireless networks that spans overwidetopographical areas, connecting neighbouring towns and cities. This kind of wireless network is used to provide services to the user through different cellular networks such as GSM, GPRS, and LTE and make use ofsatellitecommunication for transmission of signals.

2.2.2 Wireless Metropolitan Area Networks

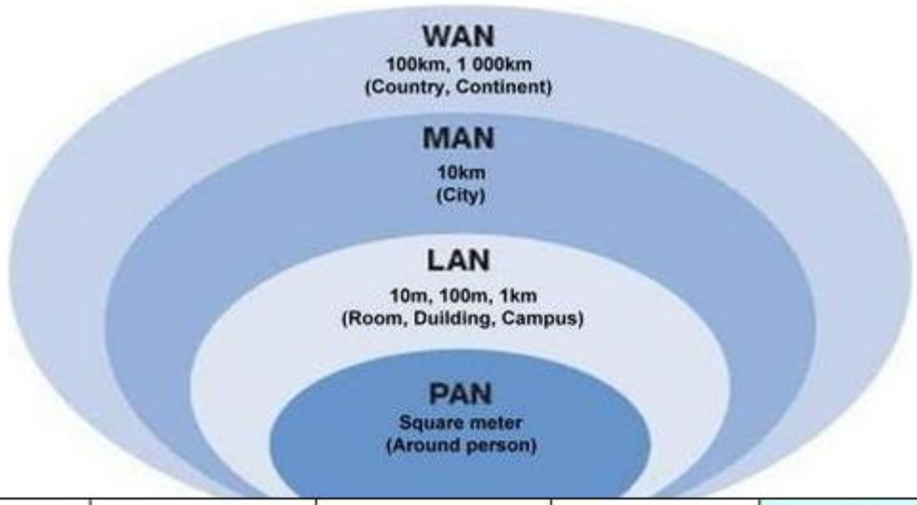
WMAN,referred as wireless local loop (WLL) is apoint-to-point or point-to-multipoint network that spreads over a large area, say a circular region with radius of 4-10 kilometres,and thus makes it suitable for providing wireless connectivity in telecommunication companies. WiMAX is a well-known example of WMAN.Wireless MAN is based on IEEE standard 802.16.

2.2.3 Wireless Local Area Networks

WLAN is a network of two or more communicating devices across a small areawith the help of wireless distribution mechanism, generallyinclude an access point for providing internet access to the users. The use of high-frequency radio waves or OFDM technologies may let users to move around a local coverage area, without losing their connectivity with the network. Depending on its applicability, it is based on various versions of IEEE 802.11 standard.

2.2.4 Wireless Personal Area Networks

A wireless Personal Area Network helps inwireless communication over short-range, connecting personal devices such as tablets, cell phones and personal digital assistants. It is based on IEEE 802.15 standard and communicate technologies such as Bluetooth, IrDA and ZigBee.



	PAN	LAN	MAN	WAN
Standards	Bluetooth, UWB	802.11 HiperLAN2	802.16 MMDS, LMDS	GSM, GPRS, CDMA, 2.5-3G, 802.16
Speed	< 1Mbps	11 to 54 Mbps	11 to 100+ Mbps	10 to 384Kbps
Range	Short	Medium	Medium-Long	Long
Applications	Peer-to-Peer Device-to-Device	Enterprise networks	T1 replacement, last mile access	PDAs, Mobile Phones, cellular access

Figure 2.1: Classification of Wireless networks and Technologies

2.3 Advent of Body Area Networks (BAN)

BANis a subset of big wireless network family referred as PAN. Its evolution is based on generic networks also known as wireless sensor networks(WSNs). BAN isdefined as a collection of low-powered, lightweight, intelligent sensor nodes employed to sense, actuate, compute andcommunicate physiological signals of human body.The main purpose for the development of BAN was to improve health monitoring systems but its usefulness spans from medical field to military and other ambient intelligence areas.

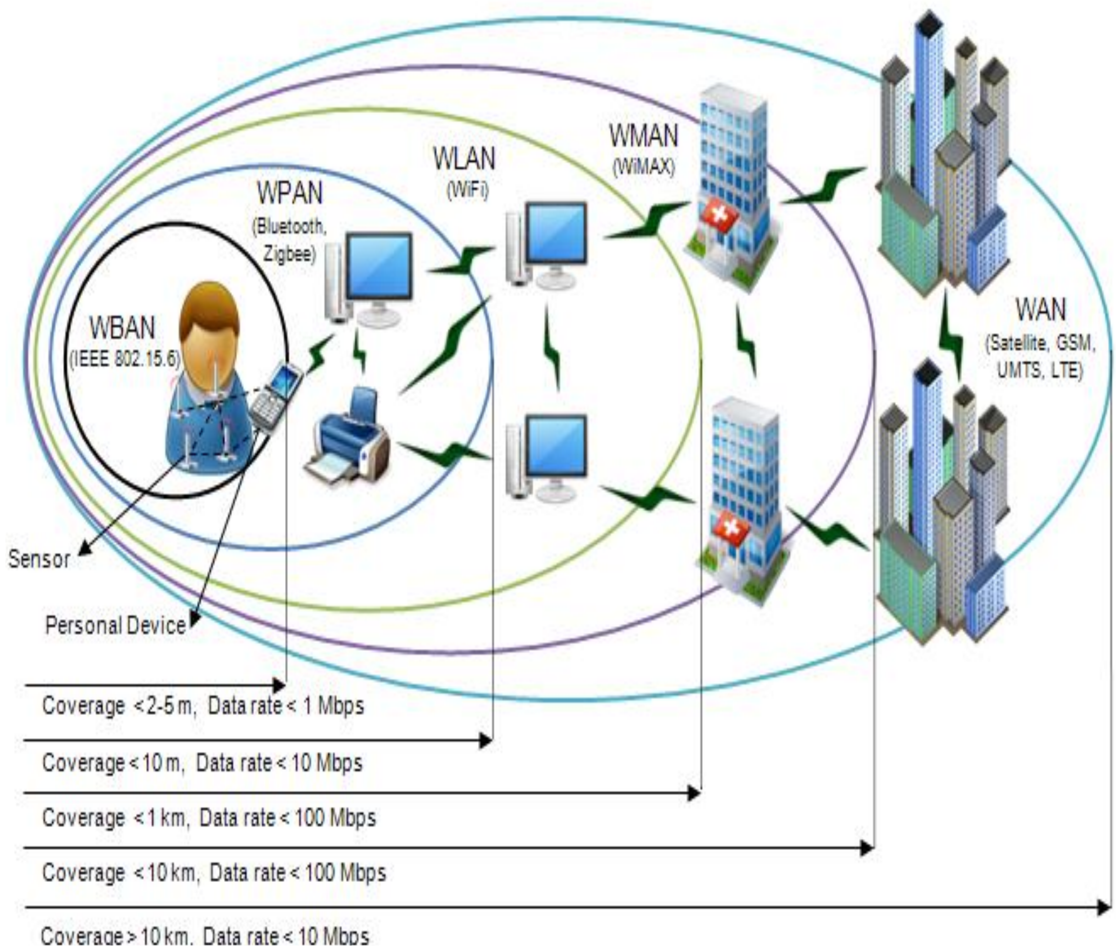


Figure 2.2: Positioning of WBAN in Wireless network hierarchy [12]

CHAPTER 3

LITERATURE SURVEY

3.1 Introduction to WBAN

Wireless Body Area Network (WBAN) is a network of intelligent, low-power, miniaturised sensors, and actuators that are located within the vicinity of the human body to facilitate the purpose of several medical and non-medical functions [12]. These sensor nodes are capable of capturing timely information regarding crucial body parameters and movements. The information collected is transmitted to the coordinator node (PDA – Personal Digital Assistant) in the form of an electronic data signal for data processing. After performing data processing, PDA transmits the information to the Central Server (CS), where data records are maintained in the form of electronic records for future assistance and consideration [13].

Data streaming from the human body to the Central Server demands higher energy consumption for information processing and transmission [14]. The reduction in the consumption of energy is, therefore, one of the most important aspects to be considered while designing an efficient wireless body area network. Following that recent technological advancements have led to the development of energy efficient MAC protocols, routing protocols and other communication standards. An efficient MAC protocol aims at maximising network life and minimising end to end delay in successful packet transmission, to achieve maximum throughput. This aim is being achieved by controlling the major sources of energy dissipation [15] including control packet overhead, collision of packets, idle listening and overhearing.

3.2 Applications of WBAN

The main purpose for the development of BAN was to improve health monitoring systems but its usefulness spans from medical field to military and other ambient intelligence areas [16]. Some of the main application areas of WBAN are listed as follows:

- **Healthcare Monitoring:** employed for early diagnosis, monitoring and treatment of acute diseases and includes:

- Patient monitoring
- Electrocardiogram (ECG)
- Electroencephalogram (EEG)
- Cancer Detection

▪ **Security and Authentication:** utilised for both physiological and behavioural biometry such as:
  - iris identification
  - fingerprint matching
  - facial pattern

▪ **Sports and Training:** maintains logs of vital movements and parameters including:
  - Posture
  - Mobility
  - Weight scale
  - Heart rate

▪ **Entertainment Application:** gaming applications and social networks make use of WBAN for various purposes including:
  - Gaming
  - Virtual reality
  - Gesture recognition
  - Consumer electronics such as mp3, cameras etc.

