IMPLEMENTATION OF MEDIUM ACCESS CONTROL PROTOCOLS FOR WIRELESS BODY AREA NETWORKS

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-: Thesis Abstract :-

Wireless Body Area Networks (WBANs) is one of the most suitable technologies for building unobtrusive, scalable, and robust wearable health monitoring systems that enable physicians to remotely monitor vital signs of patients and provide real-time feedback with medical diagnosis and consultations. A Medium Access Control (MAC) layer is effective in addressing energy efficiency in WBANs and providing longer lifetimes for WBANs nodes. In this thesis we study techniques for improving the performance of WBAN MAC protocols and develop techniques for modelling WBAN MAC protocol performance, especially considering that when work in thesis was first started 802.15.6 had not been standardised and transition approaches were needed.

When IEEE 802.15.6 was in the process of being standardized the existing IEEE 802.15.4 protocol or a modification of it was considered as an interim solution. This part of the project investigated 802.15.4's suitability for WBANs implant applications. In its unmodified form it was not suitable for in-body communication because it had to be transmitted at too high a power level. We implemented in Network Simulator (NS-2) a low power modification to study its performance. We implemented the 802.15.6 communication link channel model CM1 (implant to implant) and channel model CM2 (between an implant device and an on or out-of body device) in NS-2 and changed the power parameters of IEEE 802.15.4 so that it can be compatible for IEEE 802.15.6. Using simulation we determined path loss and received signal strength for several distances from the transmitter and receiver. We also analyzed packet delivery ratio, energy consumption and transmission delay. The simulation results in NS-2, successfully confirmed that the modified IEEE 802.15.4 protocol could be used in WBANs. Our results showed that CM1 had less path loss and its energy consumption and packet delivery ratio is also much smaller than CM2.

Emergency data delivery is an important service for medical WBANs. The utmost importance of emergency message dissemination requires high reliability and low delay. Channel access delay minimization is very important in WBANs because delayed delivery of an emergency message can endanger a human life. IEEE 802.15.6 beacon enabled networks have defined an adjustable superframe structure that consists of contention-free and contention access periods. Short superframes can satisfy the channel access delay requirements of emergency traffic but penalize the energy efficiency of all devices in the network. On the other hand, long superframes increase the energy efficiency but the channel access delay is also increased. To balance this contradicting requirement of energy efficiency and Quality of Service (QoS), we propose the Medical Emergency Body (MEB) MAC protocol that inserts listening windows dynamically within the contention free periods to reduce access delay for emergency data. MEB MAC utilizes idle time slots to insert additional listening window opportunities for emergency traffic, without affecting the network throughput. The frequency of listening window insertion is determined by the minimum delay tolerance. Our analysis shows that MEB MAC is able to reduce channel access delay for emergency traffic especially for long superframe durations.

OPNET Modeler is an industry leading discrete-event network modeling and simulation environment, commonly used due to its accuracy and better graphical user interface. It is an important tool for developing wireless protocols. In the last part of the thesis, we implemented the superframe structure and various application traffic models as recommended in IEEE 802.15.6 modifying the OPNET module of OPEN-ZB. To the best of our knowledge, this is the first ever protocol built in OPNET based on IEEE 802.15.6. It was used to implement the MEB MAC protocol. Based on simulation and analysis of results this work can be considered as a guide for researchers in evaluating OPNET for WBANs.

This is to certify that

(i) the thesis comprises only my original work,

(ii) due acknowledgement has been made in the text to all other material used,

(iii) the thesis is less than 50,000 words in length, exclusive of table, maps, bibliographies, appendices and footnotes.

Date : 17th April-2014

Signature

Acknowledgments

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Acronyms

CAP	Contention Access Period
CBR	Constant Bit Rate
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CFP	Contention Free Period
CM	Channel Model
CAD	Channel Access Delay
CSMA	Carrier Sense Multiple Access
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
ETS	Emergency Traffic Source
GTS	Guaranteed Time Slot
HBC	Human Body Communication
LR-WPAN	Low-rate Wireless Personal Area Network
LW	Listening window
MAC	Medium Access Control
MICS	Medical Implant Communication Systems
MAP	Managed Access Phase
NB	Narrowband
PAN	Personal Area Network
PHY	Physical
PDR	Packet Delivery Ratio
RAP	Random Access Phase
QoS	Quality of Service
SAR	Specific Absorption Rate
SD	Superframe Duration
SF	Superframe
TDMA	Time Division Multiple Access
UWB	Ultra-wideband
WAN	Wide Area Network
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WBAN	Wireless Body Area Network
WPAN	Wireless Personal Area Network
WSN	Wireless Sensor Network
WWAN	Wireless Wide Area Network

Chapter 1
Introduction

1.1 Introduction

The relentless strive for peoples' well-being through various implementations, has led medicine to seek synergy with other disciplines, specially engineering. With the advent of telecommunication technology wearable or mobile health monitoring [1-7] has been an emerging research issues now-a-days. Monitoring patients and maintaining their health records is important for effective disease and health management. Conventional health-care systems which include phone-based telehealth applications, paid nurse visits and assisted living/nursing homecare have many problems on their own. Moreover, the available medical monitoring systems are generally bulky and thus uncomfortable to be carried by patients. Most of the current effort has mainly concentrated on the devices that are monitoring one or few physiological signals only [5]. When multiple sensors are involved, wires are used to connect the sensors to a wearable wireless transmitter. Wired systems restrict patients' mobility and comfort level, especially during sleep studies. The elimination of wires not only promises significant cost savings but also an extensive increase in the scale of these applications. Moreover, a shortage of skilled professionals, overload and limited healthcare budgets have aggravated the impending healthcare crisis. Because of the Internet and good telecommunications infrastructure more reliable and connected delivery is possible at home now. This is why the current trend in healthcare systems has been diversified towards home and community-based care instead of institutional care by using small, low-power sensor nodes with wireless capability where the target is to achieve an affordable, instant and efficient healthcare solutions.

To develop communication standards for using wireless technologies for medical device communications in various healthcare services, consumer electronics, personal entertainment and other areas, at the end of 2007, IEEE launched a new task group of IEEE 802.15.6 [8] known as Wireless Body Area Networks (WBANs) [9-14]. Figure 1.1 shows the activities of the IEEE task groups who are developing the communication standard Wireless Personal Area Network (WPAN) [15] and WBANs.

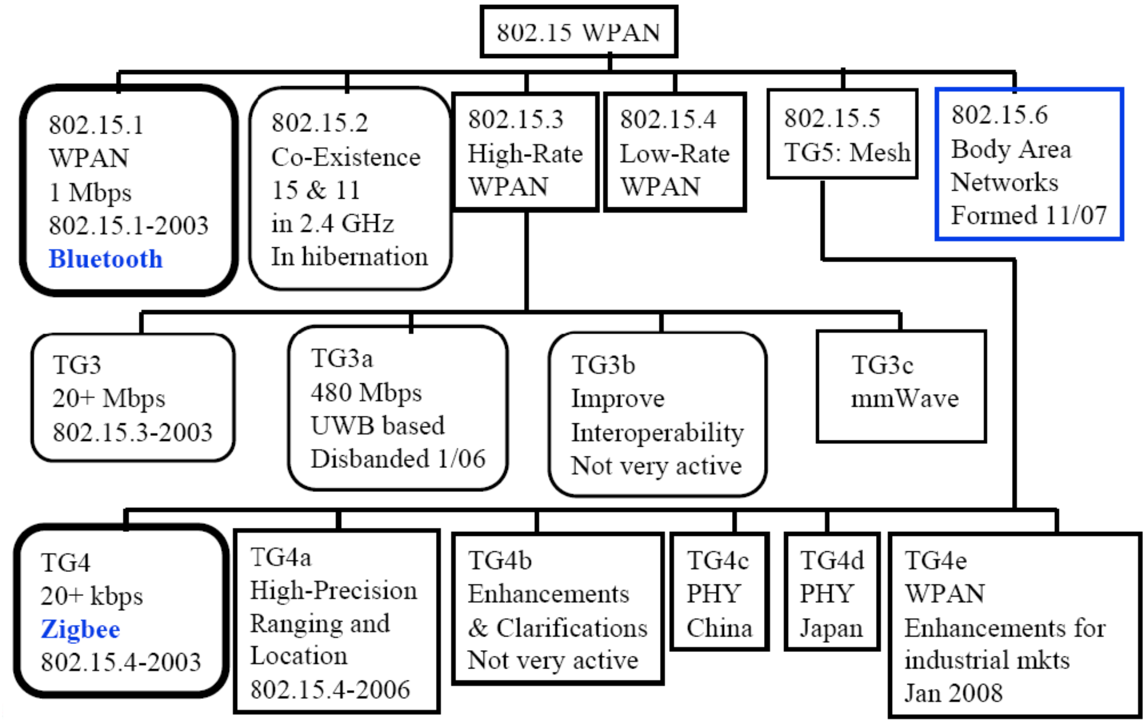


Figure 1.1: IEEE Task group's activities for Wireless WPAN/WBANs

A WBAN is formally defined as "A wireless body area network is a radio-frequency-based wireless networking technology that interconnects tiny nodes with sensor or actuator capabilities in, on, or around a human body" [9]. In healthcare sectors, WBANs allow continuous monitoring of the physiological parameters. The reasons of proliferation of this system are manifold because it can i) enable the detection of vital signs (blood pressure, blood oxygenation, body temperature) of health deterioration, ii) notify healthcare providers in urgent situations iii) deliver healthcare service to remote locations and iv) help caregivers by providing real time physiological data. Besides healthcare sectors, WBANs target diverse applications including consumer electronics, security, sports, industrial control, home automation, asset tracking, supply chain management and so forth.

1.2 WBAN Applications

WBAN applications can be categorized based on the type of sensors, radio systems, network topologies, and purpose. The major applications of WBANs besides health monitoring are as follows:

- **Military:**

  Firefighters and soldiers can be notified by WBAN sensors about different levels of toxic substances in the air and thus they can take the necessary measures in dealing with threatening situations. With WBAN sensors fitted on the body of soldiers, the commanders are not only being able to send orders to the soldiers in real time but also can obtain other information such as the location and physiological status of the soldiers while in the battlefield.

- **Sports training:**

  In the sports domain, motion and physiological sensors worn on the body of athletes, can be used, for instance, by coaches/trainers to remotely monitor the physical activities and physiological status of the athletes during training/exercise or during real matches.

- **Personal information sharing:** In the social networking and entertainment domains, WBANs can be used for exchanging digital profiles or business cards, match making (hobby, interest, game, community member), creating groups with the same preferences and emotions, etc. Traditional computer interfaces, like keyboards, mice, joysticks, and touch screens, are all replaceable by potential WBANs devices capable of automatically recognizing human motions, gestures, and activities.

- **Entertainment:**

  A WBAN is able to include both advanced and simpler appliances. An example of an advanced device would be a neural interface, followed by some simple modern day-to-day used devices such as head-mounted (computer) displays, microphones, MP3- player, cameras etc.

1.3 Motivation

Current healthcare systems are facing new challenges due to the rate of growth of the elderly population (aged 65 or over) and limited financial resources. According to the US Bureau of the Census [16], the number of old people (65–84 years old) is predicted to double from 35 million to 70 million by 2025 and will reach virtually two billion by 2050. An aging population and sluggish lifestyle are fuelling the prevalence of chronic diseases such as cardiovascular diseases, diabetes and hypertension. According to the World Health Organization cardiovascular disease cause 30 percent of all deaths in the world [17]. Diabetes currently affects 180 million people worldwide and is expected to affect around 380 million by 2025 [18], 2.3 billion people will be overweight by 2015 [19]. A rapid rise in enervating neuro-degenerative diseases such as Parkinson's and Alzheimer's is threatening millions more.

With the use of WBANs patients don't need to stay in hospital or at home or on the move, the patient also does not need to stay in bed and can move around freely. Furthermore, the data obtained during a large time interval in the patient's natural environment offers a clearer view to the doctors than data obtained during short stays at the hospital. Frequent monitoring also enables proper dosing and reduces the risk of fainting and in later life blindness, loss of circulation and other complications [11]. Examples of diseases that would benefit from continuous monitoring include hypertension, asthma, Alzheimer's disease, Parkinson's disease, renal failure, post-operative monitoring, stress-monitoring, prevention of sudden infant death syndrome etc [11,21]. WBANs can also be used to offer assistance to the disabled. For example, a paraplegic can be equipped with sensors determining the position of the legs or with sensors attached to the nerves. WBANs can facilitate visually impaired people getting aid by using an artificial retina, consisting of a numerous micro sensors, which can be implanted into the eye beneath the surface of the retina. From this discussion it is obvious that by using WBANs in medical monitoring patients can be given increased level of confidence and better quality of life. We can expect, WBANs will play a vital role in supporting high quality medical and healthcare service in near future.

Already a number of medical monitoring WBAN systems [2–7] have been developed or are being developed. CodeBlue [2] is a research project at Harvard University which uses a distributed wireless sensor network including a pulse oximeter, two-lead ECG, and a specialized motion analysis sensor board for sensing and transmitting vital signs and geolocation data. The European MobiHealth [3] project is a large scale disaster and emergency system and provides of remote monitoring services to support work and recreation in extreme environments. HealthGear [4] is project of Microsoft Research and is a real-time wearable system for monitoring person's blood oxygen level and pulse while sleeping using a blood oximeter. MITMedia Lab is developing MIThril [5] that incorporates a complete human-machine interface. AID-N [6] targets applications dealing with mass casualty incidents. NASA is developing a wearable physiological monitoring system for astronauts called LifeGuard system [7].

A Medium Access Control (MAC) [51-55] layer is the most suitable level to address the energy efficiency in WBANs. An efficient MAC protocol increases the lifetime of a sensor network to a great extent. We focused our research work on improving MAC layer based protocol to ensure more improved communication in WBANs.

1.4 Requirements and Challenges of WBANs

A sensor node in a WBAN uses a small battery to operate independently for a number of months or years [21]. Hence, energy efficiency and lifetime maximization are the foremost requirements in the design of WBANs protocols. Considering the large variety of potential applications of WBANs, protocols design needs to cater for the following challenges:

- **Energy Efficiency:**

  Radio communication poses the most significant energy consumption demand in WBANs [9]. Frequent turning on/ off the radio depletes the node energy quickly. Unlike other wireless networks, charging/replacing the exhausted battery is a very difficult task. Intelligent on-sensor signal processing has the potential to save power by transmitting the processed data rather than raw signals, and consequently to extend battery life. A careful trade-off between communication and computation is crucial for an optimal design.

- **Delay:** Delay considerations are of crucial importance in some specific applications, for example, in health care applications that handle emergency care patients when they need to be monitored continuously due to serious and urgent medical condition, or in military applications to monitor and track troop movement. Emergency data is required to be delivered reliably ahead of all other traffic. Delay minimization is a important aspect of a good protocol design.

- **Channel Access Scheme:** Channel access schemes [8,15] have notable importance in WBANs. Suitable channel access schemes are required to save energy, through which nodes can switch to low-power states and avoid expensive modes such as transmission, reception and channel listening.

- **Channel Modeling:** The channel model plays a crucial role in the design of Physical layer (PHY) technologies [8]. The dynamic environment due to twisting, running, and mobility further complicates the tentative validation of channel models. Suitable channel modeling for implants and wearable devices is necessary due to involvement of human subjects and healthcare facilities, both governed by regulations.

- **Scalability and Adaption:** WBANs Protocols should be able to adapt to variation in the network size and topology as well as variations in the wireless channel or application requirements.

- **Reliability:** Sensor readings must be exchanged amongst nodes and network sink with a given probability of success. The two major factors affecting the reliability of communication in WBANs are contention and channel errors [102]. Since contention and channel errors are distinct factors, reliability and control schemes should address them according to their specific characteristics. In many scenarios, data transmission loss is evident. Retransmission of lost messages can enhance reliability but it may increase the network energy consumption. Hence, a tradeoff is necessary.

1.5 Contribution of the Thesis

The problems we address in this thesis are related to the design of an energy efficient MAC protocol and to develop a suitable simulator in this regard. Firstly, we analyze the performance of the IEEE 802.15.4 MAC after replacing the channel model with one suitable for WBANs. Secondly, we propose a MAC protocol based on IEEE 802.15.6 where the channel access scheme is aimed ensuring quick transmission for medical emergency traffic and lastly we developed a discrete event based simulator in OPNET to verify our correctness of the proposed protocols.

Implementing Implant Channel Model in IEEE 802.15.4 :

The complexity of the human tissues structure and body shape make it difficult to derive a simple path loss model [79] for WBANs. As the antennas for WBANs applications are placed on or inside the body, a WBAN channel model needs to take into account the influence of the body on the radio propagation. When IEEE 802.15.6 was in the process of being standardized the existing IEEE 802.15.4 protocol or a modification of it was considered as an interim solution. According to [12], IEEE 802.15.4 is not suitable for in-body communication because it does not achieve the required power level for in-body nodes. We implemented the IEE 802.15.6 communication link channel model CM1 (implant to implant) [75] and channel model CM2 (between an implant device and an on or out-of body device) [75] in NS-2[80] to study its performance. We have successfully demonstrated implant WBANs simulations in NS-2 and analyze the performance of CM1 and CM2 several simulation experiments for several distances from transmitter and receiver. Our results showed that CM1 has less path loss and its energy consumption and packet delivery ratio is also much smaller than CM2.

Improvement of Channel Access Scheme for IEEE 802.15.6 :

Next we put our focus on quick channel procedures for medical emergency traffic [68-72] which is an important consideration for medical WBANs. We know, emergency data is required to be delivered reliably ahead of all other traffic because the unsuccessful transmission of emergency messages can make a huge difference between life and death. In IEEE 802.15.6 MAC two access periods, have been assigned for emergency data handling. As an emergency data frame is very short, one time slot is sometimes enough for the whole data transmission. But allocating a long period in this regard is not appropriate as the frequency of emergency traffic is not great. In contention based access phases emergency data also needs to contend to access the channel but the reliability and successful transmission is uncertain in these periods. The longest durations of the channel access phase is seen in TDMA based access phase. As TDMA based time slots are pre-assigned, emergency data cannot get access to the channel and it incurs a long delay which is not desirable. Moreover, channel sensing is a big challenge in a WBANs and it cannot be guaranteed in all WBANs frequency bands and scenarios. A dynamic environment with body movement also influences the sensitivity of the channel sensing. Unreliable channel sensing leads to the hidden node problem and adds channel sensing error which deteriorates system performance drastically. Allocating more spaces for TDMA based access phases is a good solution for WBANs but a tradeoff necessary; otherwise it can throttle the network throughput abruptly. Moreover, the length of the superframe [8] has significant impact on maximizing device lifetime. Short superframe can satisfy the channel access delay requirements of emergency traffic but penalizes the energy efficiency of all devices in the network. On the other hand, long superframe increase the energy efficiency but incurs long channel access delay. To balance this contradicting requirement of energy efficiency and QoS, we propose Medical Emergency Body (MEB) MAC protocol [88] that creates opportunities for emergency traffic to get the access of the channel even in the contention free periods. We call this approach Listening Window Insertion. A listening window is dedicated to emergency data to provide high reliability with low delay. The frequency of listening window insertion is determined by the minimum delay tolerance. The allocation of listening windows in MEB MAC is dynamic and our results show that in the long superframe duration case our scheme can achieve satisfactory performance improvement as compared to IEEE 802.15.6 or related protocols with little adverse impact on network throughput.

OPNET Simulator for IEEE 802.15.6 :

Simulation of WBANs is a challenging task due to the nature of hardware design, energy limitations, and deployment of a vast number of nodes. Up to now Castalia [94] is the only discrete event based simulator which is suitable for WBANs. It is based on the OMNeT++ [95] platform which has suitable channel model for WBANs, but their MAC layer is still 802.15.4 based. We have modified IPP-HURRAY Research Group's Zigbee Module [97] on OPNET to make it compatible for WBANs. The key aspects of our simulation model is accurate superframe structure, supporting large superframe duration with long time slot, creating a new traffic class for emergency applications, switching into appropriate channel access phases within the assigned time slots.

1.6 Thesis Outline

In this section, we introduce the thesis structure. This thesis consists of seven chapters.

Chapter 1: Introduction overviews WBANs and current wireless technologies, defines the basic requirements and challenges of WBANs and the motivation of research, and gives an introduction to the thesis.

Chapter 2: **Short Range Wireless Technologies and WBANs** introduces the IEEE 802.15.6 MAC protocol in detail and reviews the basic principles of latest wireless technologies. In this chapter we present an overview of short range wireless technologies and their suitability for WBANs. We also present the architecture and applications of WBANs along with the PHY layers specifications.

Chapter 3: MAC Protocol for WBANs mainly focuses on a literature survey of MAC protocols for WBANs. First, we categorize the MAC protocols based on the channel access schemes. After that we present the important MAC proposals for WBANs. Among these proposals we have separated protocols which focus on emergency traffic's quick channel access procedures and their limitations.

Chapter 4: Performance of IEEE 802.15.4 for Implant WBANs describes the simulation based analysis of IEEE 802.15.4 for implant WBANs after replacing channel model. We first examine about the radio propagation and channel models recommended for implant WBANs. We then briefly describe the implementation steps in the NS-2 simulator. We implement the 802.15.6 communication link channel model CM1 (implant to implant) and channel model CM2 (between an implant device and an on or out-of body device) and changed the power parameters of IEEE 802.15.4. Finally, we study the performance of CM1 and CM2 with different sets of simulation experiments.

Chapter 5: An Improved Channel Access Scheme for Medical Emergency Traffic in WBANs lays the most important foundation of the thesis by demonstrating an energy efficient and immediate channel access based MAC protocol for WBANs. We name this approach as MEB MAC where the medical emergency traffic has been assured of less channel access delay. Starting with Channel Access Delay and Short Superframe' s impact on WBANs we later put our focus on a channel access scheme for IEEE 802.15.6. After that we discuss the main proposals of MEB MAC. Finally, we demonstrate the advantages of MEB MAC over IEEE 802.15.6 and other protocols through extensive simulations.

Chapter 6: IEEE 802.15.6 and MEB MAC Implementation in OPNET summarizes the implementation detail of IEEE 802.15.6 and MEB MAC protocol in OPNET. We first discuss the necessity of a discrete event based simulator for WBANs along with the limitations of related simulator. Then we study the primary components of OPNET for network simulation. After that, we focus on a detailed description of the implementation by showing the module attributes and scenarios. Lastly we compare the IEEE 802.15.6 and MEB MAC for various types of scenarios.

Chapter 7: Conclusion summarizes the main results of this thesis with future direction for research.

1.7 Related Publications

In the following, we list our research papers that present the contributions of this thesis.

M.A. Huq, E. Dutkiewicz, G. Fang, R.P. Liu, R. Vesilo, "MEB MAC: Improved Channel Access Scheme for Medical Emergency Traffic in WBAN," 12th International Symposium on Communications and Information Technologies (ISCIT), Gold Coast, Australia, October 2012.

Gengfa Fang; Dutkiewicz, E.; **M.A.Huq** ; Vesilo, R.; Yihuai Yang, "Medical Body Area Networks: Opportunities, challenges and practices," Communications and Information Technologies (ISCIT), 2011.

Chapter 2

Short Range Wireless Technologies and WBANs

2.1 Introduction

This thesis mainly focuses on new mechanisms for WBANs to improve channel access procedures using MAC protocols. In order to understand the design principles behind our architecture, an understanding of WBAN architecture is required. This chapter provides this background. It is organized as follows. First, we compare WBANs with other wireless networks. Second, we present an overview of short range wireless technologies. Lastly, we present the characteristics of WBANs with its key features.

2.2 WBANs and Other Wireless Networks

Wireless networks can be divided into five specific types. Figure 2.1 illustrates the transmission range and enabling technology of these different type of wireless network. WBANs operate close to the human body and its communication range is restricted to a few metres [11]. While a WBANs are devoted to interconnection of a person's wearable devices, a WPAN (IEEE 802.15.4) [15] is a network for interconnecting devices centered around an individual person workspace.

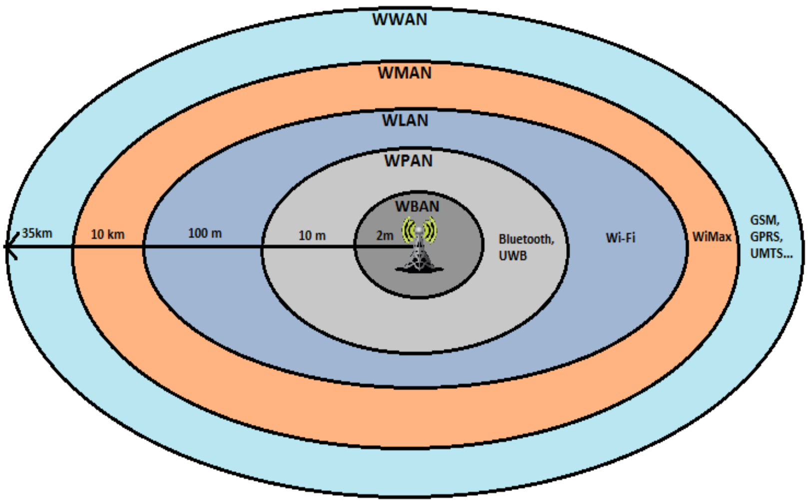


Figure 2.1: Different types of Wireless Network

The following group: Wireless Local Area Networks (WLANs) comply with the standard for the wireless networks created for the range of one room or maximally one building and its signal range is approximately 30 meters indoors and 100 metres outdoors [22]. The Wireless Metropolitan Area Networks (WMANs) are the fourth type of the wireless networks which have been proposed to provide broadband wireless access over long distances ranging from several blocks of buildings to entire cities. Networks working in accordance with this standard have a signal range of approximately 5 kms; they are used to connect users to the Internet. In recent years, wireless metropolitan area networks (WMANs). The last type are the Wireless Wide Area Networks (WWANs) which adopt technologies from mobile telecommunications networks that are already suited for covering large areas. Examples of WWANs include mobile cellular networks and satellite networks.

2.3 Short Range Wireless Technologies

Low emission power and reliability are the foremost requirements of WBANs. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has issued some guidelines [23] so that the emission power of WBANs cannot be harmful for human tissues and organs. ICNIRP also suggested that interference levels for WBANs so that they will be tolerable by other wireless systems. The amount of power absorbed by the tissue is expressed by the Specific Absorption Rate (SAR) [10]. The localized SAR into the body must be minimized and needs to comply with international and local SAR regulations. The regulations for transmitting close to the human body are similar to the ones for mobile phones, with strict transmit power requirements [11,24].

	Frequency Band	**Data rate**	**Bandwidth**	**Transmit Power**	**Range**
IEEE 802.15.1 (Bluetooth)	2.4GHz	721 Kbps	1 MHz	4,20 dBm	10 - 100m
MICS	402-405Mhz	19~76kbps	3MHz	16 dBm	0-10m
UWB	3-10GHz	850kbps	>500 MHz	-41 dBm	1,2m
IEEE 802.15.4 (Zigbee)	2.4GHz	250Kbps	5 MHz	0 dBm	0-10m

Table 2.1: Short Range Wireless Technologies

The currently available short range wireless technologies such as Bluetooth [25], Zigbee [26,27] and Wi-Fi [28], Ultra-wideband (UWB) [29] can be considered for candidate technology for WBANs/WPANs. Each of the listed technologies has its own specifications, including different modulation, data rate, transmission power, power consumption, etc. WPANs use Bluetooth or ZigBee WLANs use WiFi and WMANs use WiMax [30]. Each type of network has its typical enabling technology (the PHY and MAC layers), defined by the IEEE. Table 2.1 shows the short range wireless technologies for medical monitoring in terms of data rate, frequency band, bandwidth, transmit power and transmission range.

In the following, some popular short range wireless technologies have been summarized with their key specifications.

2.3.1 Bluetooth over 802.15.1

Bluetooth [24] is an open wireless technology standard for exchanging data over short distances from fixed and mobile devices, creating WPANs with high levels of secure connectivity. Created by telecoms vendor Ericsson in 1994, it was originally conceived as a wireless alternative to RS-232 data cables. It can connect several devices, overcoming problems of synchronization. Bluetooth has a rated 10-meter range and a peak over-the-air speed of 1Mbps in low-power mode. Studies have shown that approximately 10 Bluetooth “piconets” can operate simultaneously in the same 10-meter circle with minimal degradation yielding an aggregate speed of 10Mbps [31]. Bluetooth uses a radio technology called Frequency-Hopping Spread Spectrum (FHSS) [32], which chops up the data being sent and transmits chunks of it on up to 79 bands (1 MHz each) in the range 2402-2480 MHz.

2.3.2 Zigbee over IEEE 802.15.4

ZigBee [26,27] is a specification for a suite of high level communication protocols using small, low-power digital radios based on the IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (LR-WPANs) [13]. ZigBee is targeted at radio-frequency applications that require a low data rate, long battery life, and secure networking. The ZigBee Alliance [26] has developed to standardize application software on top of the IEEE 802.15.4 wireless standard. The alliance worked closely with the IEEE to ensure an integrated, complete, and interoperable network for the market. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other WPANs, such as Bluetooth. The major advantage of ZigBee is its capability of providing multihop routing in a cluster tree or mesh topology. The drawback of IEEE 802.15.4 is the limited data rate. Following the standard Open Systems Interconnection (OSI) reference model, the ZigBee protocol stack is structured in layers. The first two layers, PHY and MAC are defined by the IEEE 802.15.4 standard. The layers above them are defined by ZigBee Alliance. IEEE 802.15.4 can operate at three different frequency bands of 2.4 GHz (worldwide), 800 MHz band (regional), and 900 MHz band (regional). When operating at 2.4 GHz band, it achieves a maximum data rate of 250 kbps.

2.3.3 Wi-Fi over 802.11a/b/g/n

Wireless Fidelity (Wi-Fi) [28] includes IEEE 802.11a/b/g standards for WLAN. It allows users to surf the Internet wirelessly at broadband speeds when connected to an access point or in ad hoc mode. The IEEE 802.11 family of WLAN standards is composed of a number of specifications that primarily define the physical and MAC layers of the realm of WLAN technologies. The most popular are those defined by the 802.11b and 802.11g protocols, but 802.11a was the first widely accepted one, followed by 802.11b and 802.11g. Other standards in the family (c–f, h, j) are service amendments and extensions or corrections to the previous specifications. 802.11b has grown more popularity as it can offer up to 11-Mbit/s data rates in the 2.4-GHz ISM band. Since then, new standards have been developed including 802.11a (5-GHz band), 802.11g, and 802.11n using OFDM to get speeds up to 54 and 300 Mbits/s under the most favorable conditions. 802.11n is a new multi-streaming modulation technique.

2.3.4 Ultra-Wideband over 802.15.3

UWB [29] is an is a low-power high data rate technology, recently approved by the Federal Communications Commission (FCC) [35] which has been very attractive for body-worn battery-operated devices. One of the most exciting characteristics of UWB is that its bandwidth is over 110 Mbps (up to 480 Mbps) which can satisfy most of the multimedia applications such as audio and video delivery in home networking and it can also act as a wireless cable replacement of high speed serial bus such as USB 2.0 and

IEEE 1394 [36]. The approach was actually motivated by research and development performed nearly a decade earlier at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, Lexington, and at the Sperry Corporation, Natick, MA. FCC has mandated that UWB transmissions can legally operate in the range 3.1 GHz up to 10.6 GHz, at a limited transmit power of -41dBm/MHz [37]. UWB communication with large bandwidth signals provides robustness to jamming and has low probability of interception. Additionally the transmissions must occupy a bandwidth of at least 500 MHz, as well as having a bandwidth of at least 20% of the centre frequency. UWB allows longer battery life for body worn units [36].

2.3.5 MICS

The Medical Implant Communications Service (MICS) [8,38] is an ultra-low power, unlicensed, mobile radio service for transmitting data in support of diagnostic or therapeutic functions associated with implanted medical devices. It allows bi-directional radio communication with a pacemaker or other electronic implants. However, the 402-405 MHz frequency band is available for MICS operations on a shared, secondary basis.

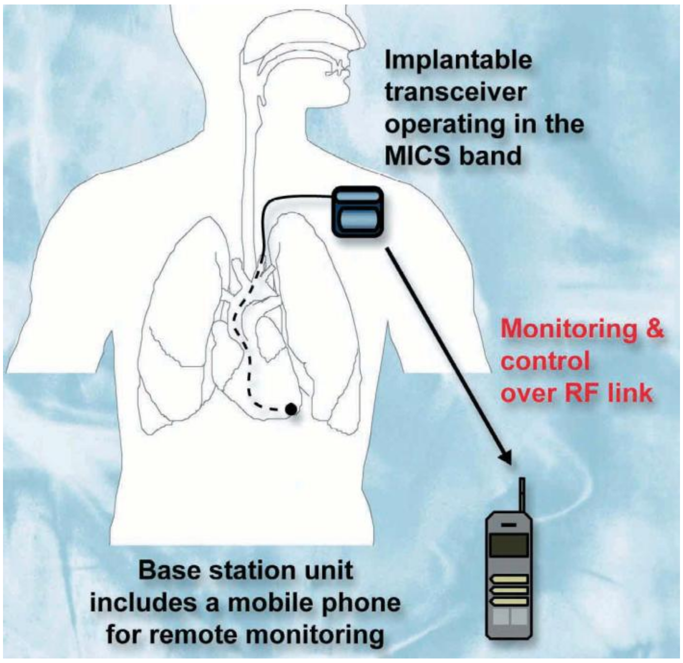


Figure 2.2: An implantable MICS transceiver [from 103]

An ultra low power RF transceiver in a Cardiac Pacemakers and outside control unit as shown in Figure 2.2 is an example of a MICS system.

As discussed in [39], the key technical and operational conditions proposed for the use of MICS transmitters are:

- Frequency Band of operation: 402-405 MHz.
- Maximum EIRP: 25 µW – this limit to apply in any 300 kHz bandwidth.
- Operation on a non-interference basis.
- Transmitters in implanted devices to transmit only when commanded to do so by external programmers/ controllers, except for medical implant events.
- Programmer/controller devices to operate on a listen before-transmit basis to identify and use the communication channel of lowest ambient noise.
- Frequency agility, to enable communication to occur on the lowest ambient noise channel determined to be available.

2.3.6 Suitability of Current Wireless Technologies for WBANs

The wireless standards discussed above are well documented and tested, but these are not an ideal choice for the wireless WBANs as they are targeted to more flexible networks than this and are used for longer transmission ranges. Bluetooth was optimized for voice links ZigBee was optimized for industrial sensors, smart grids, etc. Wi-Fi was optimized for data networks. None of the existing standards meet the peak-power consumption requirements today for WBANs. They also do not support the combination of reliability, QoS, low power consumption, high data rate and non-interference required for WBANs applications [106]. The average power consumption of the radio in the sensor nodes must be reduced below 100µW (energy scavenging limit) [40]. Today's low-power radio systems such as Bluetooth and Zigbee do not meet this tight requirement [41]. The radio interface can be designed taking into account the specific requirements of WBANs. ZigBee has been the most popular short-range standard used recently in medical monitoring systems due to its low transmitter power [42,43]. However, Zigbee wireless platform may suffer from the strong interference by WLANs because of sharing the same spectrum and transmitting at a larger signal power [44].

The power budget in the sensor node and in the coordinator device is very different. The sensor has an extremely stringent power budget, whereas the coordinator has a slightly more flexible power budget. In a star network topology, the usual communication direction is from the sensor node to the master device. The sensor node operates then mainly as a transmitter and there is a strong asymmetry in the communication link. In the air interface definition, both of these asymmetries are exploited by shifting as much complexity as possible to the master device. In this context, UWB modulation has strong advantages compared to more traditional narrow-band radio communication which has been explicitly discussed in [41]. According to the authors, in UWB, the transmitter only needs to operate during the pulse transmission which produces a low duty cycle on the radio and the expensive baseline power consumption is minimized. Moreover, since most of the complexity of UWB communication is in the receiver, it allows the realization of an ultra-low power, very simple transmitter and shifts the complexity as much as possible to the receiver in the master, which is a perfect scenario in the WBANs context. Moreover, the low hardware complexity of an UWB transmitter offers the potential for low-cost and highly integrated solutions for WBANs. Considering all these aspects UWB is becoming ideal candidate technology for WBANs.

2.4 Description of WBANs

WBANs are wireless communication standard for information exchange which is intended to endow a future generation of short-range electronics, both in body and on or around it, with. Many researchers address WBANs as a special type of a Wireless Sensor Network with its own requirements [47]. However, traditional sensor networks do not tackle the special challenges associated with human body monitoring. The human body consists of a complicated internal environment that responds to and interacts with its external surroundings. In brief, although challenges faced by WBANs are in many ways similar to WSNs, there are significant differences between the two, requiring special attention. An overview of some of these differences is given in Table 2.2

In WBANs sensors can sample, process and transmit vital signs without limiting the activities of the wearer. After collecting data via biosignal sensors WBANs forwards the data to a central hospital in real time where doctors in the central hospital takes proper decision on how to treat with that patients depending on the received data.

Challenges	**Wireless Sensor Network**	**Wireless Body Area Network**
Range	As large as the monitored environment (metres / kilometres)	Human body (centimeters / meters)
Node Number	Large number of nodes for wide area coverage.	Fewer, limited in space.
Context Awareness	Not so important	Very important as body physiology is very sensitive to context change.
Result Accuracy	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 Several years/ months, smaller battery capacity
Node Lifetime	Several years / months.	Inaccessible and difficult to replaced in an implantable setting.
Power Supply	Accessible and likely to be replaced more easily and frequently	Likely to be lower, energy supply more difficult Most likely motion (vibration) and thermal (body heat)
Power Demand	Likely to be large, energy supply easier	A must for implants and some external sensors
Energy Scavenging Source	Most likely solar and wind power	A must for implants and some external sensors
Path Loss	Low	Very High for Implant WBANs
Biocompatibility	Not a consideration in most applications.	A must for implants and some external sensors.
Security Level	Lower	Higher, to protect patient information
Wireless Technology	Bluetooth, ZigBee, GPRS, WLAN.	Low power technology required

Table 2.2: Comparison between WSNs and WBANs, based on [11].

The gathered data can be forwarded in real time to a hospital, clinic, or central repository over a local area network (LAN), wide area network (WAN), cellular network, and the like. Physicians and caregivers can remotely access this data to determine the state of the health of the patient.

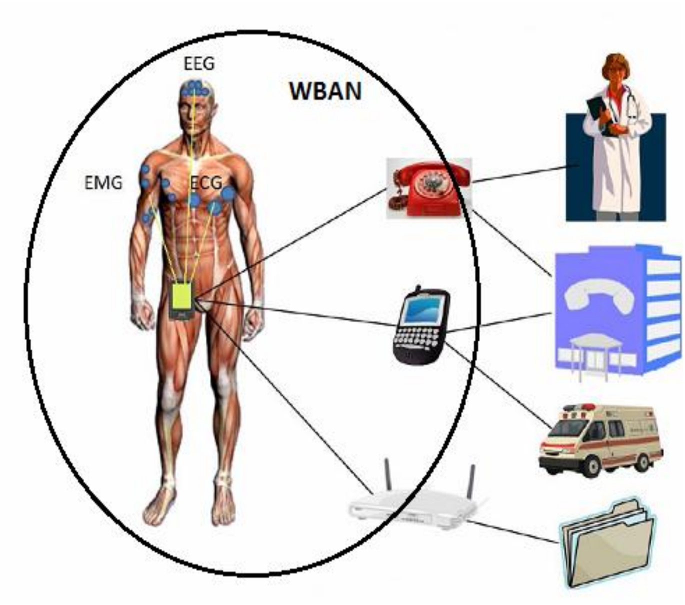


Figure 2.3: Wireless Body Area Network [from 105]

Additionally, the patient can be alerted using SMS, alarm, or reminder messages. An example of a medical WBANs used for patient monitoring is shown in Figure 2.3. WBANs provides short range low power and highly reliable wireless communications for using in close proximity to or inside our body.

2.4.1 Wearable WBANs and Implant WBANs

Depending on if it is operated outside or inside body, WBANs can be divided into wearable WBANs and implant WBANs. Table 2.3 lists the different types of wearable and implant WBANs devices. While wearable WBANs are considered for both medical and non-medical applications, implant WBANs are mainly considered for medical and healthcare applications. Wearable WBANs operate in the vicinity or on human body

Wearable BAN devices	Implanted BAN devices
EEG ECG SpO_2 pulse oximeter, Glucose Fall detection Emergency call Performance assessment	Glucose sensor; Cardiac arrhythmia: pacemaker, cardiovertor, defibrillator Intracranial pressure sensing Wireless capsule drug delivery Deep brain stimulation: retinal sensors, Parkinson's, epilepsy Insulin pump

Table 2.3: Wearable and Implant WBANs

while implant WBANs operate inside body. In the implantable situation, the characteristics of a radio propagation channel are mainly defined by tissues of a body, whereas, the radio signal of wearable WBAN is propagated through air. Wearable WBANs experiences multipath channel effects [77] including blocking while implant WBANs suffers decay during transmission. According to [104] the major differences between wearable WBANs and implant WBANs are as follows:

→ Different requirements on frequencies due to different operating environment and channels.

→ Implant WBANs requires limited power limited and have smaller form factor compared to wearable WBANs.

→ Both wearable WBANs and implant WBANs need to consider tissue protection (e.g., SAR) while implant WBANs may be subject to much strong restriction.

2.4.2 Types of Devices

A WBANs consists of two categories of nodes: sensors/actuators, and router nodes around WBANs wearers or second-tier radio devices equipped on the wearers, functioning as an infrastructure for relaying data. Users in WBANs communicate through PDA or a smart phone which acts as a sink for data of the wireless devices.

2.4.2.1 Sensor Nodes

Sensor nodes respond to and gather data on physical stimuli, process the data if necessary and report this information wirelessly. It consists of several components: sensor hardware, a power unit, a processor, memory and a transmitter or transceiver. Figure-2.4 shows the typical sensors which are commonly used in WBANs and Table 2.4 lists the functionalities of these sensors.

2.4.2.2 Actuator Nodes

Actuator nodes act accordingly from the data they receive from the sensors or through interaction with the user. The components of an actuator are similar to the sensor's: actuator hardware, a power unit, a processor, memory and a receiver or transceiver. Actuators can perform some specific actions according to the data they receive from the sensors.

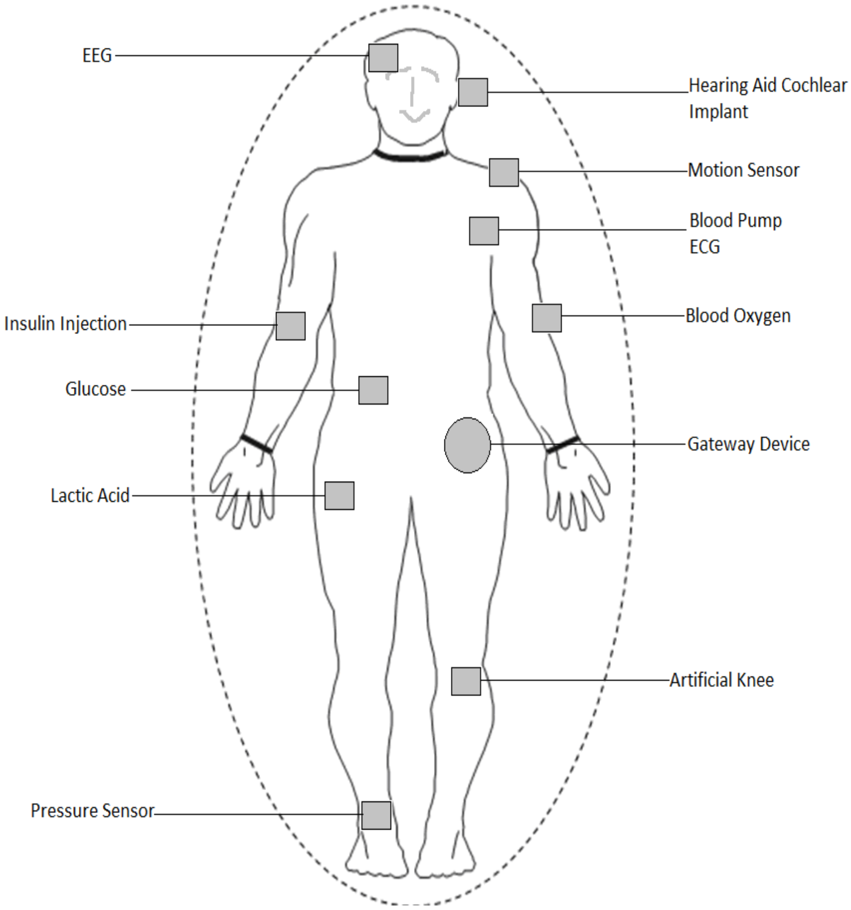


Figure 2.4: Various sensors used in WBANs

Sensor	How it works
Accelerometer	Measures the acceleration relative to freefall in three axes
Gyroscope	Measures the orientation based on the principles of angular momentum
ECG/EEG/EMG	Measures potential difference across electrodes put on corresponding parts of the body
Respiration	Use two electrodes, cathodes and anode covered by a thin membrane to measure the oxygen dissolved in a liquid
Pulse Oximetry	Measures ratio of changing absorbance of the red and infrared light passing from one side to the other side of a thin part of the body's anatomy
Carbon Dioxide	Uses the infrared light an measures the absorption of the gas presented
Blood Pressure	Measures the systolic pressure(peak pressure) and diastolic pressure
Blood Sugar	Traditionally analyses drops of blood from a finger tip, recently, uses non-invasive method including a near infrared spectroscopy, ultrasound, optical measurement of the eye, and the use of the breath analysis
Humidity	Measures the conductivity changes of the level of humidity
Temperature	Uses a silicon integrated circuit to detect the temperature changes by measuring the resistance

Table 2.4: Various sensors used in WBANs [from 10]

2.4.2.3 Personal Device (PD)

Wireless Personal Devices gather all the information acquired by the sensors and actuators and informs the user via an external gateway, an actuator or a display/LEDS on the device. The components of a PD are a power unit, a (large) processor, memory and a transceiver. This device is also called a body-gateway or a sink. In some implementations, a Personal Digital Assistant (PDA) or smart phone is used.