▪ **Military and Defence:** new features of WBAN helps to improve the personnel performance at individual and squad level
  - Battlefield surveillance
  - Assessment of soldier fatigue
  - Blast dosimeter

3.3 Requirements of WBAN

In WBANs, sensor devices capture vital body parameters and movements and transmit the collected information to the network coordinator. Streaming of data over a shared medium requires number of specifications including:

- **Energy Efficiency**

  Energy efficiency is a major requirementof WBANs as the implanted sensor nodes require long battery life in order to provide continuous and prolong health monitoring facility. Since these sensor nodes could not be easily charged or replaced, it becomes mandatory to cut down energy dissipation at tier-1 communication (described in next section). Reduction of energy consumption can be achieved by designing radio transceivers hat require ultra-low power for their operation. Designing of an energy-efficient MAC protocol that permits the sensors to be in sleep mode when not in use is also a solution to reduce energy consumption. This is achieved by lowering down the duty cycle of MAC.

- **Bit Rate**

  Requirement of bit rate varies broadly on the basis of transmission of data or type of application. For example, sensing a body temperature require less than 1kbps data rate whereas it goes up to 10 Mbps for video streaming. Bit rate also depends on whether transmission is from a single link or several links, depending on the number of nodes sends/receive data signals to/from network coordinator. In order to cut down Bit Error Code (BER), appropriate interference avoidance techniques and error correction codes must be applied to PHY and MAC layers of the network. Prioritisation of messages is also a wise solution to manage huge data traffic.

- **Security and Reliability**

  Security and reliability of transmitted data is of primary concern, especially when it is related to military and medical application areas. Level of confidentiality, integrity, availability, and authenticity of data confirms its security whereas probability of packet loss and delay of transmitted data accounts for the reliability of data. To enhance data reliability, proper choice of channel access mechanisms, scheduling techniques, size and retransmission of packets is important. However, security methods based on biometric identification are considered to be suitable and energy-efficient for securing WBAN.

- **Network Topology**

  Communicating nodes in WBAN are usually placed in star topology as shown in figure. These nodes may communicate in single-hop or multiple hops. In single hop star topology, all nodes are considered to be directly connected to the coordinator, also known as sink whereas in multi-hop communication, nodes are connected to access points through other nodes.

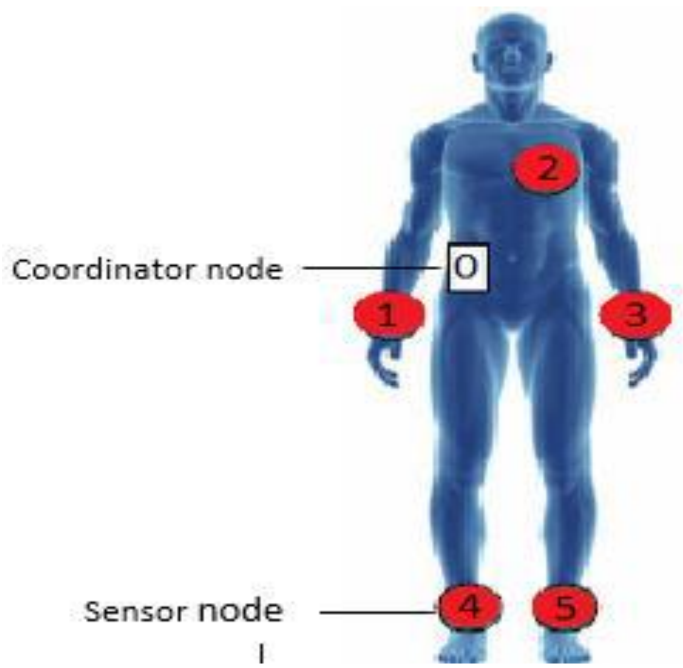


Figure 3.1: Sensor nodes arranged in star topology

Communication in single-hop star is achieved in two ways: master node to sensor nodes and from network nodes to network coordinator. However, in case of invasive sensors, human body becomes a hindrance for radio propagation. This makes multi-hop communication more appropriate for implanted sensors. Table 1 shows comparison in single-hop and multi-hop communication.

- **Signal Processing**

  The collection and processing of physiological signals in an efficient manner by consuming low power requires power-efficient signal processing mechanism. The compressed sensing (CS) method is used to test a scant analogue signal at sub-Nyquist rate, thus consuming less energy with no loss of information [16].

3.4 Communication Architecture of WBAN

The wireless body area network widely uses 3-tier communication architecture, illustrated in Figure 2.

The cardinal part of communication architecture is tier-1 that comprises of invasive and non-invasive sensor nodes [17], each of which is capable of capturing, diagnosing and communicating the body's vital information.

The sensor nodes are low powered, miniaturized, intelligent devices that are strategically placed on the body for prolonged health monitoring. However, star topology is the most common arrangement [18], in which the nodes are connected to the central coordinator in a star manner to collect the physiological signals and transfer the processed information through Zigbee or Bluetooth.

The second tier is located nearer to the sensor nodes and comprises of personal server employed on personal digital assistance (PDA) or cell phone. It provides a graphical user interface to the user and transmits processed information obtained from sensors to the central server. It is principally expedient for in-home observingof senile patients. The central server connects with sensor nodes of WBAN through network coordinator in order to communicate the information about the health status of user to top-tier through WLAN or internet [19].

The third tier is the central server (CS) that operates at top of the hierarchy [19]. The CS maintains the health information of the registered users in the form of electronic records and forwards it to numerous sources including wearer, caregiver,and medical personnel.Medical server is accountable for [18]:

- User authentication
- Assemblage and storage of health monitoring session uploads
- Introduction of session data to corresponding medical logs
- Examination of data patterns
- Identification of serious health abnormalities and contact the emergency personnel
- Providing prescribed recommendations to the user

The uploaded information is audited by the server agent and alert signals are issued in case of emergency. Data mining techniques can also be utilised to exercise the huge amount of collected data for knowledge discovery.

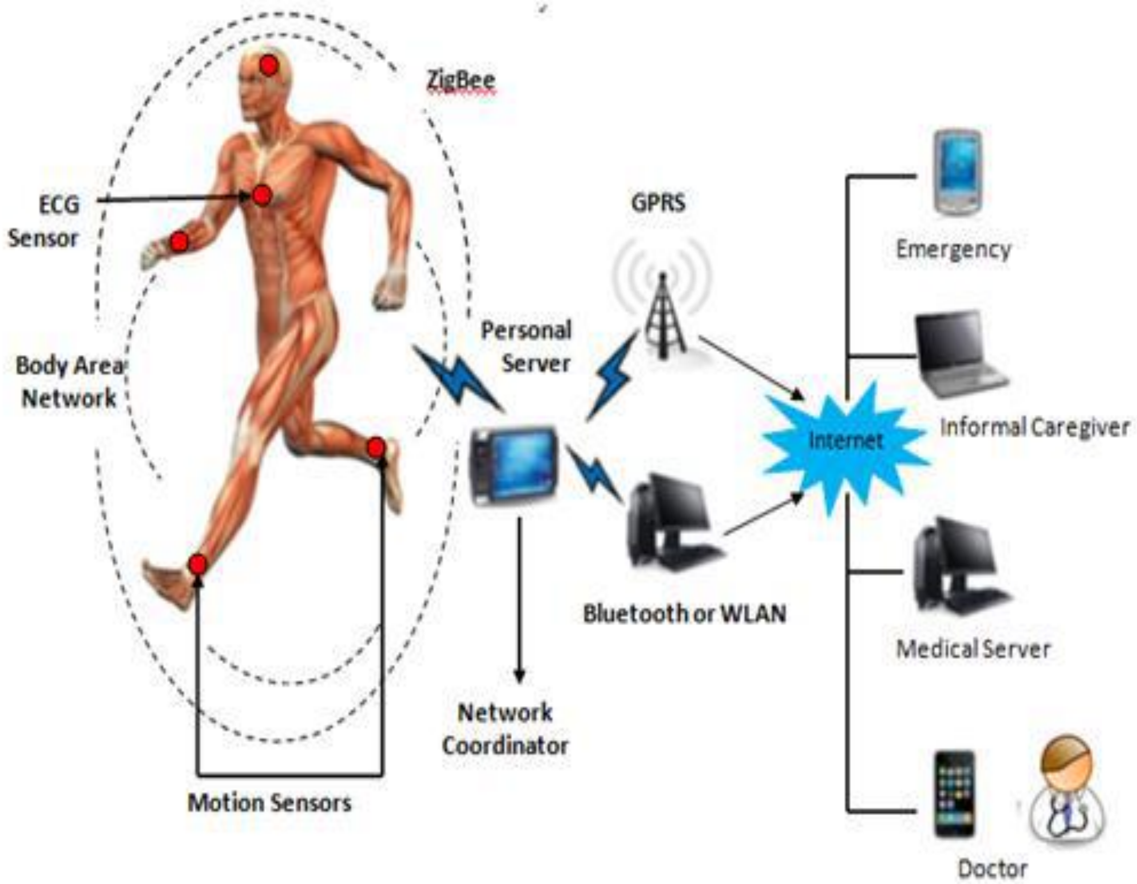


Figure 3.2: Communication Architecture of Wireless Body Area Networks

Data streaming from the human body to the Central Server demands higher energy consumption for information processing and transmission [20]. The reduction in the consumption of energy is, therefore, one of the most important aspects to be considered while designing an efficient wireless body area network. Following that, recent technological advancements have led to the development of communication standards, IEEE 802.15.4 and IEEE 802.15.6.

For accessing the shared channel, MAC protocols make use of various access mechanisms.Amongst numerous channel access techniques available for short range communication, MAC protocols either prefers Time Division Multiple Access (TDMA) or Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) techniques instead of Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). Further, studies have also suggested that due to high computational power and complex system design requirements, FDMA and CDMA are generally not considered suitable medium access mechanisms for low-powered range communication [21]. Although, CSMA/CA approach is also presumed to perform well for dynamic networks but, WBANs are not considered to be dynamic networks. This makes TDMA technique suitable for WBANs. However, the MAC protocols based on TDMA approach consider consuming extra energy for synchronization [14].

3.5 Communication Standards

3.5.1 IEEE 802.15.4

The working group for IEEE 802.15.4 [6] was approved in September 2006. It aimed to build a standard for Wireless Personal Area Network (WPAN) that operates on low frequencies and can be used for short range communications. Zigbee MAC states the conditions for Physical (PHY) and MAC layer

Zigbee MAC employs two kinds of devices: (i) Reduced Functional Device (RFD), and (ii) Full Functional Device (FFD) [13]. As RFD supports limited functionality and consumes low power, it is employed as network edge device. On the other hand, FFD supports full functionalities and thus is employed as network coordinator. The main role of FFD is to manage the network as a controller that mediates data signalling through other sensor nodes (usually deployed in a star topology).

The PHY layer of IEEE 802.15.4 functions in following three frequency bands using 27 sub channels [14].

(a) 2.4 GHz to 2.4835 GHz, divided into 16 sub-channels.

(b) 902 MHz to 928 MHz, divided into 10 sub-channels.

(c) 868 MHz to 868.6 MHz frequency band, use remaining 1 channel.

The variety of functions performed by the PHY layer of IEEE 802.15.4 includes initiation or deactivation of radio transceiver, measuring the strength of signal and indicating its quality, reception or transmission of data packets. However, MAC layer is held responsible for functions such as management of beacons, validation of frames, and channel assessment [23].

The MAC layer of IEEE 802.15.4 operates in two different modes [24]:

(a) Beacon enabled mode

(b) Non-beacon enabled mode

In beacon mode, the hub controls synchronisation and association of a device and is also responsible for transmission of data signals using periodic beacons. To do these functions, coordinator node uses a superframe that consists of active and inactive periods as shown in Figure 3.3. The active period is made up of 16 time slots and can be further separated into two parts [25]:

- **Contention Access Period (CAP)**

  In CAP, the devices can transmit the data signals randomly but within the time slot i.e. no device can start the signal transmission in the middle of the slot. All the devices that wish to communicate during CAP use slotted CSMA/CA mechanism to access the medium. Transmission of signals in this period is restricted by size of the CAP.

- **Contention Free Period (CFP)**

  CFP is used for guarantying the access of shared medium for specific number of slots, known as Guaranteed Time Slot (GTS). The coordinator can assign maximum of seven GTS to its end nodes for accommodation of time critical data in CFP.

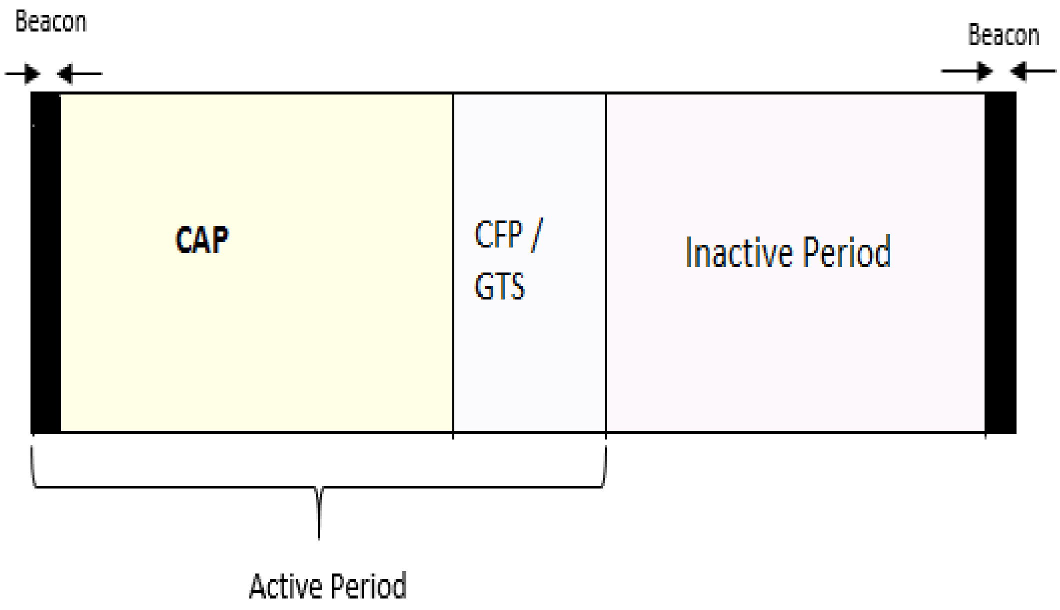


Figure 3.3: Superframe Structure of IEEE 802.15.4

Non-beacon enabled mode is extensively for those sensor devices that generally remain in sleep mode [25]. These sensors become active in case of occurrence of any critical event and send the alert signal using unslotted CSMA/CA technique. Unlike beacon enabled mode, there is no synchronisation of devices in this mode. Further, medium distribution is done randomly due to the absence of superframe and synchronisation of slots. Lastly, the use of Clear Channel Assessment (CCA) in this mode results in high energy consumption [25].

3.5.2 IEEE 802.15.6

A task group 6 of IEEE 802.15 was established in November 2007 for the standardisation of WBAN and named as IEEE 802.15.6 [26]. The aim of this group was to build a communication standard for short range communications using intelligent, low-powered and lightweight sensor nodes that can be located on or near the human body for prolonged health monitoring [27], personal assistance and other popular applications of WBAN.

IEEE 802.15.6 defines a MAC layer that operates on three different physical layers (PHY) or frequency bands: Narrowband (NB), Ultra-Wide band (UWB) and Human Body Communications (HBC) [28]. With the help of these different radio frequencies, WBAN can co-exist with other wireless systems, which include Wi-Fi and Bluetooth. However, the probability of interference with other wireless systems (especially IEEE 802.15.4) is high in case of WBAN. Importantly, baseline BAN MAC provides different ways to mitigate this interference by providing solutions which include [29]: beacon shifting, time sharing and load reduction.

For the purpose of better resource allocation, IEEE 802.15.6 split the shared medium into superframes or beacon periods of same length [30]. Each superframe consist of multiple allocation slots which are used for the transmission of data signals. Beacons are used to initialise a superframe and are generally communicated by the coordinator in each beacon period, except inactive periods. Furthermore, the access phases of a beacon period of IEEE 802.15.6 are categorised in following four types:

i. Exclusive Access Phase (EAP)

In EAP, the hub sets a time span in a beacon period for the transfer of data signals through the users of highest priority.

ii. Random Access Phase (RAP)

In RAP, the hub sets a time span for random access of medium by the sensor nodes in WBAN. The sensor nodes are notified for this access through a beacon frame.

iii. Managed Access Phase (MAP)

In MAP, the hub sets a time span for an improvised, scheduled and unscheduled access of medium by sensor nodes and the hub.

iv. Contention Access Phase (CAP)

In CAP, the hub announces a time span for contention access of the medium via preceding non-beacon frame and the medium can be accessed by the nodes of a network.

In each period of superframe, the channel can be accessed in three different ways that include:

- Random access method either employs CSMA/CA or slotted ALOHA protocol for resource allocation

- Improved and unscheduled access use unscheduled polling/posting technique for the purpose of resource allocation
- Scheduled and scheduled-polling access is used for slot allocation in one or multiple frames [23].

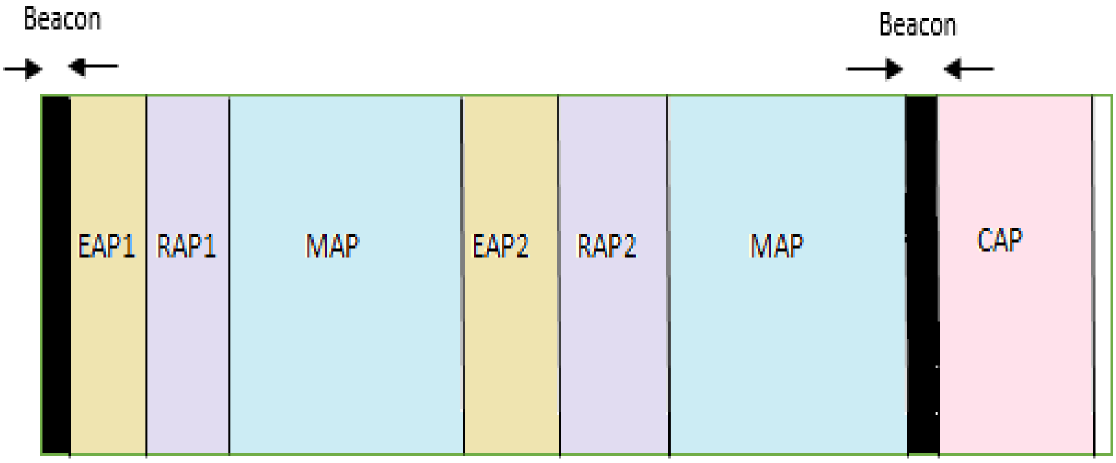


Figure 3.4: Superframe Structure of IEEE 802.15.6

CHAPTER 4

PROBLEM STATEMENT AND OBJECTIVE

4.1 Problem Statement

Data transmission from the human body to the Central Server demands high energy consumption for information acquisition and transmission. The reduction in the consumption of energy is, therefore, one of the most important aspects to be considered while designing an efficient wireless body area network. Following that recent technological advancements have led to the development of energy efficient MAC and routing protocols. An efficient MAC protocol aims at maximising network lifetime and minimising end to end delay in successful packet transmission, to achieve maximum throughput. This aim is being achieved by controlling the major sources of energy dissipation including retransmission of data packets, control packet overhead, collision of packets, idle listening, state switching, frequent transceiver switching and overhearing.