2.4.3 WBAN Architecture

The architecture of WBANs has been explicitly described in the literature [48,104]. WBANs nodes can have different topologies such as star, tree, and mesh topologies. Among these star topology is the most common where each node communicates with a central device which is called WBANs coordinator. Figure 2.5 shows the block diagram of a typical WBAN where various types of sensors are attached with the coordinator in star topology.

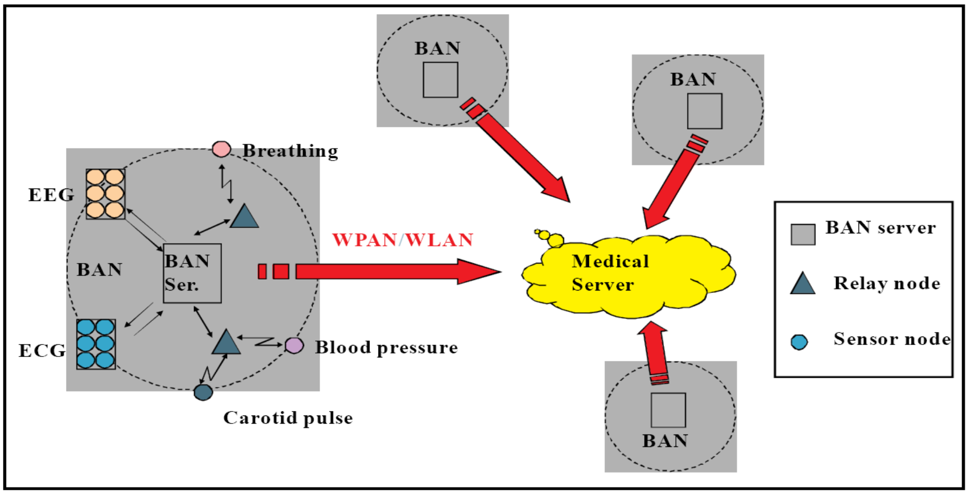


Figure 2.5: Conceptual block diagram of WBANs [from 107]

WBAN coordinators control the association of the other devices, provide the synchronization of the system and additional information by broadcasting a Beacon [8] (used to carry control information including slot allocation information) which is sent at the beginning of each superframe [8] period. WBAN coordinators aggregate data collected by all sensor nodes in the network. Then, they send this data to a medical/healthcare server through existing wireless networks such as WPAN, WLAN, mobile phone network, etc. Each WBAN can use a different infrastructure depending on its own possibility. For sensitive vital data in some situations, a WBAN server is required to be able to generate warning signs for unusual vital data. In most cases, sensor nodes should communicate with the WBAN server directly. In the case that a direct link between a sensor node and the WBAN server is not available, relay nodes can be used to establish a connection between the WBAN server and sensor nodes. It should be noted that relay functions can be implemented within sensor nodes.

2.4.4 WBAN Traffic Classification

Traffic can be categorized into on-demand, emergency, and normal traffic. On-demand traffic is initiated by the coordinator to acquire certain information. Emergency traffic is initiated by the nodes when they exceed a predefined threshold. Normal traffic is the data traffic in a normal condition with no time critical and on-demand events.

Priority	User priority	Traffic designation
Lowest	0	Background
	1	Best effort
	2	Excellent effort
	3	Video
	4	Voice
	5	Medical data or network control
	6	High-priority medical data or network control
Highest	7	Emergency or medical implant event report

Table 2.5: IEEE 802.15.6 Traffic Class

The normal data is collected and processed by the coordinator. IEEE 802.15.6 has defined seven traffic categories based on the user priorities which is shown in Table 2.5. Here we can see that Medical data has been categorized with higher user priorities (7 to 5) where Emergency or medical implant event report has been assigned with the highest (7) value.

2.4.5 Data Rates

Due to the strong heterogeneity of the applications, data rates will vary strongly, ranging from simple data at a few kbit/s to video streams of several Mbit/s. Table 2.6 provides examples of medical WBANs applications [49,50] Data can also be sent in bursts, which means that it is sent at higher rate during bursts.

Application	Data Rate
ECG (12 leads)	288 kbps
ECG (6 leads)	71 kbps
EMG	320 kbps
EEG (12 leads)	43 kbps
Blood saturation	16 bps
Glucose monitoring	1600 bps
Temperature	120 bps
Motion sensor	35 kbps
Cochlear implant	100 kbps
Artificial retina	50-700 kbps
Audio	1 Mbps
Capsule Endoscope	1-15 Mbps

Table 2.6: WBANs Applications and Data Rate [11]

The data rates for the different applications are given in Table 2.6 and are calculated by means of the sampling rate, the range and the desired accuracy of the measurements. Overall, it can be seen that the application data rates are not usually high.

2.4.6 IEEE 802.15.6 PHY

The IEEE 802.15.6 specification [8] defines Narrowband (NB), UWB and Human Body Communications (HBC) physical layers. Figure 2.6 shows the overview of IEEE 802.15.6 with the three PHY layer specifications.

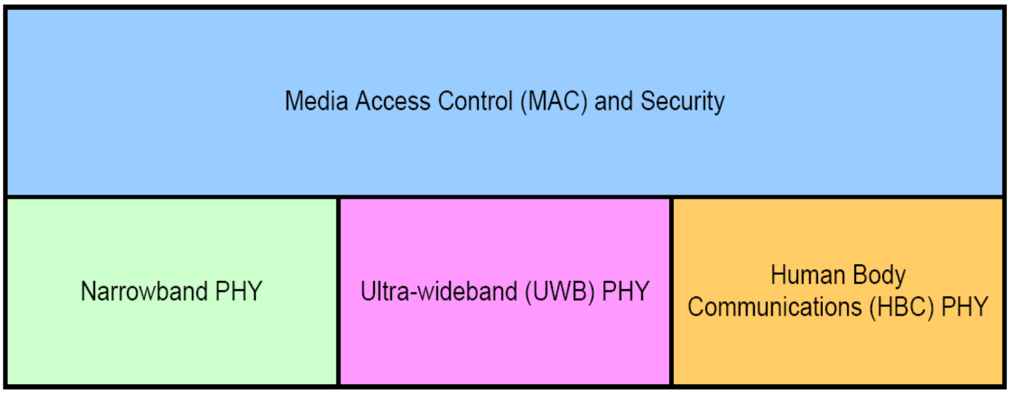


Figure 2.6: High-level overview of IEEE 802.15.6.

The NB physical layer operates in seven different frequency bands and offers a variable number of channels, bit rates and modulation schemes. The sixth band of 2360-2400 MHz (newly reserved for use by medical devices) and the seventh band of 2400-2483.5 MHz, because it is the most commonly used license exempt ISM band. The selection of each PHY depends on the application requirements.

2.5 Summary

In this chapter, a detailed description of WBANs and comparative study of emerging and existing short range wireless standards has been discussed. First, we compared WBANs with other wireless networks in terms of coverage area. After that, we highlighted the important short range wireless technologies with mentioning their suitability for WBANS. Lastly, we describe the main characteristics of WBANs in terms of standards and specifications.

Chapter 3

MAC Protocol for WBANs

3.1 Introduction

Communication in a wireless network is divided into several layers. The MAC sub-layer is to coordinate node access to the shared wireless medium. In WBANs, sensor nodes are commonly powered by a battery with finite capacity and these batteries are often very difficult to change or recharge which makes energy consumption an important constraint. MAC protocols usually employ periodic sleep and wakeup, achieving low duty-cycle to save energy and to increase the lifetime of battery-powered sensor devices. Various MAC protocols with different objectives have been proposed for wireless sensor networks and performance evaluation, optimization and enhancement of these MAC protocols is needed. In this chapter, a comprehensive survey of related MAC protocols for WBANs is conducted. The outline of the chapter is as follows. In Section 3.2, we summarize key aspects of general MAC protocols along with their classifications. In Section 3.3, we present the requirements of MAC protocols for WBANs. Then, we include important characteristics of several MAC layer based solutions for WBANs in Section 3.4. Besides the base protocols(IEEE 802.15.6 and IEEE 802.15.4), other protocols have been classified in two subsections where energy efficiency and quick channel access schemes for medical emergency traffic have been considered as selection criteria.

3.2 MAC Sub-Layer Protocol

The MAC sub-layer is the core of any communication protocol stack whose performance provides the determining factor for overall network functionality in any wireless networks. A major power consuming component of a sensor node is the radio, which is controlled by the MAC protocol. The design goal of the MAC protocol is to avoid collisions and to prevent simultaneous transmissions while preserving maximum throughput, minimise latency, provide communication reliability and deliver maximum energy efficiency.

Before elaborating more on MAC protocols we discuss some major factors which creates power waste in wireless sensor nodes: [51,52]

1. **Idle Listening:** Idle listening refers to the sensing of the channel performed by nodes for receiving possible traffic that is in fact not sent, and it would occur in many sensor network applications where traffic load is low. The power consumption in carrier sensing is as high as that of receiving a packet.

2. **Collision:** When a collision occurs, a node usually retransmits the packet, and retransmission leads to a waste of power.

3. **Control packet overhead:** While control packets assist in protecting and getting the important data packets safely through, transmitting and receiving control packets costs power as well.

4. **Overhearing:** When a node's neighbors are transmitting packets, although the packet is not designated for this node, it still receives at least the header of the packet. Since receiving costs power, this is another source of power waste.

The aforementioned problems can be solved by designing a suitable MAC protocol. With the help of the physical layer, a properly designed MAC protocol ensures the desired system performance such as high throughput and short channel access delay. A versatile MAC will support distinct applications and different types of data such as continuous, periodic, burst and non-periodic along with high level QoS i.e. efficient, fair, dependable access of the medium. MAC plays a major determining factor in improving overall network performance.

3.2.1 Classification of MAC Protocols

MAC protocols can be grouped into three major categories based on their strategies for determining channel access i) Contention based and ii) Schedule based and iii) hybrid based

3.2.1.1 Schedule-based Schemes:

Schedule-based schemes are widely used in cellular communication systems [64]. The Time Division Multiple Access (TDMA) [52,58] protocol is an example of schedule-based scheme where the channel is divided into time slots of fixed or variable duration. These slots are assigned to devices so they can communicate in a contention-free manner. In TDMA, the decision of sensor node's transmission depends on a centralized or distributed slot assignment algorithm [64] which deterministically assigns each node a transmission schedule indicating in which of the synchronized slots a node may access the channel. As a result of this scheduling, the wireless channel can be utilized well. Moreover, theoretical QoS bounds such as throughput and latency can be given since each sensor node knows when to transmit. This ensures a sleep-listen schedule [51] which is vital for energy saving. TDMA protocols have a natural advantage of energy conservation, because the duty cycle of the radio is reduced and there is neither contention-induced overhead nor collisions [65]. The major disadvantage of TDMA protocols is that devices require time synchronization. Another problem of TDMA protocols is poor scalability which means they does not scale well as the size of the network increases because the number of TDMA slots is usually fixed or difficult to change.

3.2.1.2 Contention-based schemes:

In contention-based schemes, sensor nodes contend to gain the access of the shared medium by asynchronous competition. Typical examples of contention-based MAC protocols are ALOHA [59], and Carrier Sense Multiple Access (CSMA) [59]. The advantages of contention-based approaches are simplicity, its infrastructure-free ad hoc feature and good adaptability to traffic fluctuation, especially for low traffic load [11]. Performance of the CSMA schemes is not as dependent as TDMA schemes on the network topology and scales well for changing network size and density. As sensor nodes do not have to follow a transmission schedule contention-based schemes can handle bursty and sporadic traffic since. However, collisions are a typical phenomenon in contention-based schemes as the contender nodes or offered traffic load increases and this causes extra delivery latency, high energy expenditure and retransmissions. Hence, they cannot guarantee a certain level of QoS. However, the consequential high collision rate with the contention-based MAC schedule might result in significant performance deterioration with regard to resource and energy efficiency, especially in case of high traffic load.

Table 3.1 compares CSMA/CA and TDMA protocols. We can see from this comparison TDMA based protocols outperform CSMA based protocols in all areas except the protocol adaptability to changes in network topology. On the other hand TDMA based protocols need a good synchronization scheme.

Performance Criteria	**TDMA**	**CSMA/CA**
Power Consumption	Low	High
Traffic Level	High	Low
Network Scalability	Poor	Better
Bandwidth Utilization	Maximum	Low
Packet Delay/Loss	Fixed	Depends on Traffic
Transmission Efficiency	Low	High
Time Synchronization	Essential	N/A

Table 3.1: Comparison of CSMA/CA and TDMA protocols [56]

3.2.1.3 Hybrid schemes:

Hybrid protocols [51,61] have inherent advantages of both the schedule-based and the contention-based scheduled based approach. Hybrid schemes can classify the traffic based on priority, data-types (i.e. medical, non-medical), network-load and choose appropriate channel access method. When a new device wants to join the network it uses basic CSMA but in case of time critical traffic devices send request to the central device to allocate TDMA time slots. This is why in hybrid protocol the access phases switches periodically in order to accommodate all types of traffic. Hybrid MAC protocols borrow some flexibility and ease of operation while also incorporating the scalability and high capacity performance. However, under certain traffic loads or mobility rates, these hybrid protocols remain subject to instability.

3.3 WBANs MAC Requirements

Long Battery Lifetime:

In MAC protocols for WBANs. energy efficiency is the most important feature. A detailed study survey on the requirements of WBAN MAC protocols can be found in [55-57]. Compared to other wireless networks for wider areas, because of the simplified protocol stack, WBANs experience much less energy consumption that helps the batteries to gain longer lifetime. Some of the common objectives in a WBAN are to achieve maximum throughput, minimum delay, and to maximize the network lifetime by controlling the main sources of energy waste, i.e., collision, idle listening, overhearing, and control packet overhead. Usually, implanted body sensors have very limited battery capacity, to increase the lifespan of these sensors, energy-efficient MAC protocols will play an important role. Typically, in some WBAN applications, the device should support a battery life of months or years without intervention, while others may require a battery life of only tens of hours due to the nature of the applications [56]. For example, cardiac defibrillators and pacemakers should have a lifetime of more than 5 years, while swallow able camera pills only need a lifetime of 12 hours.

Variable Data Rate

The performance feature requirements for medical and consumer electronics applications vary in terms of data rate, channel access, latency and reliability requirement. Typically periodic traffic with 10-100 kbps data rate is considered for medical applications while streaming on bursty-based traffic with data rates up to 10 Mbps are chosen for consumer electronics. The MAC protocol for WBANs should consider the electrical properties of the human body and the diverse traffic nature of in-body and on-body nodes. For example, the data rate of in-body nodes varies, ranging from few kbps in pacemakers to several Mbps in capsular endoscope [67].

Multiple PHYs

WBAN MAC protocols should provide support for simultaneous operation of in-body MICS and on-body frequency bands/channels ISM or UWB at the same time [62]. So it should support multiple physical layers communication.

Scalability and Adaptability

Other important factors are scalability and adaptability to changes in the network, delay, throughput, and bandwidth utilization. Changes in the network topology, body position and node density should be handled rapidly and efficiently.

Less Transmission Delay

Real-time life-critical applications of BANs are not only delay-sensitive but also loss sensitive. Lost or corrupt alarm/alert packets due to unreliable wireless networks have serious consequences. For real-time medical applications, assuring timely data delivery is the most important factor because collecting overdue data is meaningless and it may lead to erroneous diagnosis. For emergency applications, the MAC protocol should allow in-body or on-body nodes to get quick access to the channel and to send the emergency data to the coordinator. One such example is the detection of irregular heartbeat, high or low blood pressure or temperature, and excessively low or high blood glucose level in a diabetic patient.

Traffic Priority

Reporting medical emergency events should have higher priority than non-medical emergency events. ECG and entertainment audio are both real-time continuous data and thus late arrival of them may prove useless. However, if they both try to access the channel simultaneously, ECG has to be processed with priority. Physiological data is absolutely more important than entertainment. Moreover, the BAN should support emergency alarms with utmost importance. Real-time communication is also required in some applications such as fitness and medical surgery monitoring. Furthermore, for multimedia applications, the latency should be less than 250 ms and the jitter should be less than 50 ms [56]. However, the reliability, latency, and jitter requirements depend on the nature of the applications.

Flexible Duty Cycling

Energy consumption, node mobility, hardware malfunctioning, link failures can occur due to frequent topology changes in WBANs. Hence, the network state must have to be updated for accurate slot assignment [63]. Power-efficient and flexible duty cycling techniques are required to minimize the idle listening, overhearing, packet collisions and control packet overhead problems. Furthermore, low duty cycle nodes should not receive frequent synchronization and control information if they have no data to send or receive.

Reliability

WBANs needs reliable data transmission in order to guarantee dependable and efficient sensor data delivery. The most important challenge in designing a MAC layer protocol for WBANs is to provide guaranteed QoS for various application requirements. The QoS framework of WBANs should be flexible so that it can be dynamically configured to suit application requirements without unduly increasing complexity or decreasing system performance.

Therefore, to satisfy the above mentioned requirements MAC protocol design has been a new challenge for WBANs.

3.4 WBANs MAC Protocols

The growing interest in WBANs and the continual emergence of reliability and quality-of-service (QoS) have inspired researchers to implement suitable MAC protocol for WBANs. In this section several MAC protocols for WBANs will be discussed. We have marked base protocols as those (i.e IEEE 802.15.4 and IEEE 802.15.6) what IEEE has standardized body area communications. Then we have described some major protocols in two sections where energy efficiency and emergency channel access schemes have been given importance.

3.4.1 Base Protocols

In this section we will briefly summarize the IEEE 802.15.6 MAC and IEEE 802.15.4 MAC based on the proposal depicted in the standard.

3.4.1.1 IEEE 802.15.6 MAC

The IEEE 802.15.6 draft specifies a common MAC for all the supported physical layers and which can use one-hop star or two-hop restricted tree topologies. In these topologies, the coordinator is responsible for coordinating channel access by establishing one of the following three access modes:

- Access Modes

  Beacon mode with superframe boundaries: in which coordinator provides schedule and unscheduled based access as shown in Figure 3.1. In our work we have considered beacon enabled mode with superframe boundaries, we will explain this mode in details in section 3.4.1.2.

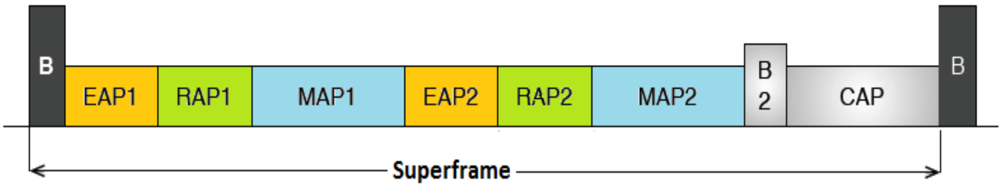


Figure 3.1: Beacon mode with beacon period boundaries

In IEEE 802.15.6 the entire channel is divided into superframe structures. Each superframe consists of a beacon which carries the WBANs identification, synchronization and slot allocation information. To check allocation status changes all nodes have to listen to the beacon in every superframe if they have reserved more than one TDMA time slot. Each superframe is divided into access phases (APs) as illustrated in Figure 3.1. The superframe structure of IEEE 802.15.6 starts with a beacon period followed by two consecutive periods each consisting of an Exclusive Access Phase (EAP), Random Access Phase(RAP), Managed Access Phase(MAP), and an optional B2 frame along with the Contention Access Phase (CAP). The details of these access periods are given in section 5.4.1.

Non-beacon mode with superframe boundaries in which the coordinator may have only the type-I/II access phase. Figure 3.2 shows the superframe of this mode.

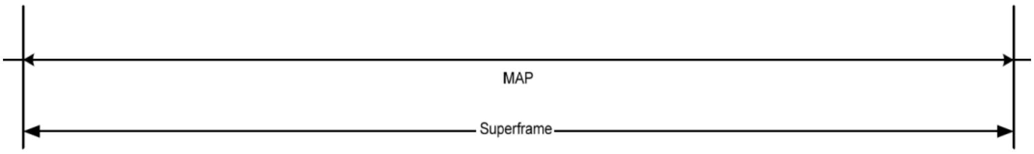


Figure 3.2: Beacon mode without beacon period boundaries

Non-beacon mode without superframe boundaries in which the coordinator only provides unscheduled polled allocations.

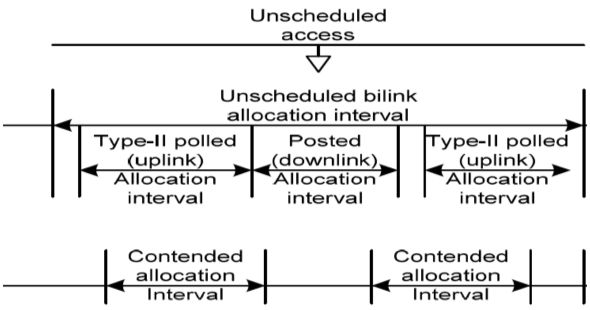


Figure 3.3: Beacon mode without beacon period boundaries

3.4.1.2 IEEE 802.15.4 MAC

The IEEE 802.15.4 [15] protocol has been considered as a communication standard for low data rate, low power consumption and low cost WPANs. As most of the radios used in WBANs are based on an IEEE 802.15.4 compliant chip set, some researchers have adapted the IEEE 802.15.4 MAC-protocol to make it more suitable for WBANs.

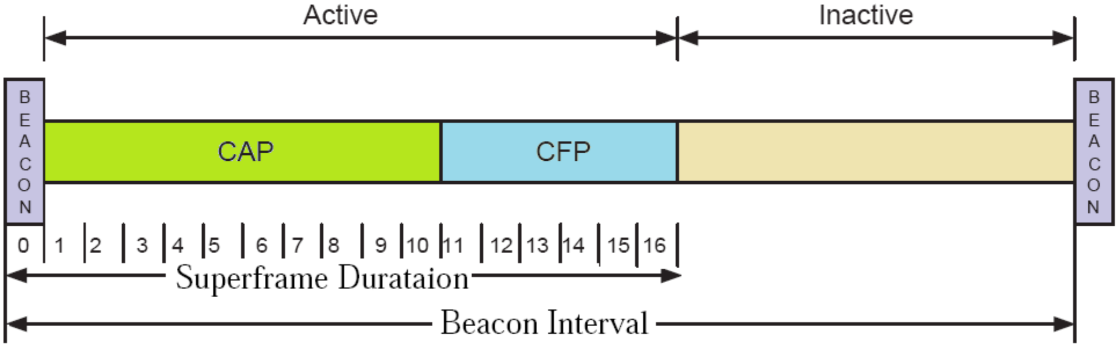


Figure 3.4: Superframe Structure of IEEE 802.15.4

A superframe structure is imposed in the beacon-enabled mode which begins with a beacon and is followed by an active and an optional inactive period as shown in Figure 3.4. Active portion is again divided into periods : one is contention access period (CAP) and another is the contention-free period (CFP). In the beacon enabled mode, nodes communicate with each other according to a slotted CSMA/CA protocol based on a superframe structure. The WPAN coordinator can reserve one or more Guaranteed Time Slots (GTSs) that are assigned to devices running such applications without need for contention with other devices. If there is no request to WPAN coordinator for GTS, the total active period can be utilized as CAP. On the other hand, in the non-beacon-enabled mode, nodes communicate with each other according to an unslotted CSMA/CA protocol. In the non-beacon-enabled mode there is no explicit synchronization provided by the PAN coordinator. Since there is no superframe defined in the non-beacon-enabled mode and no slot synchronization is available, no GTS can be reserved, and only random access is adopted for medium sharing.