For accessing the shared channel, MAC protocols make use of various access mechanisms. Amongst numerous channel access techniques available for short range communication, MAC protocols either prefers TDMA or CSMA/CA access techniques instead of FDMA and CDMA. Further, studies have also suggested that due to high computational power and complex system design requirements, FDMA and CDMA are generally not considered suitable medium access mechanisms for low-powered range communication. Although, CSMA/CA approach is also presumed to perform well for dynamic networks but, WBANs are not considered to be dynamic networks. This makes TDMA technique suitable for WBANs. However, the MAC protocols based on TDMA approach consider consuming extra energy for synchronization.

4.2 Objective

To reduce the consumption of energy in applications based on WBAN, several protocols and standards were designed. In our study, we have analysed and compared the performances of two MAC protocols namely, Zigbee MAC (IEEE 802.15.4) and

Baseline BAN MAC (IEEE 802.15.6). The comparisons were done on the basis of following three parameters:

(i) throughput

(ii) total energy consumption

(iii) latency, recorded during the transmission of data signals.

The objectives of thesis are accomplished by performing the following sub tasks:

- To analyse ZigbeeMAC protocol, based on IEEE 802.15.4
- To analyse BaselineMAC protocol, based on IEEE 802.15.6
- To compare the protocols on the basis of above mentioned parameters.

CHAPTER 5

INSTALLATION AND SIMULATION

5.1 Ubuntu

Ubuntu [31] is an open source Debian based Linux operating system. It utilises Unity as its default user interface. Occurrence of Ubuntu was led by UK-based Canonical Ltd. The aim of this operating system is to be secure "out-of-the box".

5.2 OMNeT++

OMNeT++ framework [33] is an extendible, segmental, component-based C++ simulation library, predominantly employed for developing simulators and emulators for wireless networks. OMNeT++ proposes an Eclipse-based IDE, a graphical runtime atmosphere, and a presenter of additional tools. There are extensions for real-time simulation, network imitation, database integration, SystemC assimilation, and numerous other utilities.

OMNeT++ offers a modulardesign for models. Programming of modules is done in C++ which are then aggregated into bigger modules and prototypes using a high-level language (NED). This framework has massive GUI support, and the insertion ofsimulation kernel into various applications becomes easy because of the component-based design of the framework.

5.3 Castalia – 3.2

5.3.1 Overview

Castalia [32], an OMNeT++ basedsimulator is extensively used for Wireless Sensor Networks (WSN), Body Area Networks (BAN) and for networks of low-power embedded devices. Researchers can make use of Castalia forevaluating their distributed algorithms and/or techniques in credible wireless channel and radio models, with a convincing node behaviour especially when it is related to access of radio channel. The main highlights of Castalia are:

- Progressive channel model grounded on real-time data
- Channel model explains theentire path loss map instead of only defining the connections between nodes
- Composite model for time-baseddisparity of path loss
- Complete provision for movement of nodes
- Intrusion is treated as obtained signal strength and not evaluated separately
- Progressive radio model grounded on factual radios for power efficient communication
- Comprehensive sensing and modelling abilities
- Accessibility of MAC and routing protocols
- Aimed for adaption and extension.

The modularity, consistency, and rapidity of Castalia is partiallyempowered by OMNeT++ framework.

5.3.2 Structure

The basic component structure of Castalia is shown in Figure 5.1.

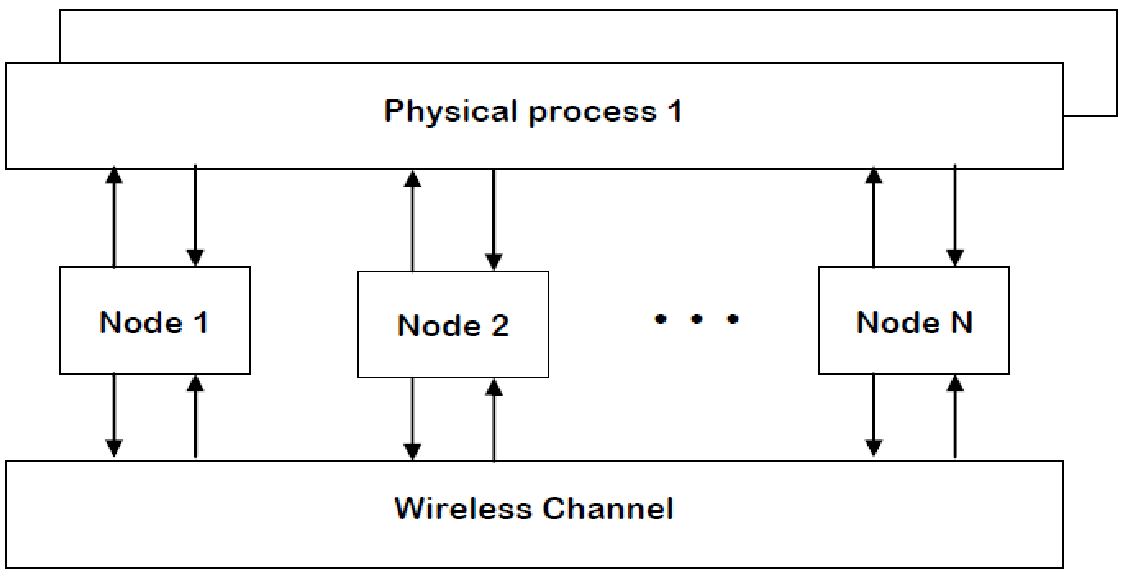


Figure 5.1: Castalia's modules and connections [32]

Figure 5.1 depicts that the nodes are not directly connected to each other. The connectivity of nodes is maintained through wireless channel module(s). The arrows indicatethe flow of messagesamong various segments. When a node has a packet to transmit, it moves the packet to the wireless channel which then decides the destination node. The nodes are also connectedvia physical procedures monitored by them. For each physical process there is a corresponding segment that holds the "truth" of the quantity, for which the physical process is signifying. The network nodesexamine the physical process in space and time to get their sensor readings.A node can be a collection of number of sensors signifying multiple physical processes.

The node module is a composite module as illustrated in Figure 5.2. The solid arrows indicate data transmission and the dashed pointersrepresent simple function calling. To indicate the consumption of energy, most of the segmentsrequest a utility of the resource manager.The changes are mostly done in application module for performing a simulation or designing a new segment to design and implement a new algorithm. The changes can also be accomplished in MAC and Routing modules, as well as the Mobility Manager segment. Castalia providesprovision for designing your own protocols, or applications by describingapposite abstract classes. Even the existing modules can be greatly tuned by numerous parameters.

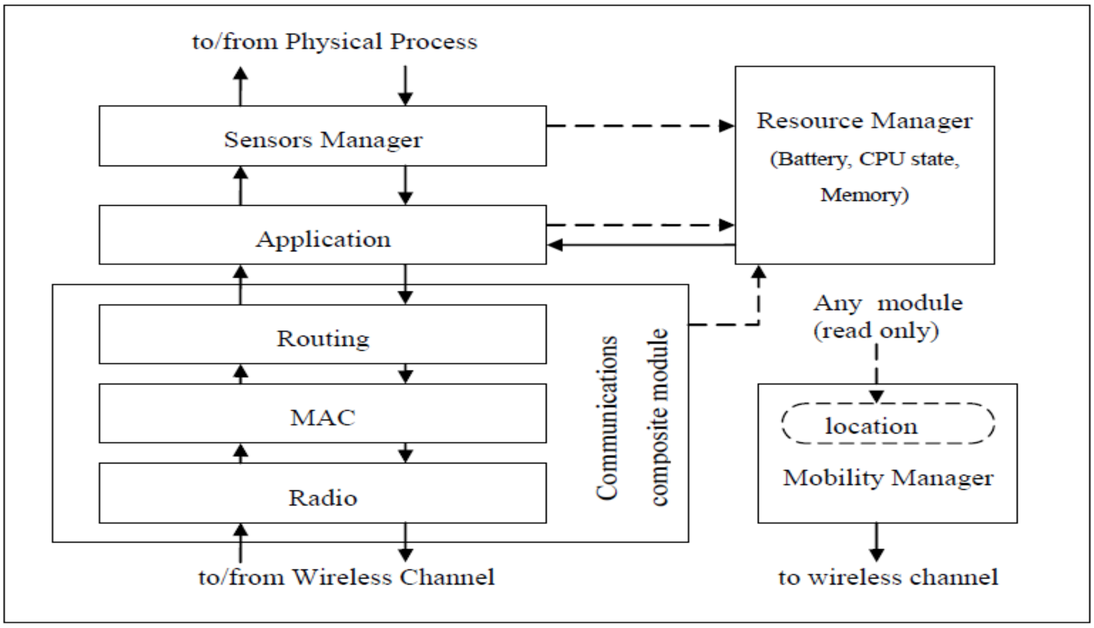


Figure 5.2: Composite node module [32]

5.4 Simulation

The simulator model comprises of three main modules i.e. physical process, wireless channel and sensors. Castalia provides CC2420.txt radio model for the integration of real demonstration of IEEE 802.15.4 operated on the frequency of 2.4 GHz with 4 bits of the symbol rate. The sensor module comprises of six sensor nodes including one coordinator node and rest acting as network edge devices. The sensor nodes were arranged in a star topology as shown in Figure 5.3. The nodes access the wireless channel using CSMA/CA mechanism. The simulation parameters involved in the experimentation are summarized in Table 5.1.