3.4.2 WBANs MAC Protocols focusing on Energy Efficiency

Reducing energy consumption has been the focus of much research with many energy-efficient communication protocols being proposed [65–68]. In this section we will focus some well-known MAC protocols for WBANs which focus on energy efficiency.

3.4.2.1 Heartbeat Driven MAC (H-MAC) Protocol

Heartbeat Driven MAC (H-MAC) Protocol [65] is a schedule-based protocol originally proposed for a star topology WBANs. The energy efficiency is improved by exploiting heartbeat rhythm information in order to synchronize the nodes. The nodes do not need to receive periodic information to perform synchronization. The heartbeat rhythm can be extracted from the sensory data and hence all the rhythms represented by peak sequences are naturally synchronized. As a TDMA protocol, H-MAC assigns dedicated time slots to each biosensor to guarantee collision-free transmission. On the other hand, by taking advantage of heartbeat rhythm that is inherent in every human body, H-MAC achieves TDMA time synchronization without distributing periodic timing information, which reduces the energy cost. In H-MAC, biosensors extract the necessary synchronization information from their own sensory biosignals, which are correlated with or directly driven by the heartbeat pulsation, in a distributed way. H-MAC protocol encounters low spectral/ bandwidth efficiency in case of low traffic.

3.4.2.2 Priority-guaranteed MAC Protocol

The Priority-guaranteed MAC protocol [66] is proposed in order to support high data rate communications where the control and data channels are both divided into two parts for consumer electronic applications and medical applications. Control channels are split into application-specific sub-channels, and hence the access contention is restricted to the same application category. The frame structure of the priority-guaranteed MAC protocol is shown in Figure 3.5. The active part of one superframe is divided into five parts: – Beacon: used for downlink synchronization and control – Control channel AC1: used for the medical uplink control – Control channel AC2: used for CE uplink control – Data channel TSRP: timeslot reserved for periodic traffic – Data channel TSRB: timeslot reserved for bursty traffic.

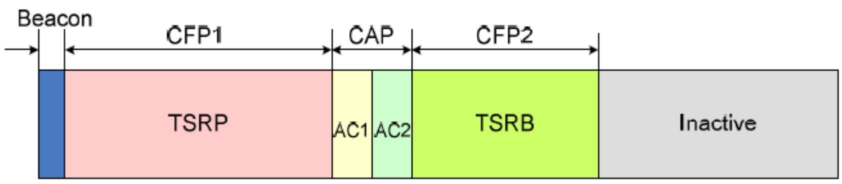


Figure 3.5: Superframe structure of the priority-guaranteed MAC [22].

The random access mechanism on the two control channels, AC1 and AC2, uses slotted ALOHA instead of CSMA-CA as channel access method for obtaining allocations. The access contention of the medical communication is protected from the much busier CE traffic with the split of the control channel. Nodes with medical traffic send resource requests on the separated AC1 channel. On the other hand, CE applications request for resource on the AC2 channel. Depending on traffic nature, the CE node will send the request to reserve the resource for a certain interval for audio/video streaming, or send the request on a per session basis for bursty traffic. Given the resource requests received on the control channels, the master node will decide the resource allocation in a centralized way. Since the master node is aware of the application category, algorithms can be easily applied to provide differentiated QoS to different applications.

3.4.2.3 Reservation-based Dynamic TDMA (DTDMA) Protocol

A Reservation-based Dynamic TDMA Protocol (DTDMA) [66] is originally proposed for normal WBANs traffic where slots are allocated to the nodes having buffered packets and are released to other nodes when the data transmission/reception is completed. In this approach, the channel is bounded by superframe structures. Each superframe consists of a

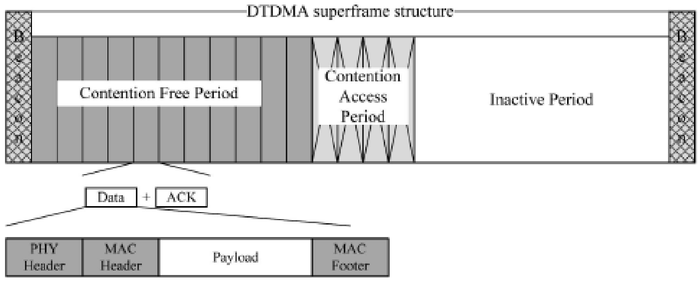


Figure 3.6 : Superframe structure for DTDMA Protocol [66]

Unlike a beacon-enabled IEEE 802.15.4 superframe structure where the CAP duration is followed by CFP duration, in DTDMA protocol the CFP duration is followed by CAP duration in order to enable the nodes to send CFP traffic earlier than CAP traffic. In addition, the duration of an inactive period is configurable based on the CFP slot duration. If there is no CFP traffic, the inactive period will be increased. The DTDMA superframe structure is as shown in Figure 3.6 DTDMA protocol provides more dependability in terms of low packet dropping rate and low energy consumption when compared with IEEE 802.15.4. However, it does not support emergency and on-demand traffic.

3.4.2.4 MedMAC

Timmons and Scanlon [67] developed MedMAC, a MAC protocol, for ultra low power WBANs applications. It is an adaptive TDMA based MAC protocol which incorporates a novel synchronization mechanism where a node can sleep through a number of beacon periods. The beacon period consists of a contention free period and optional contention access period which are made up of 2-256 timeslots as shown in Figure 3.7.

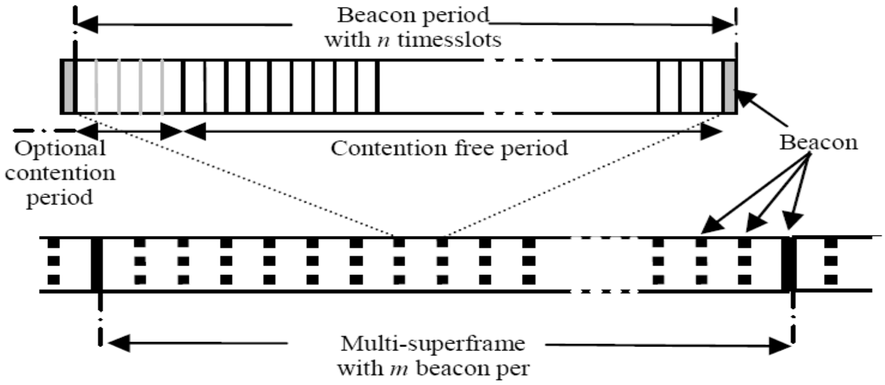


Figure 3.7: Superframe Structure for MedMAC [67]

The duration of the multi-super frame is defined by this synchronization mechanism. Synchronization between the coordinator and the other nodes can be maintained by the combination of timestamp scavenging and an adaptive guard band algorithm. In timestamp scavenging, synchronization needs an updated timestamp field. AGBA allows the node to sleep through many beacon broadcasts by introducing a guard band for each timeslots to track the actual drift. At the start of multi-superframe all the nodes are brought into synchronization by use of a timestamp. At this point, the algorithm AGBA is used to calculate the guard band (GB) for each node. Each node has a dedicated time slot which helps to avoid collisions.

3.4.2.5 DQBAN

Otal et al. [68] proposed a novel cross-layer fuzzy-logic scheduling and energy aware radio activation based MAC model for WBANs. DQBAN supports high application-dependant performance requirements in terms of reliability, message latency and power consumption, while being adaptable to changing conditions, such as heterogeneous traffic load, interference, and the number of sensors in a hospital BSN. The main idea here is to integrate in each body sensor multiple cross-layer input variables of diverse nature in an independent manner. A fuzzy-logic system is integrated in each body sensor. Using the QoS scheduler along with fuzzy logic rules helps in making this protocol more reliable in terms of data transfer and also improves system performance considerably. In this scheme body sensors consider relevant cross-layer system constraints, such as physical layer signal quality, packet system waiting time, and residual battery lifetime, to demand or refuse the next frame collision-free data slot via the scheduling minislots [72].

3.4.3 WBANs MAC Protocols focusing on Emergency Data Handling

In this section we will focus on those MAC protocol methods for handling emergency traffic. Normally, emergency data is required to be delivered reliably ahead of all other traffic as late arrival of them proves absolutely useless. Moreover, it can endanger human life. Recently some researchers have drawn their attention to minimizing channel access delay for emergency traffic. Among these IEEE 802.15.6, IEEE 802.15.4, TaMac [69], PNP-MAC [70], HBC-MAC [72] are worth mentioning. In this section we will describe these protocols and examine their limitations.

3.4.3.1 TA-MAC

In the TA-MAC protocol [69] traffic has been classified into three categories: normal, emergency and on-demand traffic. Unpredictable medical important traffic has been considered as emergency traffic. Periodic medical data i.e. routine health information has been regarded as normal traffic. On-demand traffic has been initiated by the coordinator to acquire certain information.

Figure 3.8: TA-MAC Superframe structure [69]

The superframe structure of the TaMAC protocol is shown in Figure 3.8. It contains a beacon, a Configurable Contention Access Period (CCAP), and a CFP. The CCAP period contains a few minislots (3 or 4) of equal duration and is used for short data transmission which also uses slotted-ALOHA based channel access scheme. The CFP period contains a series of GTSs which are used for data transmission. TA-MAC introduces two wakeup mechanisms, a traffic-based wakeup mechanism used for normal traffic, and a wakeup radio mechanism used for emergency/on-demand traffic. In the traffic-based wakeup mechanism, the operation of each node is based on the traffic-patterns. The initial traffic-patterns are predefined by the manufacturer and/or created and modified by the coordinator. The traffic-patterns of all nodes are organized into a table called the traffic-based wakeup table. The table is maintained by the coordinator according to the application requirements.

3.4.3.2 PNP MAC

PNP MAC [70] follows the hybrid MAC approach which considers prioritized access in both access techniques. All data are classified in advance based on their degree of importance and traffic types. PNP MAC can handle various applications with diverse QoS requirements through fast, preemptive slot allocation, non-preemptive transmission in the allocated slots, as well as flexible superframe adjustment. Figure 3.9 shows the superframe structure of PNP MAC which is divided into five access periods: advertisement, contention access period (CAP), beacon, data transmit slot (DTS), and emergency data transmit slot (ETS), and inactive periods.

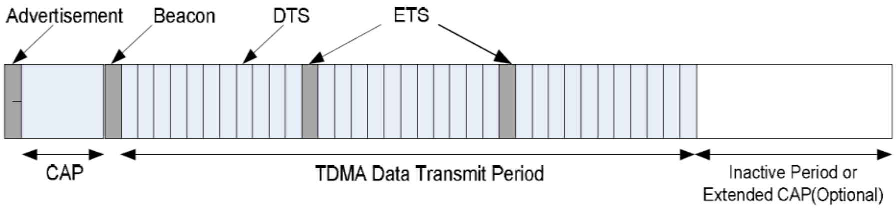


Figure 3.9: PNP MAC Superframe structure [70]

Concatenated placement of advertisement, CAP and beacon enable fast slot allocation and data transmission in PNP MAC. The WBAN coordinator broadcasts the advertisement at the beginning of each superframe. CAP is for non-periodic data, emergency alarm and command frames. To handle emergency traffic PNP MAC uses ETS in TDMA data transmit period. ETS is a contention access slot reserved for urgent delivery of unpredictable emergency data. Prioritized back-off, clear channel assessment CCA) [15] , and data slot allocation are applied to all data transmission to serve higher priority data first. In case of unavailability of data transmission slot ETS is assigned to nonemergency data as well.

3.4.3.3 HBC MAC

HBC MAC [72] uses a modified superframe format of beacon enabled IEEE 802.15.4 protocol. The superframe is composed of three parts: beacon, CAP and CFP, as shown in Figure 3.10. CFP consists of a number of GTS and may include zero or single Emergency Guaranteed time slot (EGTS) or several EGTSs. As use of CSMA/CA adds unreliability in channel sensing, therefore, within the CAP part of HBC-MAC, slotted ALOHA without carrier sensing has been adopted. CAP is used for the irregular management data and medical report data whereas CFP is used reservation based by request/confirm for bulky and/or regular data transmissions. CFP in HBC-MAC becomes active when coordinator receives requests of time-slot-allocation from the devices.

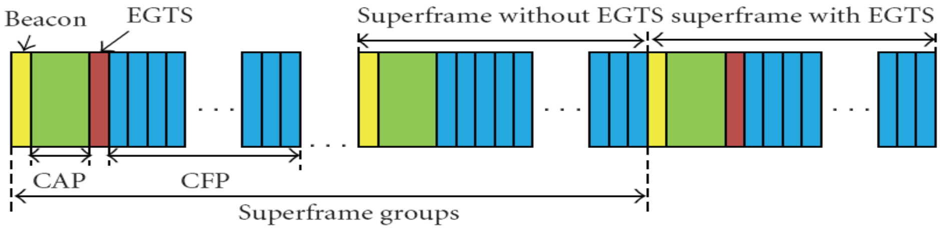


Figure 3.10: HBC MAC Superframe structure [72]

Upon receiving this request, the coordinator checks whether there are sufficient resources and, if possible, allocates the requested time slots. Here the authors propose emergency handling operation by using Emergency Guaranteed Time Slots (EGTSs). CFP consists of a number of guaranteed time slots and may include zero or single or several EGTSs. The number of EGTS depends on the various combinations of beacon intervals and emergency rates. There are three cases: i) (Superframe having EGTS at the time of Emergency events) ii) (Superframe having no EGTS at the time of Emergency events) iii) Multiple emergencies. For the first case, emergency data is transmitted immediately using EGTS without any hesitation, for the next case devices do not wait for the next superframe interval with an EGTS. When an emergency event occurs within a superframe interval without EGTS, devices try to transmit an emergency alarm in the CAP duration by using slotted CSMA/CD. For the last case, when multiple emergencies occur trying to get access to the channel, collision will take place and in this situation emergency traffic in HBC-MAC will be handled at the next CAP or EGTS period.

3.5 Summary

The overall system performance of a wireless network is not only determined by physical layer technologies but also depends on MAC protocols. In this chapter we mainly focused on the MAC layer based protocols for WBANS. We first outlined basic principles and major MAC requirements of WBANs. We studied some WBANs MAC protocols which focuses on energy efficiency and emergency channel access. Emergency traffic is required to be delivered earlier as compared to normal traffic. We examined emergency channel access based scheme by discussing their strengths and weaknesses.

Chapter 4

Performance Analysis of IEEE 802.15.4 for Implant WBANs

4.1 Introduction

In this chapter, we mainly analyze the performance of IEEE 802.15.4 with the help of proper in-body communication channel models [74-78] using NS-2 simulations. The location of nodes on the body and more specifically the paths to other nodes have a large impact on the channel quality. The complexity of the human tissues and body shape make it difficult to derive a simple path loss model for WBANs. The path loss [79] in WBANs is very high, especially when the transmitters and the receivers are shadowed by a part of the body. When IEEE 802.15.6 was in the process of being standardized the existing IEEE 802.15.4 protocol or a modification of it was considered as an interim solution. Although, IEEE 802.15.4 is considered for certain on-body medical applications, but it does not achieve the level of power required for in-body nodes. A suitable channel model is required in order to apply IEEE 802.15.4 for in-body applications. Although Network Simulator (NS-2) [80] has implemented several propagation models to predict the signal power received by the receiver, NS-2 does not have a proper channel model as required for implant WBANs. We have implemented CM1 (implant to implant) [5] and channel model CM2 (between an implant device and an on or out-of body device) in IEEE 802.15.4's NS-2 module with proper path loss and physical layer parameters as suggested in IEEE 802.15.6 standard [8]. This chapter is organized as follows. Section 4.2 briefly summarizes the IEEE 802.15.4 PHY layer and the radio propagation model in it. Section 4.3 provides an overview of radio propagation models and link budget calculations for implant WBANs. Section 4.4 investigates the impact of path loss effects on the performance of WBANs. Finally, this chapter is concluded in Section 4.5.

4.2 IEEE 802.15.4

4.2.1 IEEE 802.15.4 PHY

The IEEE 802.15.4 standard [15] specifies the PHY and MAC layers for low-rate WPANs. The PHY layer protocol defines operation in several frequency bands, the most prominent being the 2450 MHz industrial, scientific and medical (ISM) band where the protocol uses orthogonal quadrature phase shift keying (O-QPSK) modulation [81] to support a data rate of 250 Kbps. The main features of this standard are network flexibility, low cost, very low power consumption, and low data rate in an adhoc self-organizing network among inexpensive fixed, portable and moving devices. The standard can operate in multiple frequency bands: the 868 MHz band with data rates of 20 kb/s, the 915 MHz band with data rates of 40 kb/s, and the license-free ISM 2.4 GHz band with data rates of 250 kb/s. There are 27 channels that can be allocated in IEEE 802.15.4: one channel in the 868 MHz band, ten channels in the 915 MHz band and 16 channels in the 2.4 GHz band. The standard uses binary phase shift keying (BPSK) for chip modulation in the 868 MHz and 915 MHz bands, and offset O-QPSK in the 2.4 GHz band. The IEEE 802.15.4 physical parameters are summarized in Table 4.1.

Frequency Band	Coverage	Sub-Channels	Data Rate	Data Modulation	Chip Modulation
868 GHz	Europe	1	40kbit/s	16-ary orthogonal	BPSK, 300chips/s
915 MHz	America	10	20kbit/s	BPSK	BPSK, 600chips/s
2.4 GHz	Worldwide	16	250kbit/s	BPSK	OQPSK,2Mchips/s

Table-4.1: IEEE 802.15.4 Physical Layer Parameters.

4.2.2 Radio propagation model in IEEE 802.15.4

Propagation models [82] play a very important role in designing wireless communication systems. The aim of propagation model is to determine the probability of satisfactory performance of a wireless system that depends on radio wave propagation [8]. Radio propagation models are used to predict the received signal power of a packet. When a packet is received with the signal power below the receive power threshold it is dropped by the node. Most radio propagation models are derived by using a combination of analytical and empirical methods. Propagation models which are used in IEEE 802.15.4 PHY are listed below :

4.2.2.1 Free Space Model

The free Space model is normally used to simulate path loss of wireless communication when line-of-sight path exists between transmitter and receiver as derived by H. T. Friis [82]. The free space model basically represents the communication range as a sphere around the transmitter. If a receiver is within the sphere, it receives all packets. Otherwise, it loses all packets.

4.2.2.2 Two-ray Ground Reflection Model

The Two-Ray Ground model is used when both a line-of-sight path exists and a ground reflection path exists. The two-ray ground reflection model as shown in Figure 4.1 takes into account both direct and a ground reflected path. A single line-of-sight path between two mobile nodes is seldom the only means of propagation.

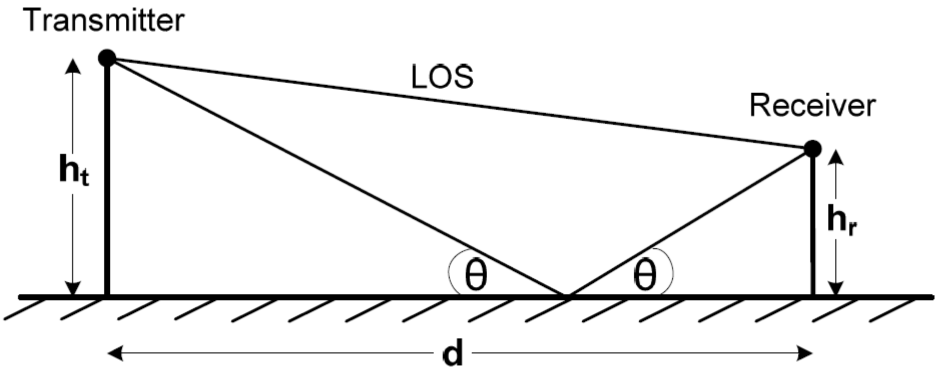


Figure 4.1 : Two-Ray Ground Reflection Model

The two-ray ground reflection model considers both the direct path and a ground reflection path. This model gives a more accurate prediction at a long distance ,d, than the free space model. However, the two-ray model does not give a good result for a short distance due to the oscillations caused by the constructive and destructive combination of the two rays. Instead, the free space model is still used as the line-of-sight is dominant.

4.2.2.3 Shadowing Model

The shadowing model simulates the shadow effect of obstructions between the transmitter and receiver. The free space model and the two-ray model predict the received power as a deterministic function of distance. They both represent the communication range as an ideal sphere. In reality, the received power at a certain distance is a random variable due to fading effects. In fact, the above two models predict the mean received power at distance d.

The shadowing model consists of two parts. The first one is known as the path loss model, which also predicts the mean received power at distance d, denoted by $P_r(d)$. It uses a close-in distance d_0 as a reference distance. $P_r(d)$ is computed relative to $P_r(d_0)$ as follows.

$$\frac{P_r(d_0)}{P_r(d)} = \left(\frac{d}{d_0}\right)^{\beta} \qquad (4.1)$$

β is called the path loss exponent, and is usually empirically determined by field measurement. The path loss is usually measured in dB.

The second part of the shadowing model reflects the variation of the received power at a certain distance. It is a log-normal random variable, i.e. the loss in dB follows a Gaussian distribution.

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{db} = -10\beta \log\left(\frac{d}{d_0}\right) + X_{dB} \qquad (4.2)$$

where X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB}. σ_{dB} is called the shadowing standard deviation, and can be obtained by measurement. The shadowing model extends the ideal sphere model to a richer statistical model.

4.3 Radio Propagation in WBANs

The effect of propagation of electromagnetic waves in the human body has been investigated in [62]. A reliable and efficient communication link is necessary to guarantee the best connection from/to in-body and on-body devices. The major factors which influence the radio propagation are path loss and fading. Path loss describes the loss in power as the radio signal propagates in space. It is caused by the dissipation of the power radiated by the transmitter and also by the propagation channel. On the other hand fading occurs due to different reasons, such as energy absorption, reflection, diffraction, shadowing by body, and body posture. The other possible reason for fading is multipath due to the environment around the body. As the antennas for WBANs applications are placed on or inside the body, the WBANs channel model needs to take into account the influence of the body on the radio propagation. Radio propagation through a human body depends on losses caused by power absorption, radiation pattern destruction and central frequency shift [79]. The absorption effects vary in magnitude with both frequency and

Tissue	**Relative Dielectric Constant**	**Conductivity**
Bone	13.14	0.09
Fat	5.58	0.07
Heart	66.02	0.94
Liver	51.18	0.66
Lung	54.55	0.68
Muscle	58.79	0.84
Skin	46.72	0.69

Table 4.2: Electrical parameters of important human tissues

at the MICS frequency band.[107]

the characteristics of the tissue. Table 4.2 lists the electrical parameters of different human tissues at the MICS band. In the following section, we provide an outline and possible scenarios of our radio channel model and measurement setup for WBAN communications.

4.3.1 Channel Models in WBANs

A channel model is needed to evaluate performance of wireless communication systems. Experimental channel modeling for implants and wearable devices is difficult due to involvement of human subjects and healthcare facilities, both governed by regulations. The dynamic environment due to body postures, multipath, and mobility further complicates the empirical validation of channel models.

The IEEE 802.15.6 channel modeling subgroup released the final channel model [75] in April 2009. Possible communication links for WBANs are depicted in Figure 4.2. These scenarios along with their descriptions and frequency bands are listed in Table 4.3. The scenarios are determined based on the location of the sensor nodes (i.e. implant device, scenarios are grouped into classes that can be represented by the same Channel Models (CMs).

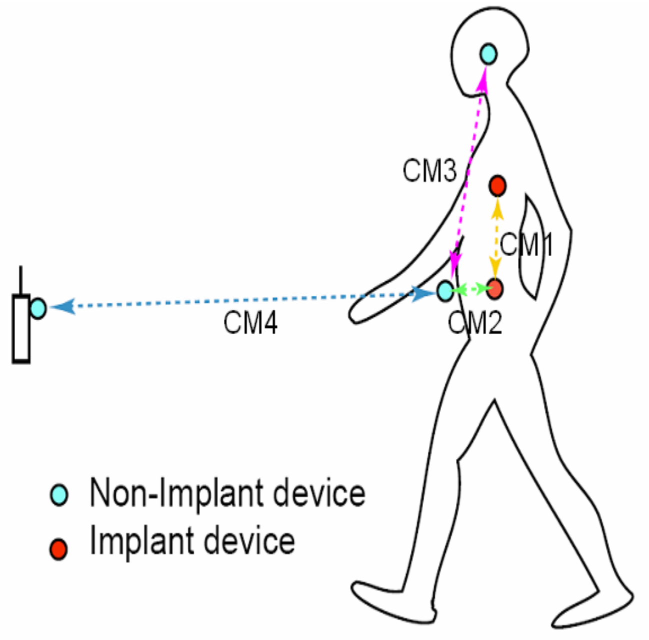


Figure 4.2: Communication Links for WBANs. [from 75]

Scenario	Description	Frequency Band	Channel Model
S1	Implant to Implant	402-405 MHz	CM1
S2	Implant to Body Surface	402-405 MHz	CM2
S3	Implant to External	402-405 MHz	CM2
S4	Body Surface to Body Surface (LOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM3
S5	Body Surface to Body Surface (NLOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM3
S6	Body Surface to External (LOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM4
S7	Body Surface to External (NLOS)	13.5, 50, 400, 600, 900 MHz 2.4, 3.1-10.6 GHZ	CM4

Table 4.3: Scenarios and Descriptions of Different Channel Models of WBANs.

CM1 represents the communication link between implant devices and CM2 is between an implant device and an on or out-of body device. CM3 and CM4 are related to body surface and external device). The wearable devices whereas CM3 is related to the surface of the body and CM4 is related to off the body and surface of the body. Among these channel models we will mainly focus on CM1 and CM2 in our analysis.

4.3.2 Radio Propagation Model for CM1 and CM2

4.3.2.1 Link budget Calculation

Link budget [83] is an important property in a wireless network in order to understand the successful packet reception rate. Link budget of a WBAN node is affected by the antenna used on a node. The radiation pattern of an antenna will also influence the link budget. The link budget depends on the radio propagation conditions and packet transmission and reception techniques. Research shows that the induced path loss in a channel near the human body is higher than free space, with the path loss exponent ranging from 2.18 to 3.3 and higher [84],[85]. It is concluded that the path loss in WBANs is very high that, compared to the free space propagation, an additional 30-35 dB at small distances(i.e 140~150 mm) is noticed [11].

The total path loss between a WBAN transmitter and receiver can be calculated by using equations (4.3) and (4.4):

$$PL(d) = PL(d_0) + 10n\log 10\left(\frac{d}{d_0}\right) + S \qquad (4.3)$$

$$S \sim N(0, \sigma_s) \qquad (4.4)$$

where $PL(d_0)$ is the path loss at a reference distance d_0 (50mm) . d is the distance between transmitter and receiver, n is the path loss exponent, and S is loss due to shadow fading. Shadowing effects are modelled by a random variable with a normal distribution with zero mean and standard deviation i.e., $N(0, \sigma_s^2)$.

The parameters corresponding to CM1 and CM2 are shown in the Tables 4.4 and 4.5. Details of the model derivation can be found in [75].

Implant to Implant	$PL(d_0)(dB)$	n	$\sigma_s(dB)$
Deep Tissue	35.04	6.26	8.18
Near Surface	40.94	4.99	9.05

Table 4.4: Parameters for CM1 - Implant to Implant for 402-405 MHz.

Implant to Body Surface	$PL(d_0)(dB)$	n	$\sigma_s(dB)$
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

Table 4.5: Parameters for CM2: Implant to Body Surface for 402-405 MHz.

The calculation of path loss is very important to determine the minimum reception power required by a receiver so that the packet can be received successfully. As shown in [83] the relationship between minimum reception power P_{Rx}(min) and path loss can be expressed as the following equation :

$$P_{Rx}(\min) = P_{Tx} - PL(d) \qquad (4.5)$$

Here P_{Tx}, is the transmission power. Both P_{Tx} and path loss $PL(d)$ are expressed in dB. This minimum reception power will depend on the receiver's sensitivity which is related to SNR. The value of SNR can been calculated by the following equation (4.6):

$$SNR = 10\log\left(\frac{P_{Rx}}{Noise}\right) \qquad (4.6)$$

The minimum receiver sensitivity numbers for the highest data rate at each operating frequency band are listed in Table 4.6.

Frequency Band (MHz)	Information Data Rate (kbps)	Minimum Sensitivity (dBm)
402 – 405	75.9	–98
	151.8	–95
	303.6	–92
	455.4	–86

Table 4.6 — Receiver Sensitivity Numbers [8]

The power level at which the packet was received at the MAC layer is compared with the receiving threshold and the carrier-sense threshold. If the power level falls below the carrier sense threshold, the packet is discarded as noise. If the received power level is above the carrier sense threshold but below the receive threshold, the packet is marked as a packet in error before being passed to the MAC layer. Otherwise, the packet is simply handed up to the MAC layer.

4.4 Channel Model Implementation in NS-2

NS-2 is widely used as a generic and powerful network simulator with open source code, and simulation results generated by NS-2 are generally considered veracious and acceptable. With abundant components libraries, NS-2 has the capability of not only simulating protocols of WANs and LANs in fixed-line Internet, but also performs well in simulation of wireless and mobile networks. In NS-2's IEEE 802.15.4 module [87] several propagation models are available i.e. Free Space, Two Ray Ground, and Shadowing models in order to predict the signal power received by the receiver. In Section 4.2.2 we discussed the basics of these propagation models. NS-2 mainly uses thresholds to determine whether one frame is received correctly by the receiver [109]. We have added a propagation model to produce our simulation results. We mainly modified the NS-2 shadowing model and on top of it we implemented wbanCM with the proper values as suggested in Table 4.4 and 4.5. After that we have changed the power parameters, the considered values have been shown Table-4.7.

Parameter	Value
RxThresh (Reception Threshold)	-95 dBm
CSThresh(Carrier Sense Threshold)	-95 dBm
CPThresh (Capture Threshold)	10
txPower (Transmit Power)	0.012 W
rxPower (Receiption Power)	0.015 W
idlePower (Idle Power)	0.000002552 W

Table 4.7: Considered Power Variables in Simulation

NS-2 sets CSThresh to determine whether one frame is detected by the receiver. If the signal strength of the frame is less than CSThresh, this frame is discarded in PHY module and will not be visible to MAC layer. NS-2 has another threshold RxThresh for the signal strength of one frame received by the receiver. If one frame is received and received signal strength is stronger than RxThresh, the frame is received correctly. Otherwise, the frame is tagged as corrupted and the MAC layer will discard it. When multi-frames are received simultaneously by one mobile node, it calculates the ratio of the strongest frame's signal strength to the signal strength sum of other frames. NS-2 uses the capture threshold (CPThresh) for this ratio. If it is larger than CPThresh, the frame will be received correctly and other frames are ignored. Otherwise, all frames are collided and discarded.

4.4.1 Simulation Results

4.4.2 Simulation Scenario and Parameters

In this section we investigate the performance of a beacon-enabled IEEE 802.15.4 MAC, for in-body communications. The wireless physical layer parameters are considered according to a low-power Zarlink MICS Radio Platform, ZL70102 [88]. This radio transceiver operates in the 402-405MHz band with an optimum transmission power of -16dBm. We used the CM1 and CM2 propagation models throughout the simulation. We consider single node and multiple nodes (up to 7) scenario which were connected with a coordinator in a star topology. The initial energy of the node is 5J. The packet size is 70bytes. The transport agent is UDP protocol, CBR traffic is considered as the traffic pattern.

4.4.3 Simulation of Path Loss and Received Signal Strength:

To characterize the path loss and received signal strength within an implant to implant and implant to body surface area, we analyzed 9 different distances ranging from 50 mm to 250 mm in our experiment. We have considered only two nodes: one transmitter and one receiver in our simulation. In Figures 4.3 and 4.4 we characterize the result of average path loss for CM1 and CM2 as a function of transmitter-receiver separation. The deep tissue implant scenarios considers endoscopy capsule applications for upper stomach (95mm below body surface) and lower stomach (118mm below body surface).[109]. The near-surface scenarios include applications such as Implantable Cardioverter-Defibrillator (ICD) and Pacemaker.

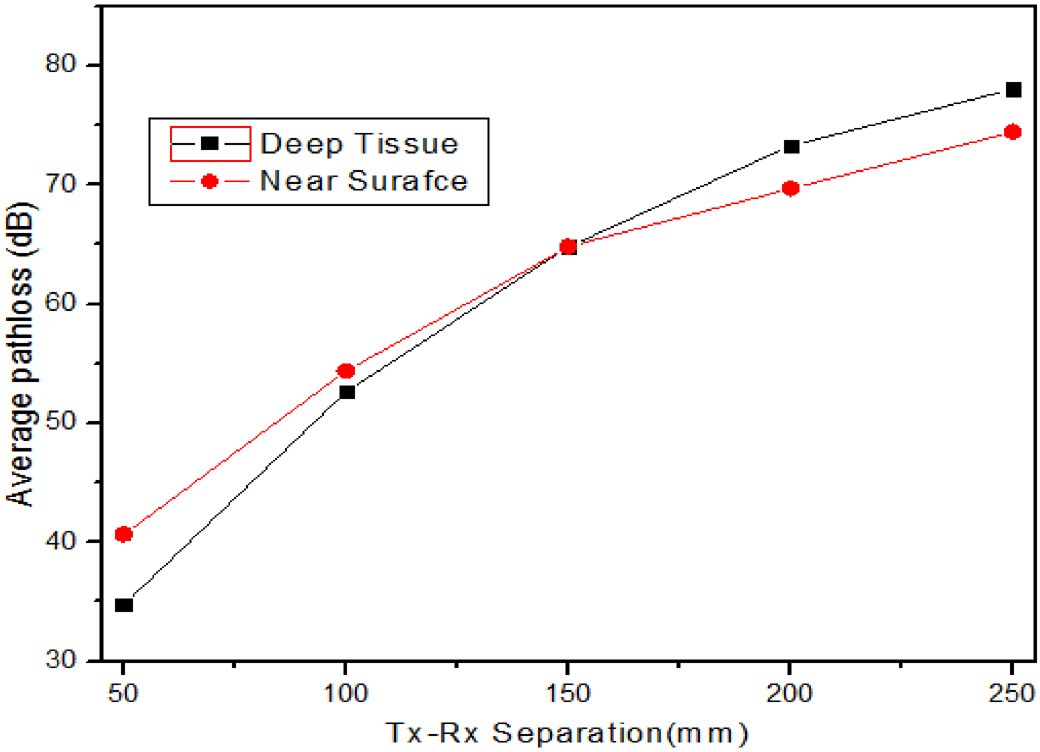


Figure 4.3: Pathloss for CM1.

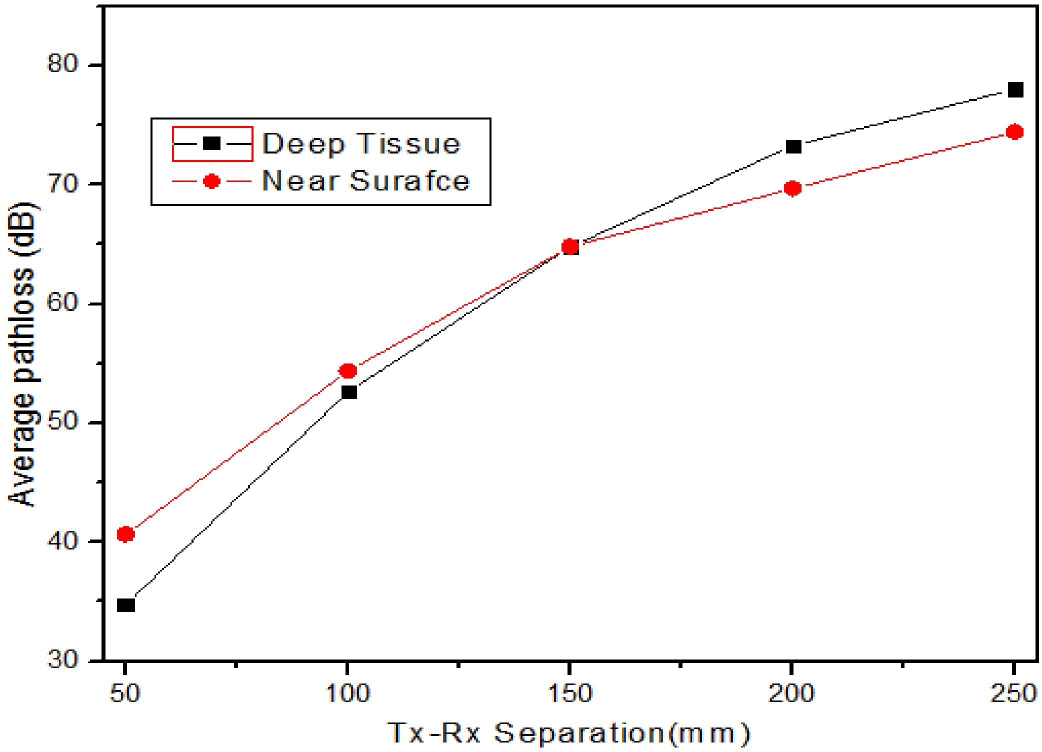


Figure 4.4: Pathloss for CM2.

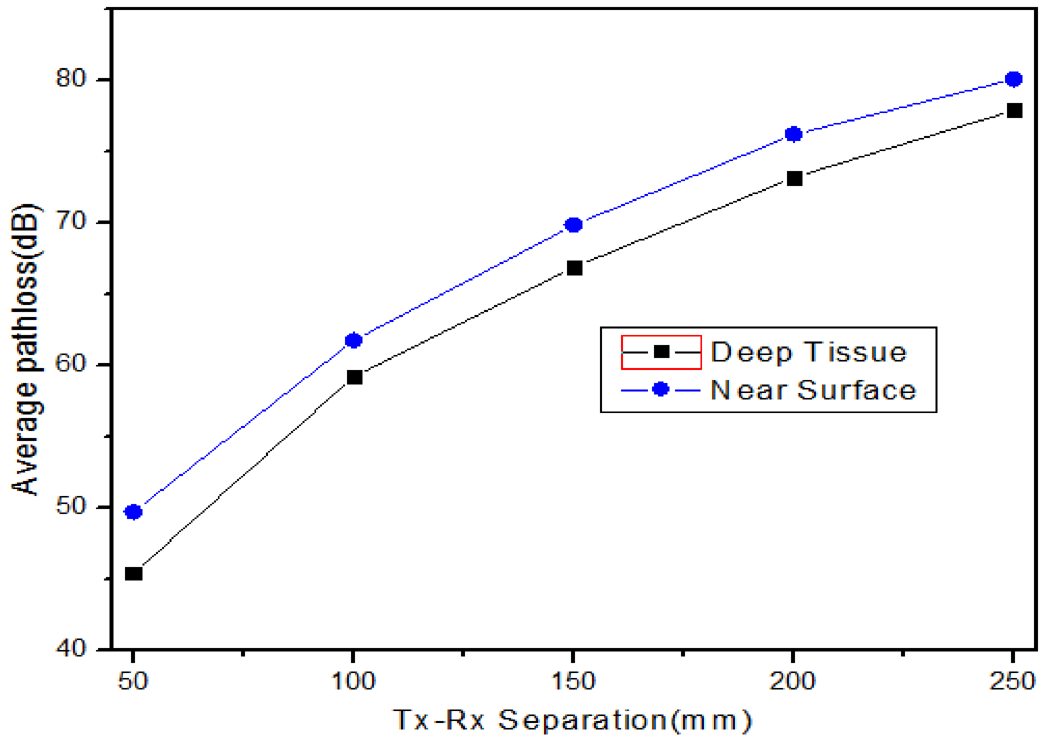


Figure 4.4: Pathloss for CM2

We represent the average path loss for CM1 in Figure 4.3. for both type of scenarios with the increase of transmitter- receiver separation. Although the average path loss has increased over the transmitter-receiver separation but after 140mm distance we see that path loss for deep tissue is larger than for the body surface scenario. In Figure 4.4 we show the path loss for CM2 for both of the cases where value of path loss for deep tissue scenario is always higher than near surface scenario in any point. From these figures this is evident that path loss for deep tissue scenario in CM1 is always lower than CM2 up to 200 mm and after that pathloss for CM2 slightly increased over CM1.

In Figures 4.5 and 4.6 we show the corresponding received signal strength (RSS) for the same transmitter-receiver separation considered in Figure 4.3 and 4.4. The maximum transmission power (-16 dBm) is considered for both channel models. We can see that in 250mm distance the RSS value becomes marginal with the RxThresh's value(-95 dBm).

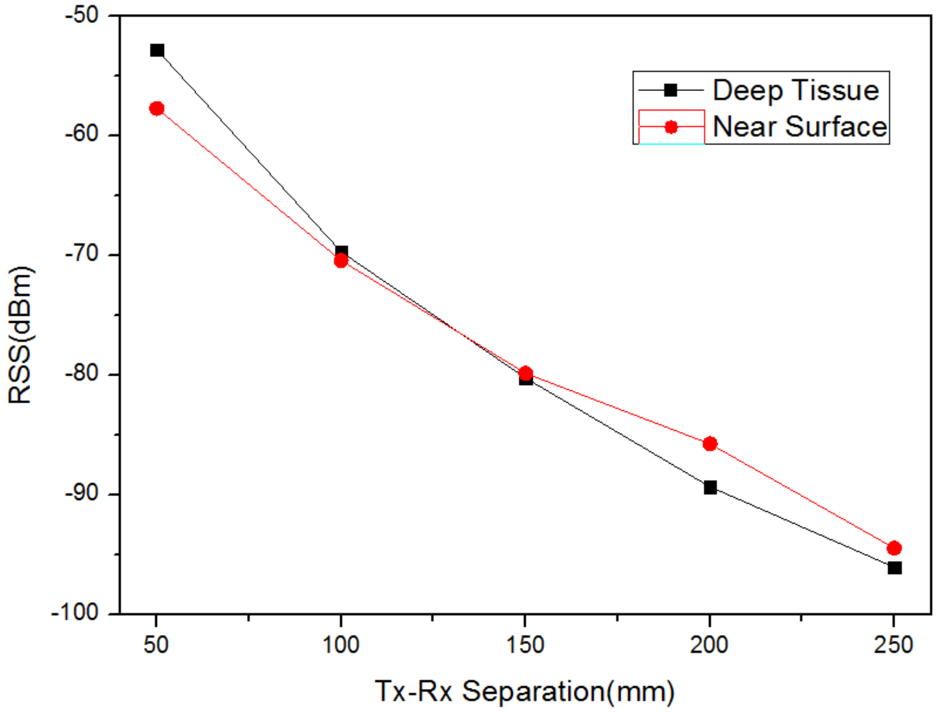


Figure 4.5: Received Signal Strength for CM1.

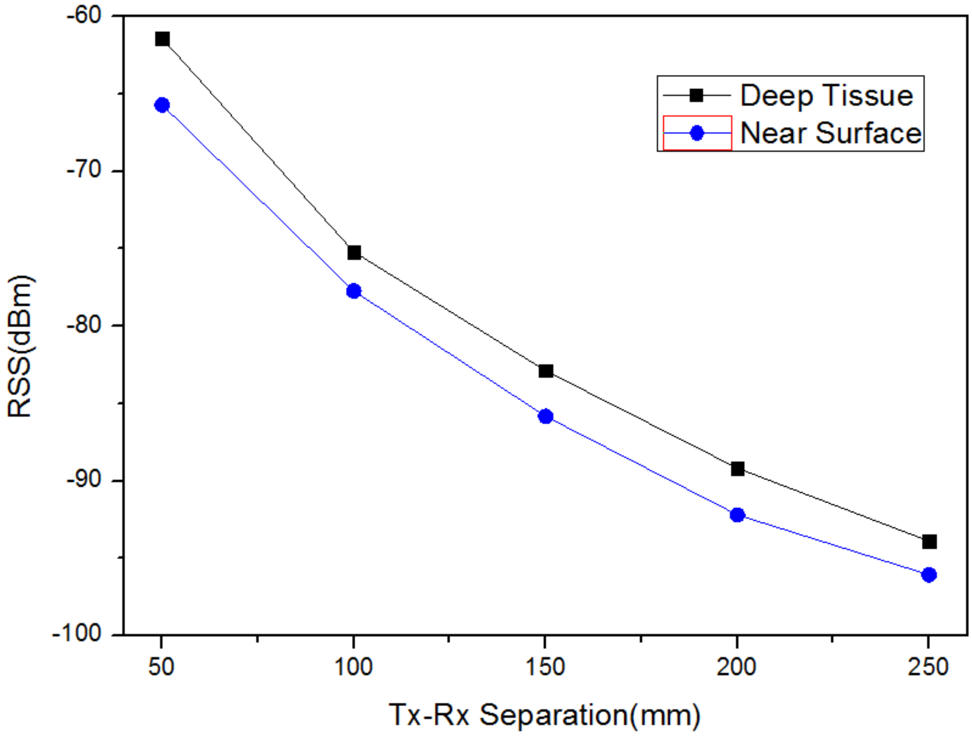


Figure 4.6: Received Signal Strength for CM2.