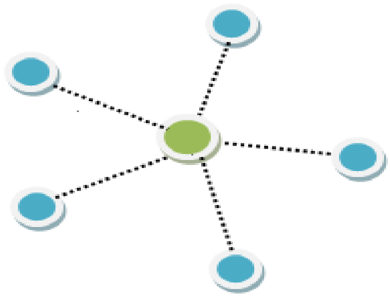


Figure 5.3: Star topology of WBAN

Table 5.1: Simulation Parameters

Parameters	**Values**
Nodes	6
Topology	Star
MAC protocols	IEEE802.15.4 IEEE 802.15.6
Access Mechanism	CSMA/CA
Frequency Band	2.4 GHz
Evaluation Parameters	Throughput, latency, consumed energy
Simulation Time	3600 seconds

CHAPTER 6

RESULTS AND DISCUSSION

Castalia simulator is an extensively designed simulator which is generally used to evaluate wireless networks, comprising low-power embedded devices. This simulator also offers various MAC model implementations, among which we have compared and evaluated the performances of Zigbee MAC and Baseline BAN MAC protocols on the basis throughput, delay, and consumption of energy.

The results of the simulations are discussed in this section. The simulations were carried out under three different environmental variations (scenarios):

Scenario 1: Varying GTS modes and temporal variations

Scenario 2: Varying Power supply to the nodes

Scenario 3: Varying random and scheduled time slots

The throughput, delay and energy consumption of both the protocols were recorded and analysed under all the above-mentioned scenarios.

```
jasleen@jasleen-VirtualBox:~/Castalia-3.2/Simulations/BANtest$ CastaliaResults -i 160615-232620.txt

+--------------------+---------------------------------------+------------+
|             Module |                                Output | Dimensions |
+--------------------+---------------------------------------+------------+
|        Application |       Application level latency, in ms | 1x1(31)    |
|                    |              Packets received per node | 1x1        |
|  Communication.MAC |                    Data pkt breakdown | 1x1(4)     |
|                    | Fraction of time without PAN connection | 5x1(3)   |
|                    |              Mgmt & Ctrl pkt breakdown | 6x1(3)     |
|                    |              Number of beacons received | 5x1       |
|                    |                  Number of beacons sent | 1x1       |
|                    |                       Packet breakdown | 1x1(4)     |
|                    |                  pkt TX state breakdown | 1x1       |
|                    |                              var stats | 6x1(2)     |
| Communication.Radio |                     RX pkt breakdown | 6x1(5)     |
|                    |                             TXed pkts | 6x1        |
|    ResourceManager |                        Consumed Energy | 6x1        |
|     wirelessChannel |                Fade depth distribution | 1x1(14)   |
+--------------------+---------------------------------------+------------+
```

Figure 6.1: General output parameters of simulation

The information obtained from the simulation was converted into readable text file with the help of CastaliaResults script. Each output has A × B dimension, where A is the number of sections responsible for the output and B indicates the number of nodes responsible for producing the output of the module. However if the result was not scalar then its multiplicity was shown in parenthesis (Figure 6.1).

6.1 Analysis of Energy Consumption

Energy Consumption is considered as one of the important parameters to be taken into consideration while designing a MAC protocol for WBAN. Therefore, the total energy consumed by both the protocols was evaluated, while they were subjected to different conditions and were represented in the form of graphs as shown below.

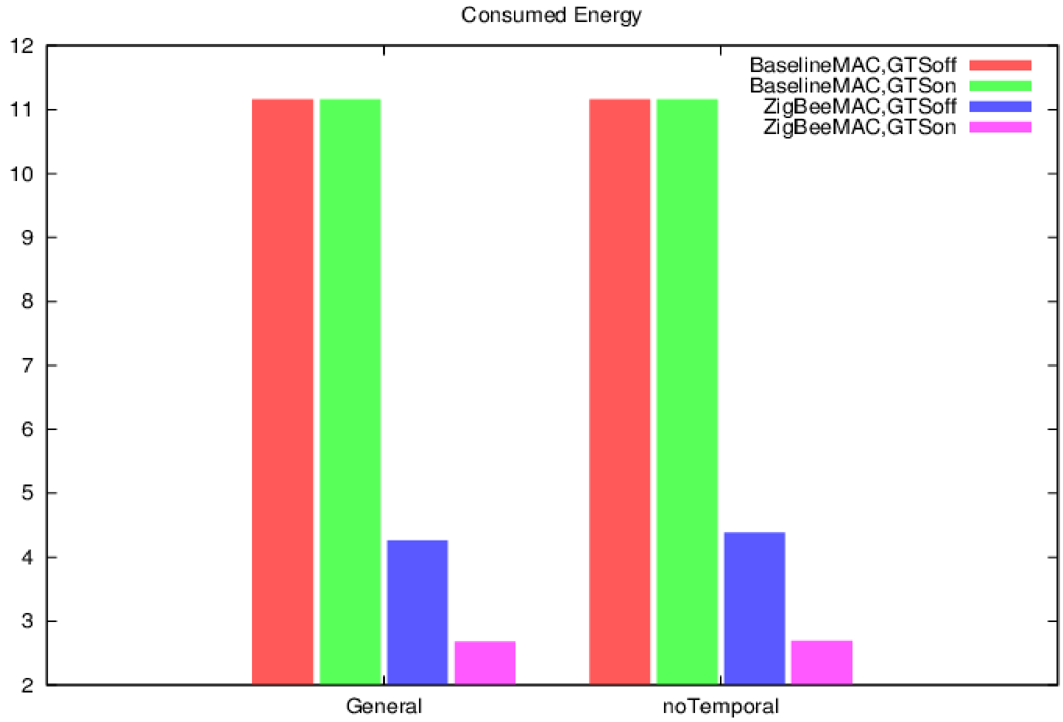


Figure 6.2: Comparison of Energy Consumption(Scenario 1)

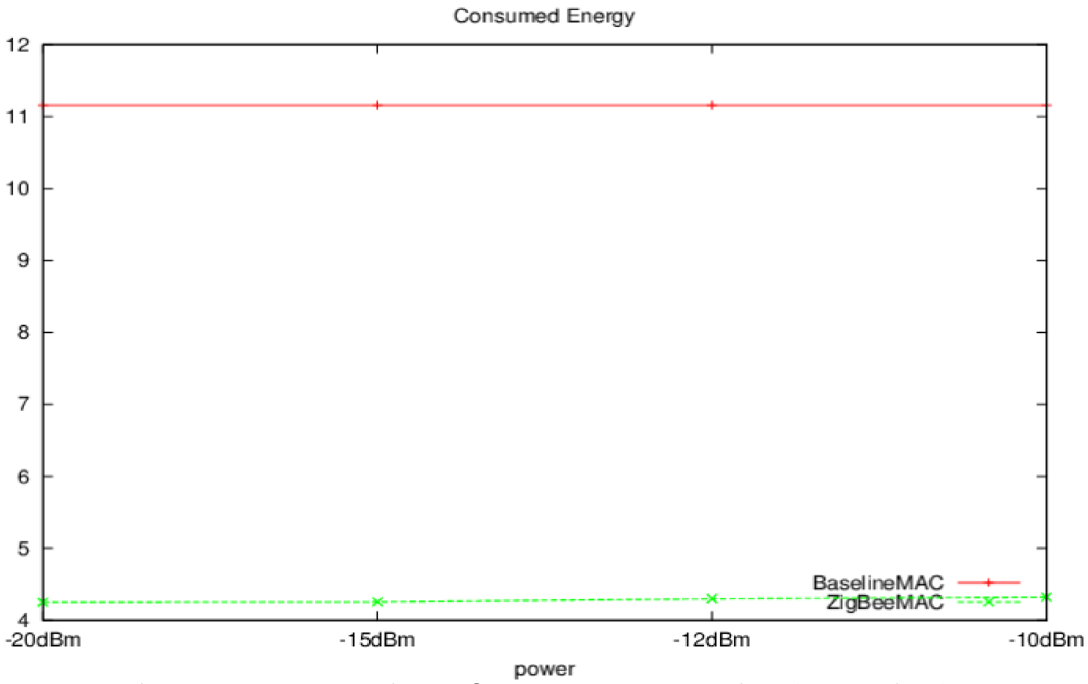


Figure 6.3: Comparison of Energy Consumption (Scenario 2)