From the above figures it is evident that the path loss has increased with the separation of the transmitter and receiver with a corresponding decrease in the RSS which was expected. The simulated path loss graphs shown in figures 4.3 and 4.4 are very identical with those who used MATLAB and other tools in literature [75],[86]. This dependency of RSS on the path loss is well established in the well known channel modeling schemes and has been verified for a few threshold values of RSS mentioned in the draft.

4.4.4 Packet Delivery Ratio and Energy Consumption

In this section we will show packet level performance of IEEE 802.15.4 MAC with the modified channel model.

Packet Delivery Ratio:

The average Packet Delivery Ratio (PDR) is the number of packets received to the number of packets sent averaged over all the nodes.

$$PDR = \left(\frac{\mathrm{Re}ceived\_packets}{Total\_no\_packets} \right) 100\% \qquad (4.7)$$

Energy Consumption:

As defined in [108] the average Energy Consumption (EC) of each packet has been considered as follows:

$$\mathrm{EC} = \left(\frac{\mathrm{E_{tx}} + \mathrm{E_{rx}} + \mathrm{E_{idle}} + \mathrm{E_{sleep}}}{\mathrm{N_p}} \right) \qquad (4.8)$$

where N_p is the average number of packets transmitted by each node per second; E_{tx}, E_{Rx}, E_{idle}, and E_{sleep} are the energy consumed in a second in transmitting, receiving, idle, and sleep states of each node, respectively.

Average end to end delay: The average end to end delay is defined as the average delay in transmission of a packet between two nodes and is calculated as follows:

$$Delay_{avg} = \frac{\sum_{1}^{n} (t_{sent\_time} - t_{received\_time})}{total\_receiced\_packets} \qquad (4.9)$$

Each node is fixed in the beacon-enabled star topology, where WBAN coordinator is located at the center. The simulation duration is 300s, the application traffic is constant bitrate (CBR) UDP source, which is popularly used in most simulations. The CBR traffic is an ideal model for some of the medical applications, where the nodes send data based on pre-defined traffic patterns. When defining the parameters of the communication model of CBR, we experiment with sending rates 100 packets per second, networks containing single and seven(for multiple nodes scenario) CBR sources, and packet size of 70 bytes.

In Figures 4.7 and 4.8 we have analyzed PDR and average energy consumption for CM1 and CM2 respectively. As we have seen in Section 4.4.3 path loss of deep tissue and near surface scenarios are almost identical in CM1 and CM2, in this section we have generated the result considering the deep tissue based scenario only.

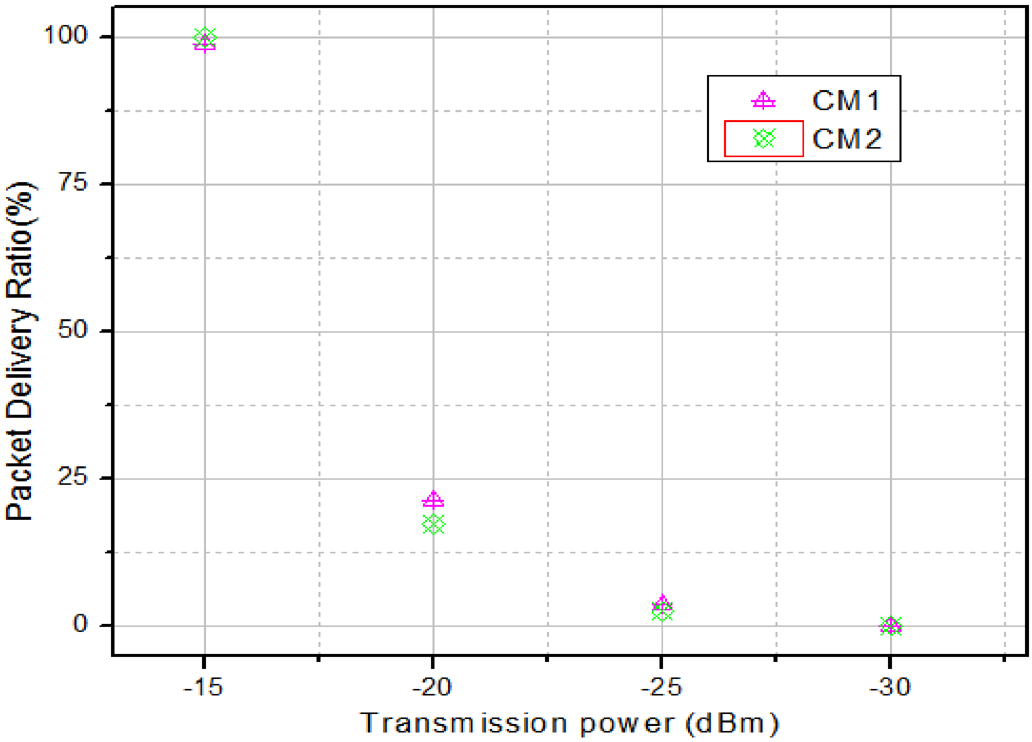


Figure 4.7: Packet Delivery ratio for CM1 and CM2.

In Figure 4.7 the transmission power is varied from -15dbm to -30dbm and we can see that CM1 has better PDR as compared to CM2 for all power levels. Transmitter and receiver's separation was set to 200mm. We also see that if we reduce the transmission power to -30dBm no packet will be received in both CMs. The main reason for the difference in PDR between CM1 and CM2 because CM1 has less pathloss as compared to CM2. It is possible that the difference is due to reflections at the skin in the CM2 model. However, investigation of the details of the CM models was outside the scope of the thesis.

Although the modified channel model what we developed in NS-2 was based on shadowing model we did not consider shadow fading's effect in simulation as it was not our main focus. Here we mainly focused on characterizing the performance of CM1 and CM2 with the modified channel model.

The average energy consumption's result is shown in Figure 4.8 where the initial energy is considered as 5 Joule. As expected, we can see in 500 sec simulation time the energy consumption for CM1 and CM2 is 0.55 joule and 1.75 joule respectively. We can deduce that in implant to implant scenario less energy will be consumed.

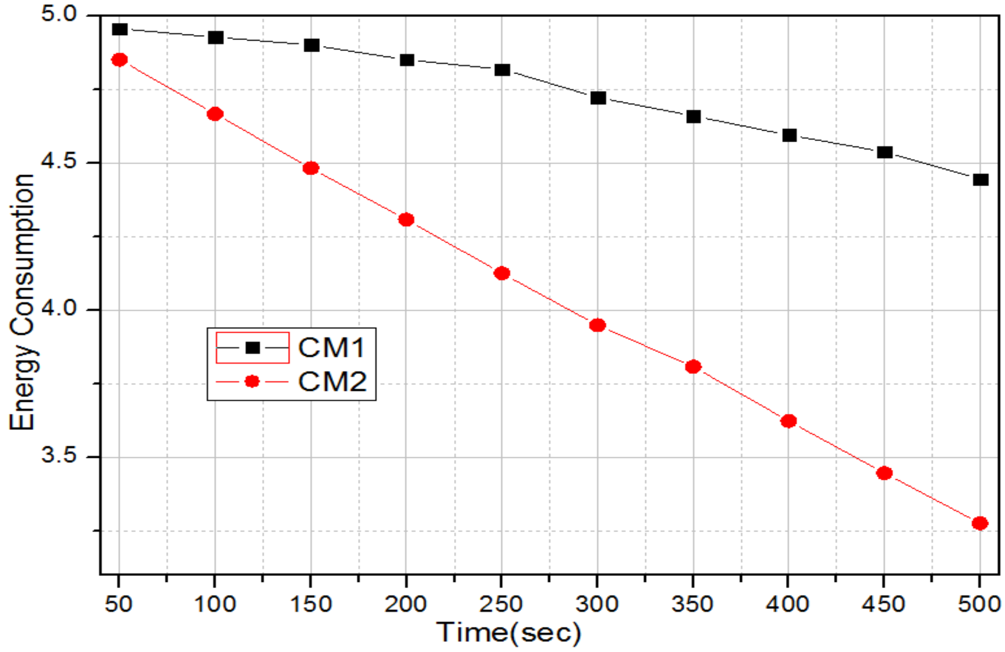


Figure 4.8: Energy Consumption for CM1 and CM2.

In Figures 4.9 and 4.10 we have shown PDR and end-to-end delay in terms of transmitter and receiver's separation where transmission power has been considered as -25dBM.

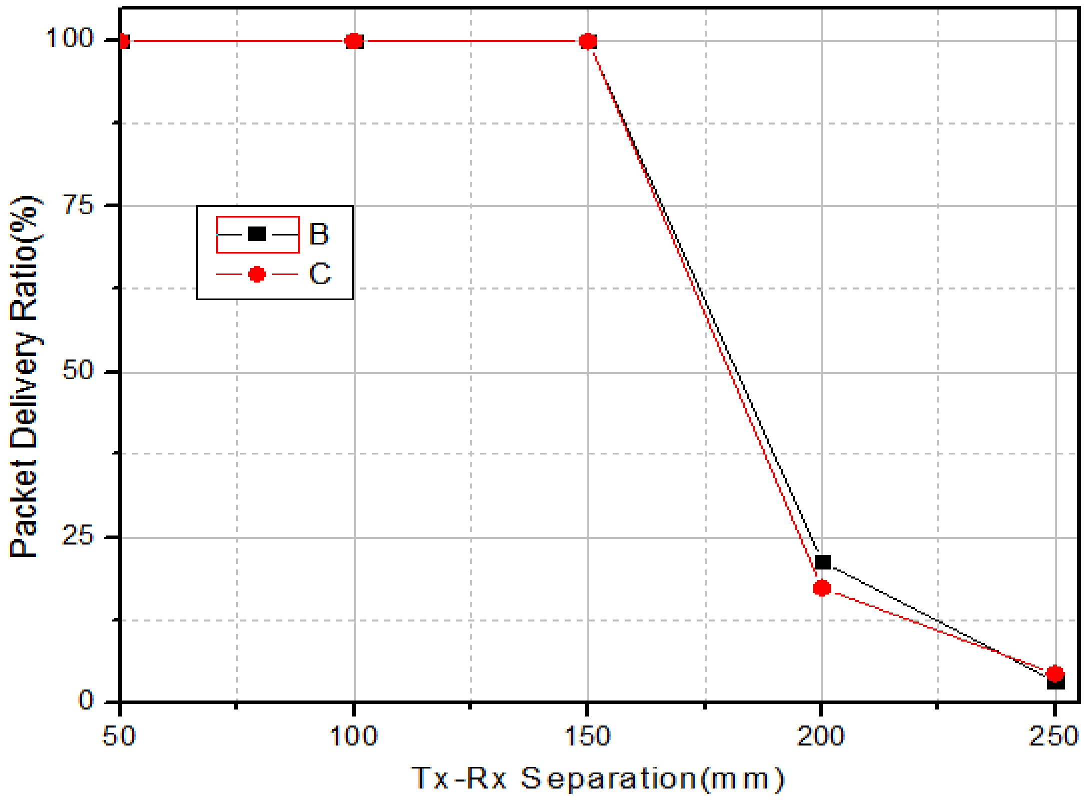


Figure 4.9: PDR comparison for CM1 and CM2.

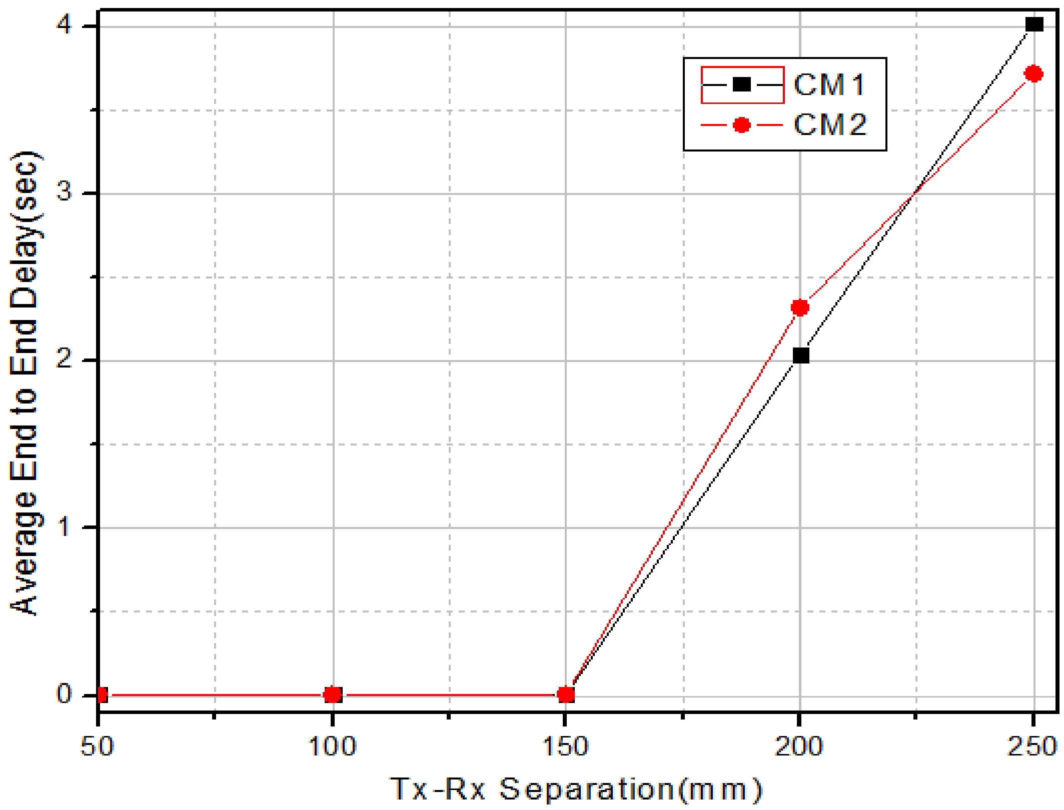


Figure 4.10: Average delay comparison CM1 and CM2.

We can see form Figure-4.9 that up to 150 mm distance from the transmitter all the packets have been received correctly but beyond that due to heavy path loss PDR decreases significantly for both of the CMs. For CM1 and CM2, at 200 mm separation PDR has reached 21.32% and 17.29%, respectively. In the 250 mm separation, we can see that PDR of CM1 has slightly decreased and it reaches 3.2% whereas the pathloss for CM2 in this point was 4.36%.

The average delay* graph for the same considered distances is shown in Figure 4.10. We can see that up to 150 mm separation, channel access delay is very low for both CMs. After 150 mm average delay increases for both CMs and at 200 mm end-to-end delay for CM1 and CM2 reach 2.04 sec and 2.32 sec, respectively. At 250 mm separation, a end-to-end delay reaches the maximum of 0.54 sec. These results of Figure 4.10 show good agreement with the results shown in Figure 4.9. As we have seen from the figures 4.3 and 4.4, pathloss for CM1 becomes higher than CM2 after 200 mm separation, this effect is also looking evident in PDR and end-to-end delay plot in Figure 4.9 and Figure 4.10 respectively.

4.5 Summary

The main objective of this chapter was to investigate 802.15.4's suitability for WBANs implant applications. Normally IEEE 802.15.4 protocol is not suitable for implant WBANs in its unmodified form. We have tested IEEE 802.15.4 protocol with the correct channel model for implant WBANs to understand its performance. The main contributions of this chapter are as follows: We analyzed the performance of IEEE 802.15.4 MAC with the help of proper in-body communication channel models using NS-2 simulations. IEEE 802.15.6 communication link channel model CM1 and channel model CM2 have been implemented in NS-2. We investigated various PHY and MAC layer based performance through extensive simulations in regard to path loss, RSS, PDR, energy consumption, delay and separation.

* Here average delay means end to end delay.

Chapter 5

An Improved Channel Access Scheme for Medical Emergency Traffic in WBANs

5.1 Introduction

Emergency data delivery is an important service for medical WBANs. The successful dissemination of emergency messages can make a huge difference between life and death. The utmost importance of emergency message dissemination requires high reliability while the intermittent nature of alarms requires minimum channel access delay for almost instantaneous delivery. Current MAC schemes have significant limitations to ensure quick channel access for emergency traffic. IEEE 802.15.6 beacon enabled networks have defined an adjustable superframe structure that consists of contention-free and contention access periods. Short superframes can satisfy the channel access delay requirements of emergency traffic but penalize the energy efficiency of all devices in the network. On the other hand, long superframes increase the energy efficiency but the channel access delay is also increased. To balance these contradicting requirements of energy efficiency and Quality of Service, we propose the Medical Emergency Body (MEB) MAC [88] protocol that inserts listening windows dynamically within the contention free periods. The frequency of listening window insertion is determined by the minimum delay tolerance. Furthermore, MEB MAC utilizes idle time slots to insert additional listening window opportunities for emergency traffic, without affecting the network throughput. Our analysis is validated by extensive simulations in MATLAB. The organization of this chapter is as follows. Firstly, we focus on channel access schemes for IEEE 802.15.6 protocol. Then we discuss the impact of the channel access delay and short superframe duration on WBANs. The limitations of the existing MAC approaches to handle emergency traffic are summarized in next section. After that, we discuss the design principles of the MEB MAC protocol and finish by comparing the performance of MEB MAC with some popular MAC schemes.

5.2 Impact of Channel Access Delay and Short Superframes on WBANs

In WBANs real-time life-critical applications are not only delay-sensitive but also loss sensitive. The utmost importance of emergency message dissemination requires timely and lossless medium access while the intermittent nature of alarms requires quick channel access delay for almost instantaneous delivery. During a mass casualty disaster, one of the most urgent problems at the scene is the overwhelming number of patients that must be monitored and tracked by each first responder. Emergency alarms are a key traffic class for medical WBANs and the successful dissemination of emergency messages can make a huge difference between life and death. Lost or corrupted alarm/alert packets due to unreliable wireless networks have serious consequences. Channel Access Delay(*CAD*) [89,90] minimization is very important in WBANs because delayed delivery of an emergency message can endanger a human life. A complete list of the MAC technical requirements are derived from the approval of TG6 technical requirement document [8]. The document mandates emergency management capabilities for the IEEE 802.15.6 specification. The specification must support alarm state notification across WBANs in less than 1 second and must provide prioritization mechanisms for emergency traffic and notification.

IEEE 802.15.6 beacon enabled networks have defined an adjustable superframe structure that consists of contention-free and contention access periods. Short superframes can satisfy the channel access delay requirements of emergency traffic but penalizes the energy efficiency of all devices in the network as devices need to wake up frequently to synchronize with the beacon. On the other hand, long superframes increase the energy efficiency but the channel access delay is also increased. In [91] authors made extensive analysis on the importance of long superframe duration and showed how long superframe duration can improve device lifetime. In our implementation we made all of our analysis based on long superframe durations.

5.3 Limitations of Existing MAC Approaches to handle Emergency traffic

In recent years a number of MAC protocols for WBANs have been proposed in the literature. Some researchers have turned their attention to the emergency message dissemination and quick channel access procedures. These include IEEE 802.15.6, IEEE

802.15.4, TaMAC[69], HBC MAC[72], PNP MAC[70]. Channel access schemes and basic principles of these protocols already have been discussed in Section 4.1.1.1. In this section we will describe the limitations of these MAC protocol in case of handling emergency traffic.

5.3.1 IEEE 802.15.4

In IEEE 802.15.4, GTS slots are allocated for emergency traffic if the coordinator receives requests from the nodes for transmitting time critical traffic. Although GTS can handle emergency traffic in IEEE 802.15.4 it lacks some desirable features. First of all, allocating seven GTSs for emergency traffic is not enough for WBAN applications. Moreover, the high latency associated with the GTS allocation creates significant problem. In order to use a GTS, a device requests the allocation of GTS and receives a beacon which confirms the successful allocation at the next beacon interval. To get the access to the channel at least one beacon interval needs to be passed. Such allocation latency is not acceptable for time-critical medical applications. Furthermore, GTS allocation is on a first-come, first-served basis, it does not consider traffic priorities. High priority applications can be left waiting when all GTSs are already allocated to low priority applications. Moreover, there is no reliable support for on demand and emergency traffic. Thus, the whole concept of superframe structure of 802.15.4 cannot be applied to efficient emergency data handling.

5.3.2 PNP MAC

PNP MAC uses Emergency Transmit Slot (ETS) in the TDMA data transmit period for urgent delivery of unpredictable emergency data. ETS is a contention based access slot reserved for emergency traffic but in case of unavailability of emergency data ETS can be assigned to nonemergency data as well. Normally, channel sensing is a big challenge in a WBANs and it cannot be guaranteed in all WBANs frequency bands and scenarios. A dynamic environment with body movement also influences the sensitivity of the channel sensing. Unreliable channel sensing leads to the hidden node problem and adds channel sensing error which deteriorates system performance drastically [65]. In case of implantable devices in WBANs, for both implant-implant and implant-on body communications; the devices can conduct channel sensing only within 250 mm [104]. Due to these reasons ETS in PNP MAC will increase unreliability for emergency traffic.

5.3.3 TaMAC

In the TaMAC protocol, in the case of emergency and on-demand traffic, resources are allocated using a wakeup radio [73] signal. The disadvantage of this approach is that emergency traffic receives significant delay because of the wake up response signal and beacon sending time. The use of the two radios is also a strong overhead as researchers are currently focusing on the reduction of the size of the circuit.

5.3.4 HBC MAC

In HBC-MAC the authors proposed a specific emergency handling operation by using Emergency Guaranteed Time Slot (EGTS). The number of EGTS depends on the various combinations of beacon intervals and emergency rates. As the presence of EGTS is not regular in the superframe the uncertainty of quick channel access for emergency traffic will always remain. The number of EGTS is initially one. For this reason the chance of collision will increase and collided emergency traffic must have to wait for the next CAP or the next EGTS.

5.3.5 IEEE 802.15.6

In the IEEE 802.15.6 MAC two access periods have been assigned (i.e. EAP1 and EAP2) for emergency data handling. As an emergency data frame is very short, one time slot is sometimes enough for the whole data transmission. But allocating a long period in this regard is not appropriate as the frequency of emergency traffic is not great. In other access phases like in CAP and RAP emergency data also needs to contend to access the channel but the reliability and successful transmission is highly uncertain in these periods.

5.4 Overview of IEEE 802.15.6

Before explaining our proposed MAC scheme, in this section we will briefly summarize the channel access scheme and superframe duration of IEEE 802.15.6.

5.4.1 Channel Access Schemes in IEEE 802.15.6

Channel Access phases of IEEE 802.15.6 were discussed in section 3.3, here we will briefly summarize the channel access schemes of IEEE 802.15.6 protocol. Figure 5.1 shows the superframe structure of IEEE 802.15.6.