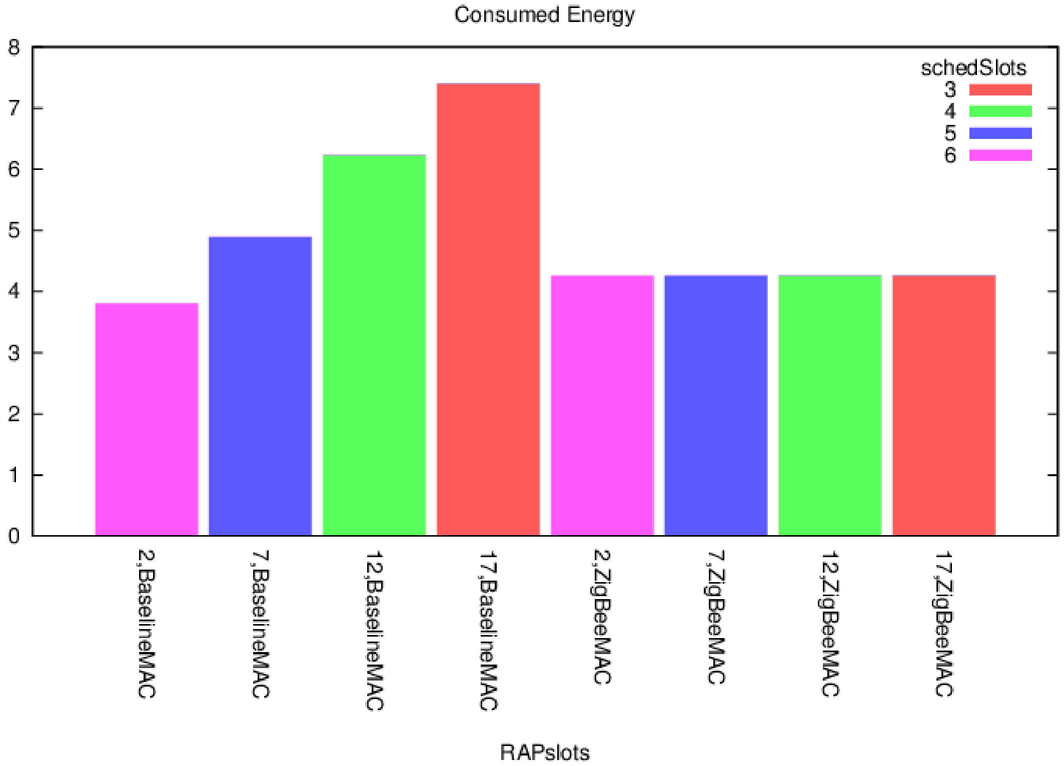


Figure 6.4: Comparison of Energy Consumption (Scenario 3)

The results as shown in the above graphs demonstrated that the Baseline BAN MAC protocol has more energy consumption compared to the Zigbee MAC protocol. Furthermore, the temporal variations generally did not affected the energy consumption, but a significant reduction in energy consumption was observed for Zigbee MAC protocol, when GTS mode was turned ON (Figure 6.2). Further, it was observed that the energy consumption was not affected by varying power supply. However, a significant reduction in energy consumption using Baseline BAN MAC protocol was observed when number of scheduled time slots for packet transmission were increased (Figure 6.4). The best cases are compared in Table 6.1 which illustrates that Zigbee MAC performs best when GTS mode is ON and there are no temporal variations whereas Baseline MAC performs best when scheduled time slots are more than random access time slots.

Table 6.1: Comparison of Minimum Energy Consumption (in joules) in different scenarios

Protocol	**Vary GTS and Temporal Variation**	**Vary Power Supply**	**Vary Random and Scheduled time Slots**
ZigbeeMAC	2.5 (GTS on)	4.2 (constant)	4.258 (RAP = 17, scheduled = 3)
Baseline MAC	11 (constant)	11.2 (constant)	3.804 (RAP = 2, scheduled = 6)

6.2 Latency Analysis

The differences in latency for successfully transmitted packets through Zigbee MAC and Baseline BAN MAC protocols were demonstrated as follows:

Scenario 1: Latency in packet transmission under different GTS modes and varying temporal conditions

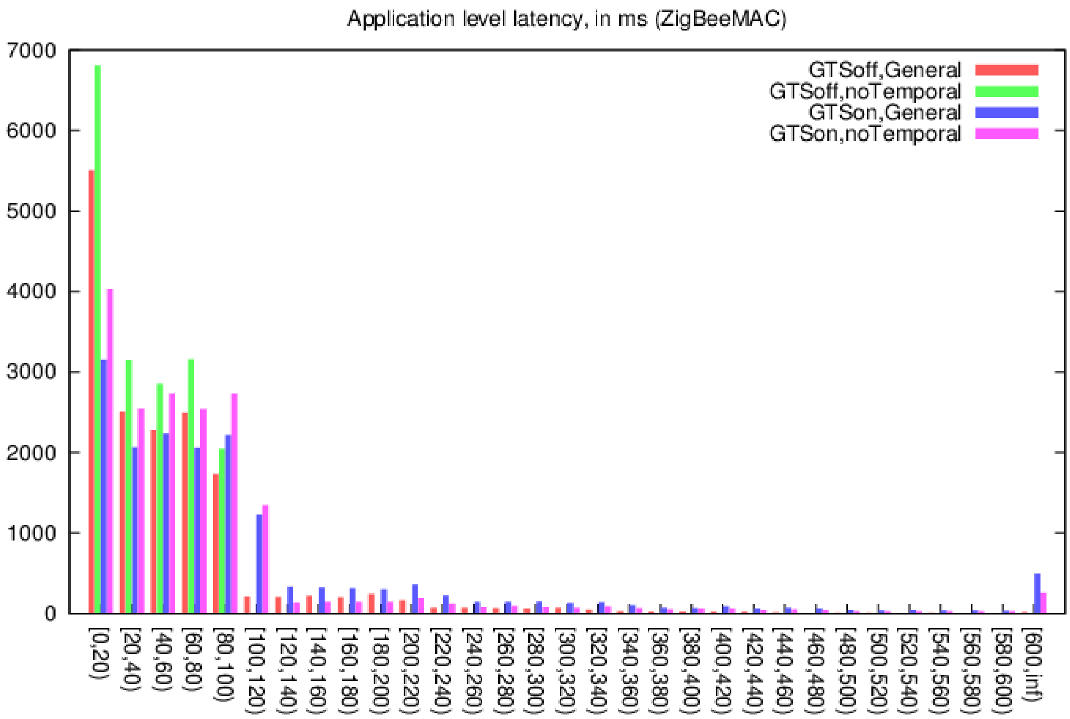


Figure 6.5: Latency during packet transmission in ZigbeeMAC protocol (Scenario 1)

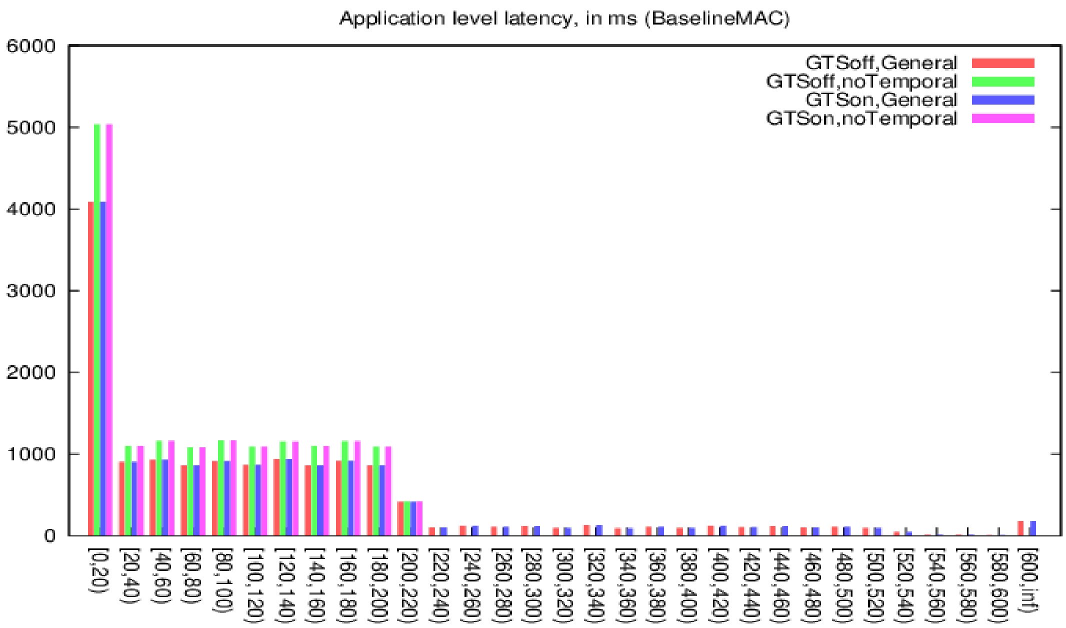


Figure 6.6: Latency during packet transmission in BaselineMAC protocol (Scenario 1)

Scenario 2: Latency in packet transmission when power supplied to the nodes is varied

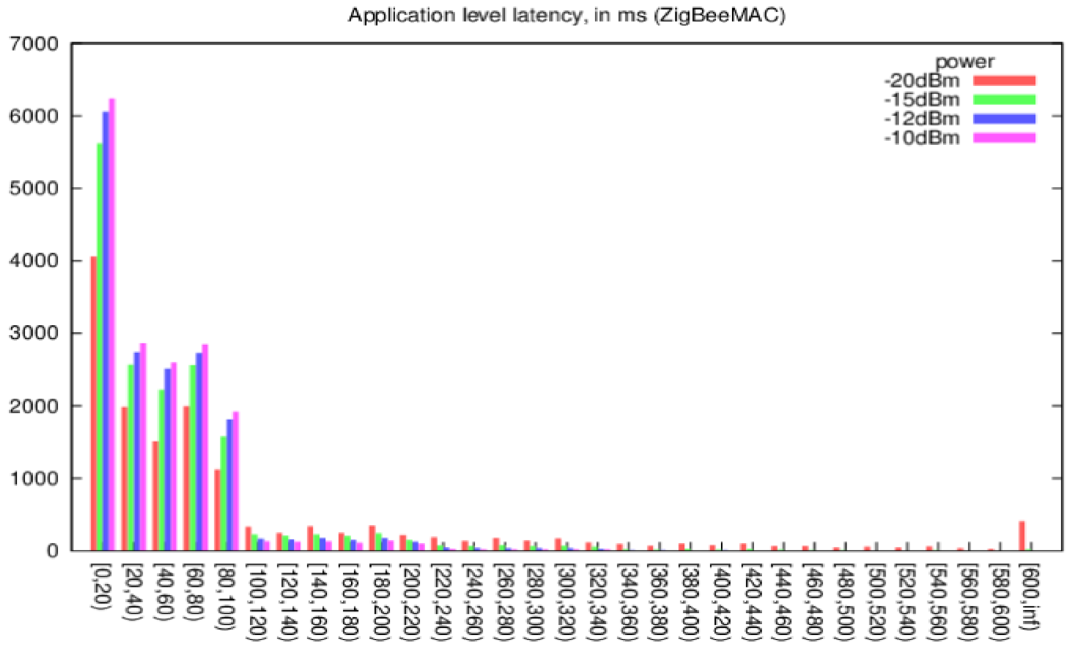


Figure 6.7: Latency during packet transmission in ZigbeeMAC protocol (Scenario 2)