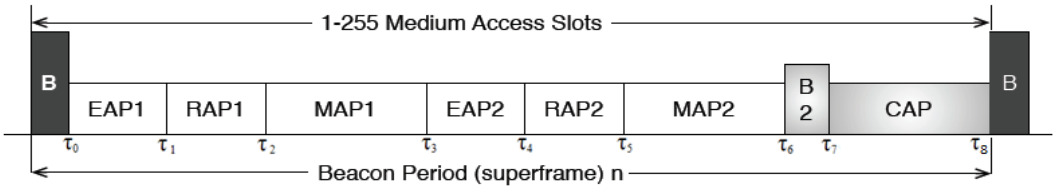


Figure 5.1: Superframe structure of IEEE 802.15.6

In this protocol, EAP, RAP and CAP are contention based periods and MAP is a scheduled based period. EAP, RAP and MAP are divided into two periods. The contention-based access methods for obtaining the allocations are either CSMA/CA if narrowband PHY is chosen or Slotted Aloha in the case of using UWB PHY. EAP1 and EAP2 are used for the highest priority traffic such as reporting emergency events. RAP1, RAP2, and CAP are used for any type of data. The MAP I/II phases are used for uplink allocation intervals, downlink allocation intervals, bilink allocation intervals, and delayed bilink allocation intervals. In MAP1 and MAP2, polling is used for resource allocation. Depending on the application requirements, the coordinator can disable any of these periods by setting the duration length to zero.

5.4.2 Superframe Duration:

Duration of the superframe *(D_{SF})* in IEEE 802.15.6 is given by the total number of allocation slots (N_{TS}) and the duration of the allocation slots (*Tslot*) as follows:

$$D_{SF} = N_{TS} * Tslot \quad (5.1)$$

$$Tslot = (pAllocSlotMin + pAllocSlotLength * pAllocSlotResolution) \quad (5.2)$$

where *pAllocSlotLength* is defined by the coordinator , and it takes a value from 0-255. Both *pAllocSlotMin* and *pAllocSlotResolution* depend on the underlying physical layer and the draft specifies them equal to 1 ms for the narrowband physical layer [1]. Using these values from (5.1) and (5.2), the minimum and maximum allocation slot duration is in the range of 1 to 256 ms and consequently the superframe duration is in the range of 1 ms to 65.536 sec.

5.5 MEB MAC Protocol

To overcome the limitations of the existing approaches the proposed MEB MAC protocol not only assigns the highest priority for emergency traffic during contention based periods, it also inserts Listening Windows (*LWs*) dynamically during the contention free periods so that emergency traffic can get the access to the channel as quickly as possible. A listening window is dedicated to emergency alarms to provide high reliability with low delay. To reduce this delay, in MEB MAC we propose to insert *LWs* in MAP in a traffic adaptive manner. In MEB MAC, we consider long superframe durations and long contention free periods to make our protocol more energy efficient and reliable. More details of this approach are given below.

5.5.1 Priority Classification

To prioritize the emergency traffic channel access in CSMA based periods we have assigned four backoff classes in MEB MAC. Priority has been assigned by the degree of importance and the type of data.

Backoff Class	Priority	Data Types
0	1	Emergency alarm
1	2	Medical Data
2	3	Non-Medical Data-- Periodic
3	4	Non-Medical Data—Non Periodic

Table 5.1 Priority and Back-off class

Table 5.1 shows the considered priority classification. A high priority node will choose a short back off duration which will result in low channel access delay. Generally, a priority classification should depend on application requirements.

5.5.2 Superframe Structure:

The MEB MAC protocol is developed for a star topology where a central coordinator controls the entire operation of the network. Hybrid MACs are more flexible and efficient in terms of bandwidth allocation [105]. For accessing the channel MEB MAC uses a hybrid MAC approach which includes both contention based and scheduled based schemes where the nodes adapt to a common schedule for data communication. The schedules are exchanged periodically during the synchronization period. As energy consumption is not a major factor for the coordinator we have assumed that the coordinator will always stay awake and there will not be any inactive period in the superframe. MEB MAC essentially follows the superframe structure of IEEE 802.15.6, which is also divided into three major periods: RAP, MAP and CAP as illustrated in Fig. 5.1. The important aspect of this structure is that EAP has not been included here at all. Normally the frequency of emergency traffic is not rapid; this is why dedicated space allocation for emergency traffic is not appropriate because it can reduce the throughput significantly. Moreover, if the devices send emergency data in MAP1 or in MAP2 this incurs a long waiting time to get access to the channel. Because of the disadvantages of the channel sensing error and backoff delay of the CSMA/CA approach, in MEB MAC we have paid attention to allocating more emergency traffic in TDMA time slots so that the emergency traffic can get access to the channel very quickly and reliably. In order to reduce the channel access delay of emergency traffic, rather than allocating a dedicated period we propose to insert *LW* periodically using contention based access(Slotted Aloha) in the scheduled access phase so that the access delay can be minimized efficiently.

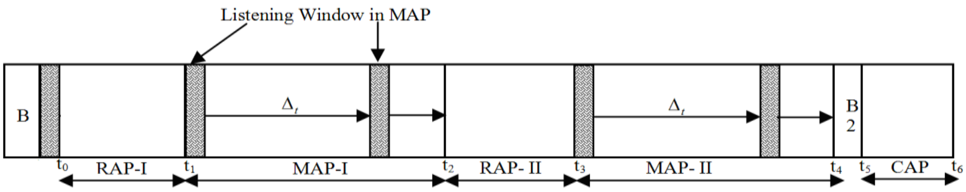


Figure 5.2: Superframe Structure of MEB-MAC

A typical example of insertion is shown in Figure 5.2. In MEB MAC we consider a long superframe duration and based on that we design our channel access phases in such a way so that the maximum length can be allocated in MAP1 and MAP2. Here, we assume a fixed superframe size but the duration of the access periods can be adaptively configured by the coordinator based on the current traffic characteristics.

5.5.3 Listening Window Allocation

We use multiple numbers of *LWs* in MAP1 and MAP2 to get fast channel access for emergency traffic. The advantage of inserting LWs is that emergency devices can try to transmit their data without sending requests to the coordinator.

Algorithm 5.1: Inserting listening window in MEB MAC Superframe

1. *Initialize* N_{ts} , Δ_t ;
2. *Calculate* $D_{map} = D_{map1} + D_{map2}$.
3. *Set* $NLW_{\min} = \left\lceil \frac{D_{MAP}}{\Delta_t} \right\rceil$ *// Minimum no. of LW*
4. *Calculate* $\mathcal{E}_{ts} : N_{TSmap} - N_{RTSmap}$
5. ***if*** $\xi_{ts} < NLW_{min}$
6. *Set* $NLW_{min} \rightarrow \mathcal{E}_{ts}$
7. ***end if***
8. $LWI_{TS} = \left\lceil \frac{D_{MAP}}{NLW_{\min} * T_{slot}} \right\rceil$
9. ***for*** *(i = 1, j=1; i<N_{ts}; i++)*
10. ***if*** *(i==1)*
11. $LW_j = TS_i$; *// 1st LW after Beacon*
12. *j = j+1;*
13. ***End if***
14. ***if*** $(TS_{RAP1Start} > TS_i > TS_{RAP1End})$ *or* $(TS_{RAP2Start} > TS_i > TS_{RAP2End})$ *or* $(TS_{CAPStart} > TS_i > TS_{CAPEnd})$
15. ***Don't Insert any LW***
16. ***Else*** $(TS_{MAP1Start} > TS_i > TS_{MAP1End})$ *or* $(TS_{MAP2Start} > TS_i > TS_{MAP2End})$
17. ***while*** $(TS_i <= TS_{MAP1End}$ *or* $TS_{MAP2End})$ ***Do***
18. $LW_j = TS_i$; *//Insert LW in Current time slot*
19. $i = i + LWI_{TS}$; *// Next LW after* LWI_{TS} *slots*
20. *j = j+1;*
21. ***end while***
22. ***end if***
23. ***end for***

When the devices want to transmit in the scheduled access based period they try to synchronize with the coordinator at the time of beacon forming and send requests. The coordinator has full knowledge of the requests and it assigns time slots for MAP I/II periods in the next superframe accordingly. Based on the amount of requests, time slots will be allocated for *LWs* to accommodate the amount of emergency traffic. Algorithm 5.1 depicts the process of inserting *LWs* in the MEB MAC superframe. At first, the coordinator will initialize the total number of time slots *(N_{ts})* and the different access phases associated with the superframe. The duration of the total MAP period is the sum of the durations of MAP1 and MAP2 periods ($D_{map} = D_{map1} + D_{map2}$). The minimum number of *LWs (NLW_{min})* is calculated in step-3 where Δ_t is the maximum channel access delay that emergency traffic can tolerate. The value of Δ_t is application dependent. Number of empty time slots ($\mathcal{E}_{ts}$) in MAP can be calculated from the difference between the Total Number of Time Slots (N_{TSmap}) and Requested Time Slots (N_{RTSmap}) to the coordinator. If $\mathcal{E}_{ts}$ is larger than current NLW_{min} then NLW_{min} will take the value of the $\mathcal{E}_{ts}$ and LW interval LWI_{TS} will be computed as shown in step 8. In this algorithm TS_i is indicating the current time slot whereas $TS_{RAP1Start}$, $TS_{RAP2Start}$, $TS_{CAPStart}$, $TS_{MAP1Start}$, $TS_{MAP2Start}$ are indicating the start time slot of RAP1, RAP2, CAP and MAP1 and MAP2 access phases and $TS_{RAP1End}$, $TS_{RAP2End}$, TS_{CAPEnd}, $TS_{MAP1End}$,$TS_{MAP2End}$ final time slot of these respective access phases. As RAP1, RAP2, CAP have contention based access, these access phases will be completely ignored from LW insertion. First LW will be placed after the beacon frame and for the MAP1 and MAP2 periods, LW will be periodically inserted after LWI_{TS} time slots interval and this insertion will continue until the end of the MAP1 or MAP2 periods.

5.6 Recovery of Collided Emergency Traffic in MEB MAC

In WBANs, if a node fails to transmit a packet and does not receive an expected acknowledgement to its last frame transmission within a timeout interval, it will assume that a collision* has occurred. Let i indicates the index of current time slot in the superframe where $i \in (0, 255)$ and TS_{i-1} is the slot position where the last collision took place for the emergency traffic. $\Re TS\_eme$ is the time-slot where the emergency traffic will be retransmitted and WT_{LW} represents the wait duration** of this retransmission attempt. As described before T_{slot} is the duration of one time slot. When emergency traffic gets collided in MEB MAC the collision recovery follows the following equations described in equation (5.3) and (5.4). Here r is a random variable where $r \in (0, .5)$ and $CW_{rem\_TS\_MAP}$ is the remaining time slot in the current MAP.

$$\Re TS\_eme = TS_{i-1} + \lceil r * CW_{rem\_TS\_MAP} \rceil \qquad (5.3)$$

$$WT_{LW} = \Re TS\_eme * T_{slot} \Rightarrow \left(TS_{i-1} + \lceil r * CW_{rem\_TS\_MAP} \rceil \right) * T_{slot} \qquad (5.4)$$

*collision -- If two or more emergency traffics try to transmit in the same LW collision can take place.

** wait duration -- Here wait duration also indicates the retransmission in the nearest possible LWs.

Algorithm 5.2 depicts this whole procedure where t_e^i is the random arrival time of emergency traffic in MAP, Tx_i is indicating transmission status and *CCnt* is indicating the collision counter which will keep track of the repetition of this process. When the value of *CCnt* will reach the maximum retransmission ($\Re_{\max} = 4$) the packet will be discarded.

Algorithm 5.2 RCET: Quick Recovery of Collided Emergency Traffic

---

1. *CCnt = 1;*

2. **if** ($TS_{MAP1Start} <= t_e^i <= TS_{MAP1End}$) or ($TS_{MAP2Start} <= t_e^i <= TS_{MAP2End}$)

3. **while**($CCnt <= \Re_{\max}$ or Tx_i = Unsuccessful) **Do**

4. **if** (*ACK* is received)

5. Tx_i = Success;

6. **else** Tx_i = Unsuccessful;

7. *CCnt++;*

8. Set $\Re_x$;

9. Transmit in $\Re TS\_eme$;

10. **Go to** Step 4.

11. **end if**

12. **end while**

13. **If** ($CCnt = \Re_{\max}$)

14. Discard the Packet

14. **end if**

14. **end if**

5.7 Performance Analysis

Throughput and delay are the key factors to determine the overall performance of a network. In this section we will briefly summarize theoretical analysis of these metrics.

5.7.1 Average Channel Access Delay

Channel access delay is the duration from the time when a packet arrives at the transmit queue until the designated packet gains access to the channel. The average channel access delay for emergency traffic in different access phases are shown in Equations (5.5) and (5.6) for IEEE 802.15.6 and MEB MAC respectively.

For IEEE 802.15.6

$$
\begin{aligned}
d_0 &= 0 && ;if\ \tau_0 > t_e^i > \tau_1\ or\ \tau_3 > t_e^i > \tau_4 \\
d_1 &= \frac{1}{2} D_{RAP1} && ;if\ \tau_1 > t_e^i > \tau_2 \\
d_2 &= \frac{1}{2} D_{RAP2} && ;if \tau_4 > t_e^i > \tau_5 \\
d_3 &= \frac{1}{2} D_{MAP} && ;if\ \tau_2 > t_e^i > \tau_3\ or\ \tau_5 > t_e^i > \tau_6 \\
d_4 &= \frac{1}{2} D_{CAP} && ;if\ \tau_7 > t_e^i > \tau_8
\end{aligned} \tag{5.5}
$$

For MEB MAC

$$
\begin{aligned}
d_1' &= \frac{1}{2} D_{RAP1,} && ;if\ t_0 > t_e^i > t_1 \\
d_2' &= \frac{1}{2} D_{RAP2,} && ;if\ t_2 > t_e^i > t_3 \\
d_3' &= \frac{1}{2 * N_{LW}} D_{MAP} && ;if\ t_1 > t_e^i > t_2\ or\ t_3 > t_e^i > t_4 \\
d_4' &= \frac{1}{2} D_{CAP} && ;if\ t_5 > t_e^i > t_6
\end{aligned} \tag{5.6}
$$

Here d_1, d_2 , d_3, d_4 and d_1', d_2', d_3', d_4' are the average delay experienced by emergency traffic in RAP1, RAP2, MAP (MAP-I and MAP-II) and CAP and d_0 in Equation (5.5) indicates the delay in EAP (EAP-I or EAP-II) in IEEE 802.15.6. In Equation (5.5) τ_0 to τ_8 indicate the start and end time of the different access phases of IEEE 802.15.6 which were shown in Figure 5.1. On the other hand t_0 to t_6 in Equation (5.6) represents the start and end time for MEB MAC which was shown in Figure 5.2. As mentioned before, t_e^i is the random arrival time of emergency traffic in MAP. We can see from the above equations, average channel access delay in EAP is 0 (as EAP is assigned for emergency traffic). In Other access periods it will be the half of the access period's length. In Case of

MEB MAC in MAP1 and MAP2 average channel access delay will be less due to insertion of LWs which has been shown in d_3' in equation 5.6.

Now the average channel access delay within a superframe for IEEE 802.15.6 and MEB MAC, $d_{avg\_X.15.6}$ *and* d_{avg_MEB} can be calculated as follows:

$$d_{avg\_X.15.6} = \frac{1}{N_{TS}}(N_{TsEAP1}d_0 + N_{TsRAP1}d_1 + N_{TsMAP1}d_3 + N_{TsEAP2}d_0 + N_{TsRAP2}d_2 + N_{TsMAP2}d_3 + N_{TsCAP}d_4) \quad (5.7)$$

$$d_{avg\_MEB} = \frac{1}{N_{TS}}(N_{TsRAP1}d_1' + N_{TsMAP1}d_3' + N_{TsRAP2}d_2' + N_{TsMAP2}d_3' + N_{TsCAP}d_4') \quad (5.8)$$

Here N_{TsEAP1}, N_{TsEAP2}, N_{TsRAP1}, N_{TsRAP2}, N_{TsMAP1}, N_{TsMAP2}, N_{TsCAP} are the total number of time slots for EAP1, EAP2, RAP1, RAP2, MAP1, MAP2 and CAP respectively.

5.7.2 Maximum Throughput

Maximum throughput *(MT)* is calculated from the following formula:

$$MT = \frac{N_{Occupied}}{N_{Total}} \times DataRate \quad (5.9)$$

where

$N_{Occupied}$ = Time slots which have been used for data transmission

N_{Total} = Total number of time slots in the superframe

$DataRate$ = Data rate of the channel.

5.8 Simulation Modeling

5.8.1 Simulation Parameters

We have implemented MEB MAC protocol in MATLAB and compared its performance with IEEE 802.15.6 and PNP MAC. Although Matlab is capable of network simulation for the physical and data link layers, it lacks important features such as internetworking and scheduling. This is why PHY layer and Channel models are not considered in our simulation. Our simulation results are based on the arrival time that are simulated using random seeds. We have considered a star topology with the beacon enabled mode where multiple devices are attached to a central coordinator. Table 5.2 shows the allocation of the slots of IEEE 802.15.6 and MEB MAC for different access phases.

Parameters	IEEE 802.15.6	MEB MAC
Total number of slots	256	256
Number of Slots in EAP1	8	0
Number of Slots in RAP1	24	24
Number of Slots in MAP1	80	88
Number of Slots in EAP2	8	0
Number of Slots in RAP2	16	16
Number of Slots in MAP2	80	88
Number of Slots in CAP	40	40

Table 5.2: Slot allocation for Different Access Phases in Simulation

The total number of slots in a superframe is set to 256 slots where we allocate 24 slots for RAP1 88 slots for MAP-I, 16 slots for RAP2, 88 slots for MAP-II and 39 slots for B-II+CAP. The data rate is 250kb/sec.

For MEB MAC we have assumed minimum number of LWs in superframe based on the highest delay tolerance(.9 sec) which results 32 LWs within MAP(MAP1+MAP2)=>(88+88)=> 176 slots. The setup for PNP MAC is not shown in Table 5.2. Actually, PNP MAC is IEEE 802.15.4 MAC based. Its superframe structure and duration are completely different than IEEE 802.15.6 protocol. Specific information of slot allocation for different access phases (CAP, CFP, ETS) in the superframe has not been described clearly. In our simulation, we have considered 16 CAP Slots 238 CFP Slots and 10 ETS slots in the superframe of PNP MAC protocol.

5.8.2 Simulation Results

5.8.2.1 Channel access delay comparison

Figure 5.3 shows a delay trace of emergency traffic based on random arrivals of 3000 sample values in a superframe enough to achieve a 95% confidence interval. We have considered four

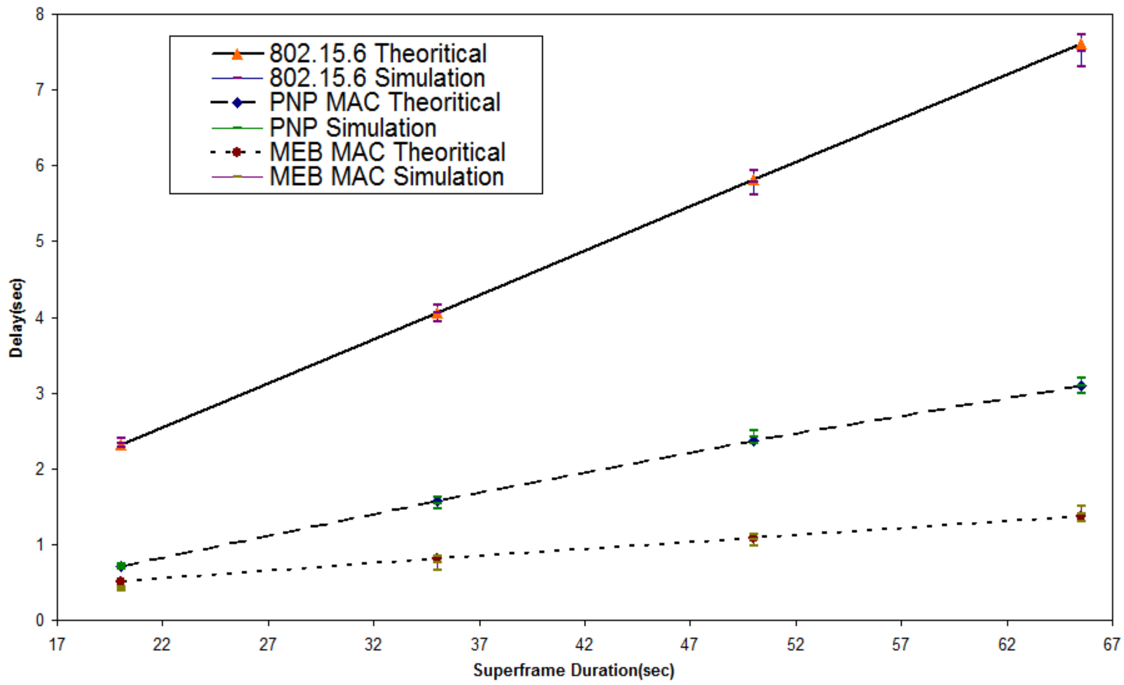
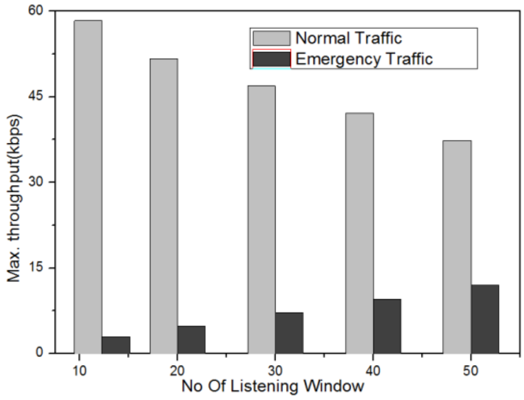


Figure 5.3: Channel access delay comparison

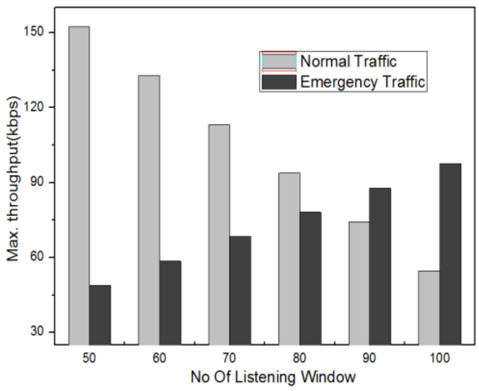
superframe durations i.e. 20sec, 35sec, 50sec, and 65.5 while the slot position is moving from the beginning toward the end of the superframe. As observed in Figure 5.1, channel access delay becomes larger in IEEE 802.15.6 if emergency traffic appears in MAP-I and MAP-II access phases which is also evident from Figure-5.3. For all of the four considered superframe durations the average channel access delay for IEEE 802.15.6 is 2.34sec, 4.05sec, 5.77sec and 7.72sec respectively while the channel access delay for MEB MAC and PNP MAC was always significantly lower than IEEE 802.15.6. MEB MAC has showed its superiority in any superframe duration. Although, in lowest *superframe* duration (in 16 sec) PNP MAC's and MEB MAC's channel access delay is closer to each other but for longer superframe duration the channel access delay of MEB MAC has outperformed PNP MAC and IEEE 802.15.6. In 65.5 sec long superframe we can observe a significant performance improvement for MEB MAC and the average channel access delay difference for this setting between MEB MAC and IEEE 802.15.6 and PNP MAC is 6.2 sec and 1.6 sec respectively. This figure also demonstrates very good match between the simulation and theoretical results.