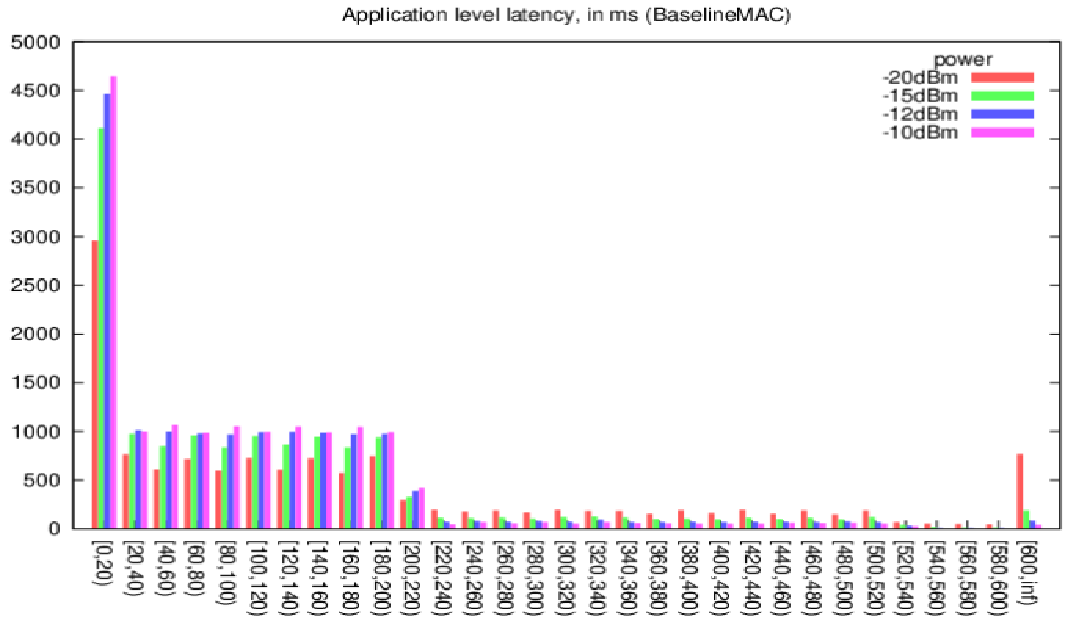


Figure 6.8: Latency during packet transmission in BaselineMAC protocol (Scenario 2)

Scenario 3: Latency in packet transmission when number of random access slots and scheduled access slots are variable.

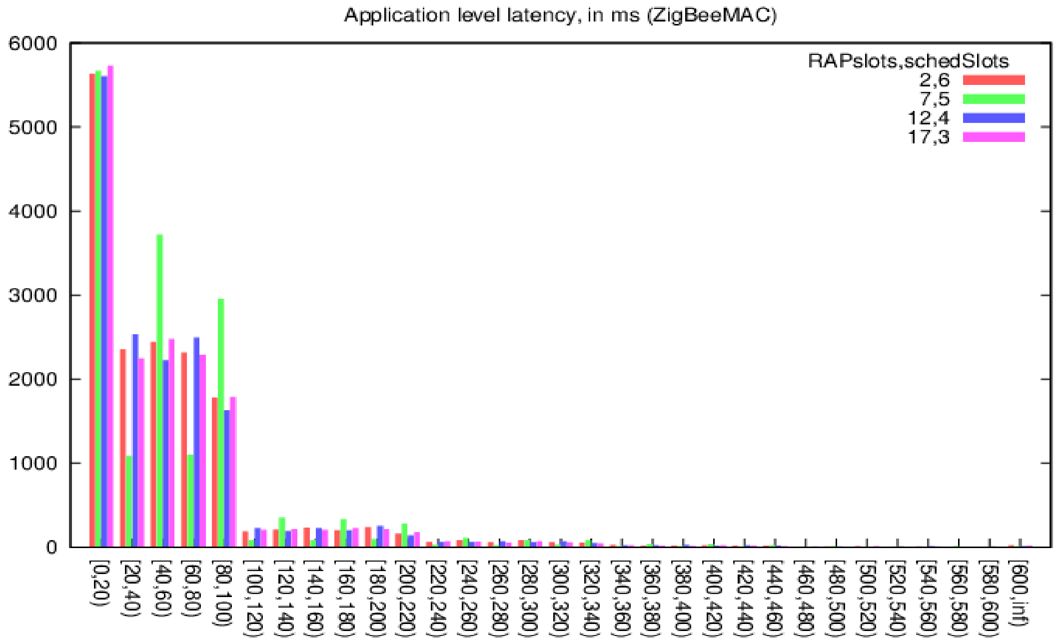


Figure 6.9: Latency during packet transmission in ZigbeeMAC protocol (Scenario 3)

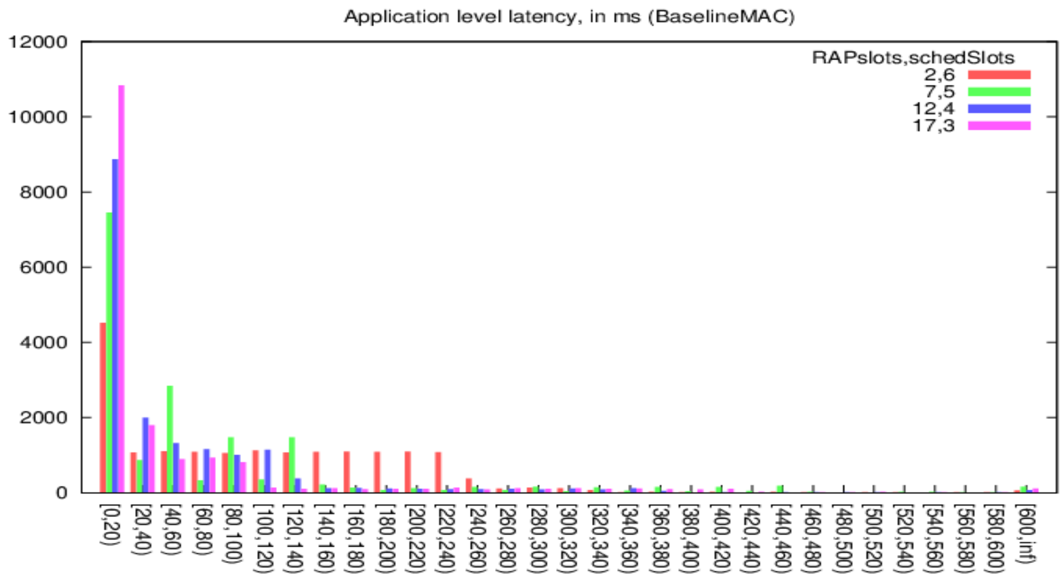


Figure 6.10: Latency during packet transmission in Baseline MAC protocol (scenario 3)

Our analysis demonstrated that irrespective of the protocol type, most of the packets were successfully delivered under 120 milliseconds (ms) of latency (which lower than an acceptable value *i.e.* 250 ms), that makes both the protocols suitable for biomedical applications. However, when GTS mode is ON, the number of packets delivered through Zigbee MAC (6900 packets) protocol with delay of 20 ms were much more than that what were delivered through Baseline BAN MAC protocol (5000 packets) . Furthermore, it can be noticed that both protocols transmit the maximum number of packets at -10 dBm of power supply. However a huge increase in packet transmission of Baseline MAC is observed when scheduled slots =3 and random access slots = 13.

The comparison of maximum number of transmitted packets under 20 ms of delay is illustrated in table 6.2.

Table 6.2: Comparison of Maximum packet transmission with 20 ms delay in different scenarios

Protocol	Vary GTS and Temporal Variation	Vary Power Supply	Vary Random and Scheduled time Slots
ZigbeeMAC	~6900 (GTS on)	~ 6200 (-10 dBm)	~5900 (RAP = 17, scheduled = 3)
Baseline MAC	~5000 (no temporal)	~ 4700 (-10 dBm)	~11000 (RAP = 17, scheduled = 3)

6.3 Throughput Analysis

Packets received per node, considered as throughput were compared for both Zigbee MAC and Baseline BAN MAC protocols subjected to different scenarios and the observations are illustrated as follows:

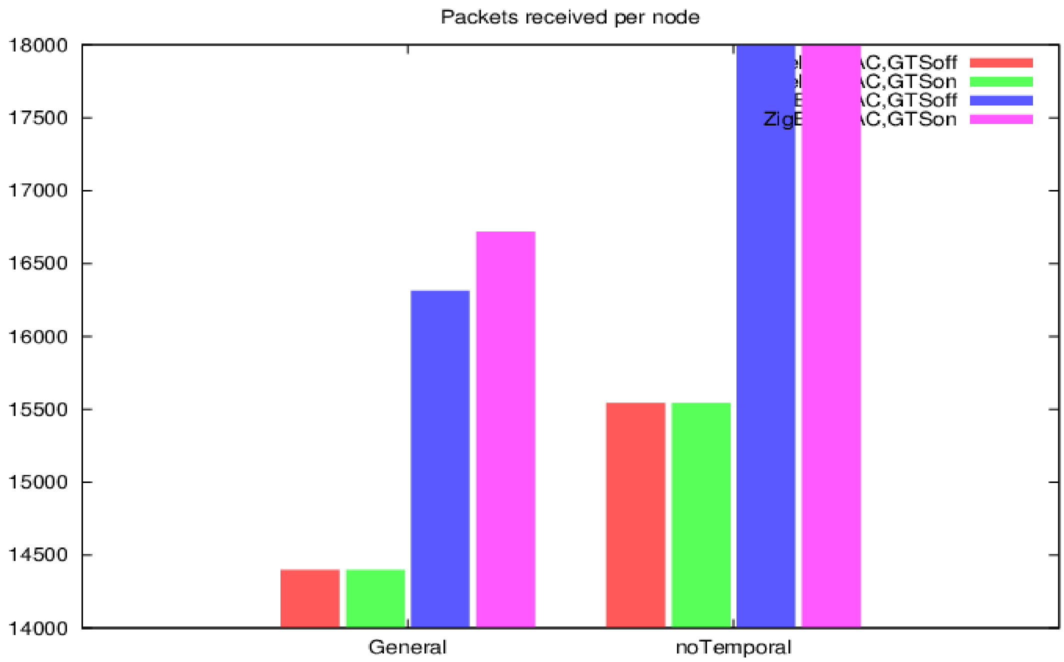


Figure 6.11: Throughput Analysis of MAC protocols in Scenario 1

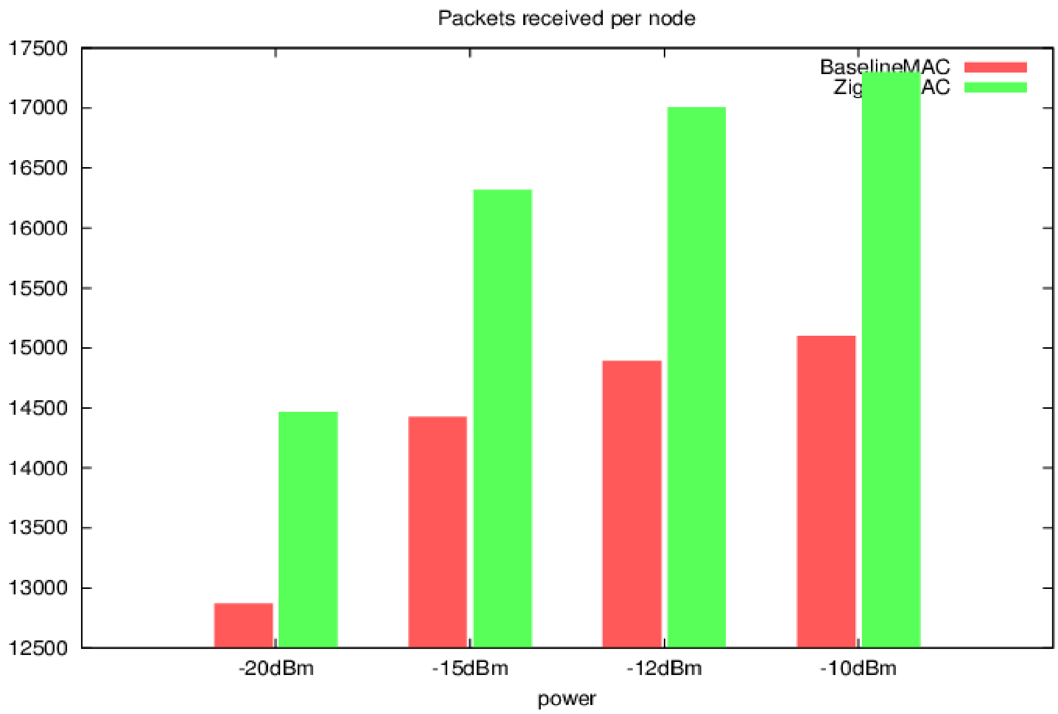


Figure 6.12: Throughput Analysis of MAC protocols in Scenario 2

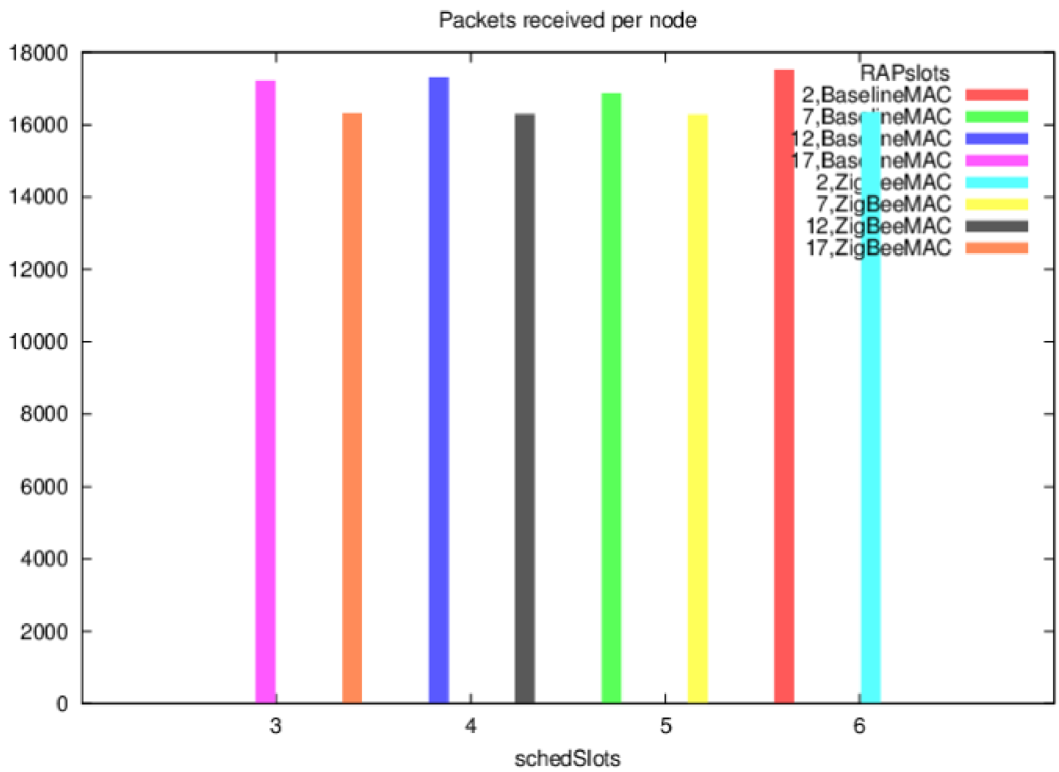


Figure 6.13: Throughput Analysis of MAC protocols in Scenario 3

In our study it was observed that Zigbee MAC records its highest throughput when temporal variations were not considered. But we observed that even with consideration of temporal variations Zigbee MAC protocol performed better than that of Baseline BAN MAC (Scenario 1). It was further noticed that both the MAC protocols records their maximum throughput at -10 dBm of power supply. In scenario 3, we have noticed a remarkable improvement in throughput of Baseline BAN MAC protocol which was due to the increase in number of slots for scheduled access. Table 6.3 compares the values of maximum throughput of both protocols subjected to various environmental variations.

Table 6.3: Comparison Maximum Throughput of both the MAC protocols

Protocol	Vary GTS and Temporal Variation	Vary Power Supply	Vary Random and Scheduled time Slots
ZigbeeMAC	17995.4 (no temporal)	17301.6 (-10 dBm)	16355 (RAP = 2, scheduled = 6)
Baseline MAC	15544.8 (no temporal)	15102.8 (-10 dBm)	17520 (RAP = 2, scheduled = 6)

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

Advancements in the field of WBAN have encouraged the development of numerous medical and non-medical applications. However, the stringent energy requirements of WBAN have led to the optimisation of MAC protocols.

The objective of the work was to analyse the working of IEEE 802.15.4 (Zigbee MAC) and IEEE 802.15.6 (Baseline BAN MAC) standards. On evaluating the performance of both the protocols using OMNET++ based Castalia-3.2 simulator. Through the evaluations, it is observed that Zigbee MAC performs better than Baseline BAN MAC protocols in terms of throughput, energy consumption and latency when it is subjected to no temporal variations and GTS mode is ON. Itwas further observed that both protocols perform best when -10dBm of power is supplied to the nodes. However, a remarkable improvement in the performance of Baseline BAN MAC protocol is observed when number of scheduled slots for packet transmission are increased. Furthermore, Zigbee MAC protocol performs best when random channel access is permitted along with GTS whereas efficient functioning of Baseline MAC protocol requires a proper combination of scheduled and random access slots to access the channel.

7.2 Future Scope

Due to the applicability of body area networks, they can have enormous applications in medical health and other areas. Further, market analyses show a great promise and integration of BAN into health delivery, which will enhance health and wellness. However, this requires a deeper knowledge of the underlying principles related to the functioning of BAN. Therefore, this provide great opportunities involving the designing of energy efficient MAC protocols that can work with multiple standards to improve the efficiency of existing BAN.

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ANNEXURE I

LIST OF PUBLICATIONS

Communicated

Jasleen Kaur, A.K. Verma, "Comparative Analysis of MAC protocols for Wireless Body Area Networks", in *International Conference on Signal Processing, (*2016), to be held from November 7-9, 2016 at Samrat Ashok Technological Institute (SATI), Vidisha, Madhya Pradesh, India.

ANNEXURE II

VIDEO PRESENTATION

https://youtu.be/0yZWAIWowec