5.8.2.2 Effect of Inserting LWs on Channel Access Delay and Throughput

In Figures 5.4 and 5.5 we observe the effect of inserting LWs on maximum throughput and channel access delay. If we allocate more LWs where emergency traffic is less frequent it will severely throttle the network throughput. As MEB MAC controls the number of LWs in a traffic adaptive manner, the unused bandwidth will always be utilized.

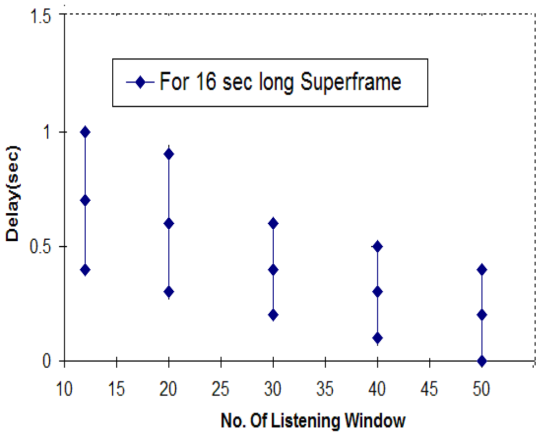


(a) 16 sec long *SF* duration

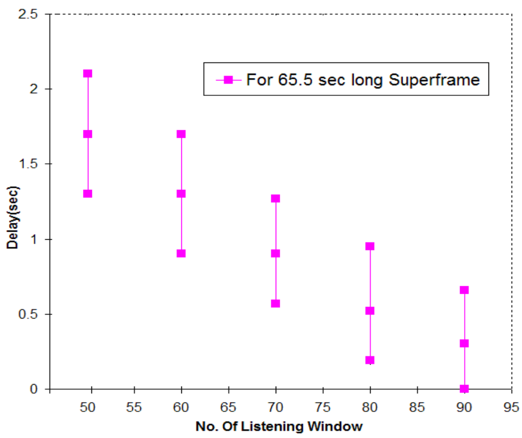


(b) 65.5 sec long *SF* duration

Figure 5.4: Effect of inserting *LW* on Throughput



(a) 16 sec long *SF* duration



(b) 65.5 sec long *SF* duration

Figure 5.5: Effect of inserting *LW* on *CAD*

Figure 5.4(a) and 5.4(b) represent the maximum throughput achieved by the normal and emergency traffic in MEB MAC based on the *LW* allocation for 16 sec and 65.5 sec long superframe durations. From these figures it is evident that if we use more *LWs* and if we have more emergency data then throughput will not be affected too much. Figure 5.5(a) and 5.5(b) depict another effect of inserting *LWs* on channel access delay for emergency traffic. We can see that for any superframe duration, if the number of *LWs* increases, channel access delay will decrease significantly.

5.8.2.3 Channel access delay & Packet Loss (For Congested Scenario)

In this section performance of MEB MAC and protocols will be evaluated for congested* scenarios. When multiple emergency traffic tries to gain the access of the channel at the time same time congestion can occur. Especially here congested scenarios mean the cases when three and seven nodes contend for channel access on a particular time. We generate random emergency traffic in a 65.5 sec long superframe duration with the same arrival time with random intervals in order to evaluate the impact of the channel access delay and packet loss ratio. As shown in Figure 5.6, for 3 nodes' congestion scenario channel access delay of MEB MAC, PNP MAC, IEEE 802.15.6 are 2.4 sec, 7.8 sec ,9.9 sec. The corresponding readings were 5.1 sec, 16.2sec, 19.9sec for seven nodes' congestion scenario. In both cases the channel access delay was worse for IEEE 802.15.6 and PNP MAC.

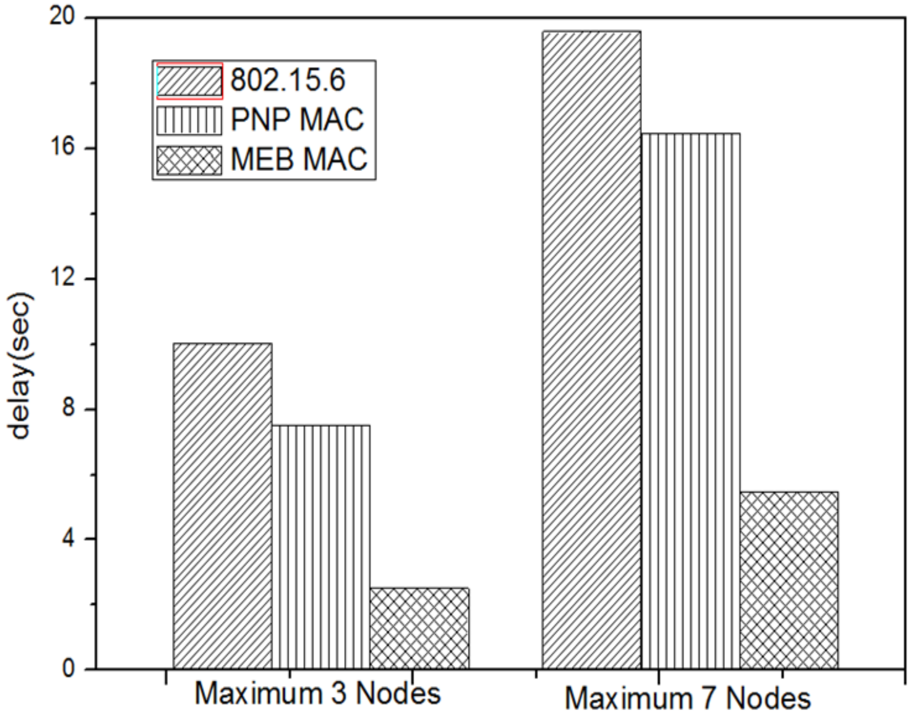


Figure 5.6: Channel access delay comparison for Congested scenario

Figure 5.7 shows the percentage of lost packets due to congestion for the same simulation setup. We can see from 3 nodes congestion scenario, the packet loss rate for MEB MAC was 24% and 51% less than the IEEE 802.15.6 MAC and PNP MAC.

* Here congestion does not mean collision will take place only in the LWs, it can occur anywhere in the superframe.

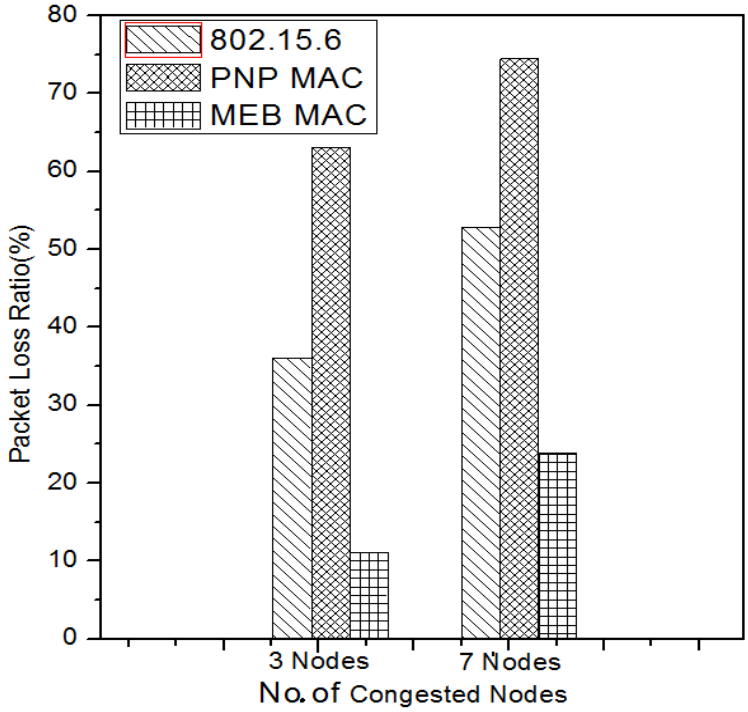


Figure 5.7: Packet Loss Rate with the increase in congested nodes

Even in the case of the heavily congested scenario (7 nodes congestion) the packet loss rate for MEB MAC was 25% while it was 54% and 85% for IEEE 802.15.6 and PNP MAC, respectively. From these above figures it is obvious that MEB MAC's performance is quite stable as compared to other protocols in error prone situations.

Table 5.3 lists the packet loss rate for various superframe duration for congested scenario. Here we have shown the result of 3 nodes congestion only. We can see MEB MAC has experienced less packet loss rate in every types of superframe duration as compared to other protocols.

	Packet Loss Rate (%)		
Superframe Duration (Sec)	**IEEE 802.15.6**	**PNP MAC**	**MEB MAC**
65.5	36.08	63.04	11.13
50	38.69	57.39	23.54
35	44.34	62.6	37.41
20	48.69	71.73	45.16

Table-5.3: Packet Loss Rate for various superframe duration

Although for short superframe duration i.e. 35 sec, 20 sec the packet loss rate's gap between MEB MAC and IEEE 802.15.6 is very close, but for longer superframe duration MEB MAC outperformed IEEE 802.15.6 and PNP significantly.

5.9 Summary

In this chapter, we proposed MEB MAC, a novel traffic adaptive MAC protocol where the main focus was given to reduce channel access delay for medical emergency traffic. To ensure emergency traffic's quick channel access in contention free access periods LWs have been placed in this regard. The allocation of LWs is dynamic and our results show that in the long superframe duration our scheme can achieve satisfactory performance improvement as compared to IEEE 802.15.6 or related protocols with little adverse impact on network throughput. To validate the accuracy of our proposed scheme, we tested it for various types of superframe sizes, number of nodes and traffic loads. Our analysis shows that MEB MAC is able to reduce channel access delay significantly for emergency traffic especially for long superframe durations.

Chapter 6

IEEE 802.15.6 MAC and MEB MAC Implementation in OPNET

6.1 Introduction:

In the wireless network field researchers and developers use simulation models to test their distributed algorithms and protocols using realistic wireless channel and radio models, with a realistic node behavior especially relating to access of the radio. Simulation models also help researchers to validate the performance by comparing measured data with the theoretical values. Developing a simulator according to standard specifications is very necessary to obtain the correct measurement result. The OPNET Modeler is an industry leading discrete-event network modeling and simulation environment, commonly used due to its accuracy and its a user-friendly graphical user interface. In this chapter, we explain the implementation details of IEEE 802.15.6 and MEB MAC in OPNET.

6.2 Related Work

Due to their manifold attributes WSNs have already gained significant attention in recent years. Simulation of WSNs is a challenging task due to the nature of hardware design, energy limitations, and deployment of a vast number of nodes. Recently, researchers have paid attention to developing analytical and simulation models for WBANs. Due to the unique features of WBANs, development of a simulation tool has been highly essential. Although Matlab [96] is capable of network simulation for the physical and data link layers, it lacks important features such as internetworking and scheduling. Opnet Modeler [93], NS-2 [80] and OMNeT++[95] are widely used and popular network simulators. They include a simulation model with proper attributes of physical and data link layers. Up to now Castalia [94] is the only discrete event based simulator which is suitable for WBANs. It is based on the OMNeT++ platform. It has a suitable channel model for WBANs, but its MAC layer is still 802.15.4 based. The authors of [104] evaluate NS-2 as a simulator for ZigBee WSNs and their conclusion is that the accuracy of its simulation results are questionable since the Medium Access Control (MAC) protocols, packet formats, and energy models are very different from those used in real WSNs [98,99].

The National Institute of Standards and Technology (NIST) has developed an OPNET simulation model for the IEEE 802.15.4. This model lacks some desirable features like the GTS mechanism in the implementation. Researches from IPP-HURRAY [97], have developed a quite accurate simulation tool for IEEE 8021.5.4 with slotted CSMA/CA and GTS mechanism in OPNET. They have extended this simulation model by implementing a deterministic real-time traffic and ZigBee network layer. OPNET simulation model implements the physical and medium access control layers defined in the IEEE 802.15.4-2003 standard. We have modified IPP-HURRAY's IEEE 802.15.4 module to make it compatible for WBANs. The key aspects of our simulation model are an accurate superframe structure, supporting large superframe duration with long time slot, creating a new traffic class for emergency applications and switching into appropriate channel access phases within the assigned time slots.

6.3 Introduction to OPNET Modeler

OPNET Modeler is the foremost commercial product that provides network modeling and simulation software solution among the OPNET product family. It is used widely by researchers, engineers, university students, and the US military due to its user-friendly graphic user interface, supported by object-oriented and hierarchical modeling, debugging, and analysis.

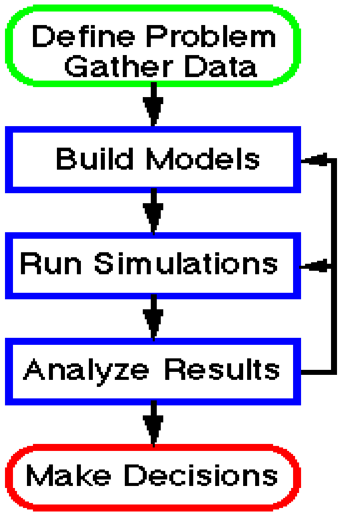


Figure 6.1: Phases of OPNET Simulation Modeling

OPNET Modeler is a discrete event simulator that has evolved to support hybrid simulation, analytical simulation, and 32-bit and 64-bit fully parallel simulation, as well as providing many other features. Performance analysis of a protocol is obtained through discrete event simulations. Specific tools are included with each OPNET license that assist users through the following phases of the modeling and simulation cycle. Figure 6.1 shows the different phases of OPNET simulations.

6.3.1 Modeling Domains

The development environment consists of three hierarchical modelling domains Figure 6.1 For model Building and Configuration we can use following Editors:

- Network Domain: The network domain consist of nodes, links and subnets. The internal architecture of a node is described in the node domain.

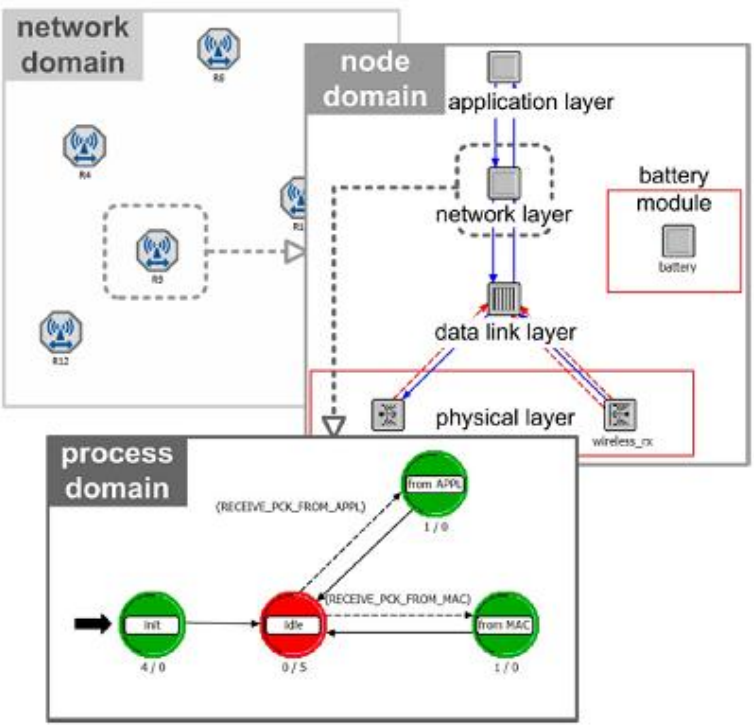


Figure 6.2: Modeling Domains

- Node Domain : The node level defines the behaviour of the node and controlling the flow of data between different functional elements inside the node.

- Process Domain: The process editor creates process models which control the underlying functionality of the node models. Within the process domain, the behavior of a node is defined using state transition diagrams. Processes can dynamically create child processes, Processes can respond to interrupts.

Operations performed in each state or transition are described in embedded C/C++ code blocks. Process model contains forced and unforced states.

In a forced state, the process:

- Evaluates all condition statements
- If exactly one condition statement evaluates to true, the transition is traversed to the next state

In an unforced state, the process:

- Places a marker at the middle of the state
- Releases control to the Simulation Kernel and becomes idle
- Resumes at the marker and processes the exit execs when next invoked

6.4 Implementation of IEEE 802.15.6 protocol in OPNET

In this section we will describe the implementation details of MEB MAC superframe structure

6.4.1 Features

We have implemented the beacon-enabled IEEE 802.15.6 protocol with exact superframe structure as suggested in the standard. The key attributes of our Simulation model are discussed below:

Implementation features:

- Beacon-enabled mode ·
- Slotted CSMA/CA MAC protocol ·
- Superframe structure
- Computation of the power consumption
- Battery Module.
- Emergency Time Slot or Listening window allocation, de allocation and reallocation functions.
- Generation of the Emergency application data as separate traffic class.
- Generation of the acknowledged and unacknowledged application data (MAC Frame payload = MSDU) transmitted during the Contention Access period (EAP,CAP,RAP).
- Generation of the acknowledged or unacknowledged application data transmitted during the Contention Free Period (MAP).

Non-Implementation features:

- Non-Beacon Enabled Mode
- Packet Format (same as Zigbee)

6.4.2 Structure of the IEEE 802.15.6 sensor node:

In this thesis we construct a wban_sensor_node OPNET module that implements an IEEE 802.15.6 sensor node. The structure of WBAN sensor node is shown in figure 6.3. It consists of four functional blocks:

6.4.2.1 The Application Layer

The Application Layer will consist of three data traffic generators (i.e. Traffic Source and Emergency Traffic Source, GTS Traffic Source) and one Traffic Sink.

Traffic Source:

The Traffic Source generates unacknowledged and acknowledged data frames transmitted during EAP, CAP and RAP the using slotted CSMA/CA. Normally non-time critical traffics is unacknowledged and medical/important traffics are acknowledged traffic.

GTS Traffic Source:

GTS traffic is TDMA based time traffic which will be generated if a coordinator receives a request for time slot allocation from the devices. The GTS data traffic incoming from the application layer is stored in a buffer with a specified capacity. GTS traffic Source deals with important traffic in MAP.

ETS Traffic Source

The Emergency Traffic Source (ETS) will produces acknowledged time-critical data frames with the highest priority. Emergency traffic can be generated at any time within a superframe. In MEB MAC, LWs will be placed to handle emergency traffic in MAP.

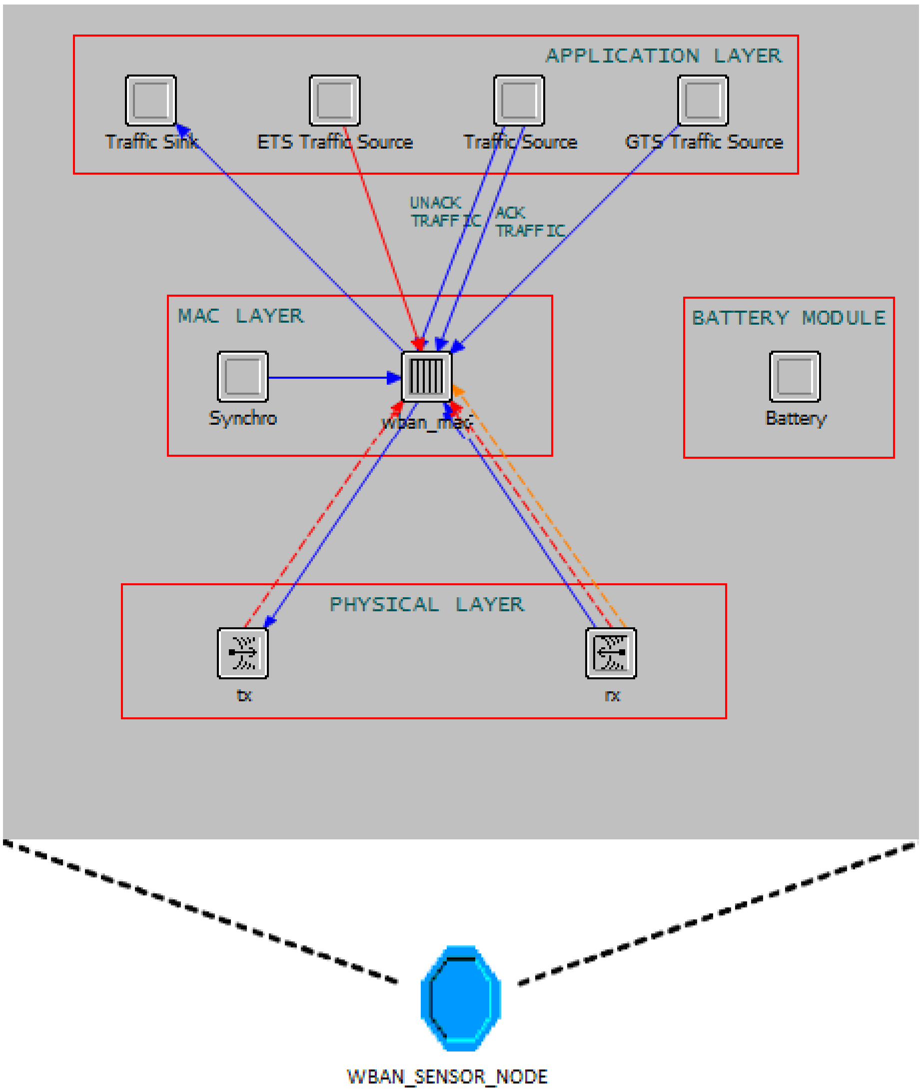


Figure 6.3: IEEE 802.15.6 Device Node Model Architecture

Traffic Sink

The Traffic Sink module will receive frames forwarded from lower layers and obtains the network statistics.

6.4.2.2 The MAC Layer

The MAC Layer implements the slotted CSMA/CA and TDMA based access mechanisms. Concept of LWs are implemented in the MAC layer in case of MEB MAC. MAC layer is also responsible for generating beacon frames, controlling superframe and synchronizing the network when a given node acts as WBAN coordinator.

6.4.2.3 The Physical Layer

The Physical Layer will consist of a wireless radio transmitter (tx) and receiver (rx) compliant to the IEEE 802.15.6 specification, operating in the 2.4 GHz frequency band and a data rate equal to 250 kbps. The transmission power is set to 1 mW and the modulation technique is Quadrature Phase Shift Keying (QPSK).

6.4.2.4 Battery

The Battery Module computes the consumed and the remaining energy levels. The default values of the current draws are set to those of the RF transceivers such as the Nordic nRF24L01+ [101]. The devices use coin cell batteries of 560 mAh capacity that provide constant operating voltage during their lifetime.

6.4.3 User-defined Attributes

6.4.3.1 wban_analyzer_node

This node captures global statistical data from whole WBAN (only one node within WBAN). The hierarchical structure of the user-defined attributes of the wban_analyzer_node node model follows.

	Attribute	Value
?	┌ name	Analyzer
?	├ model	wban_analyzer_node
	├ Enable Logging	enabled
?	└ Log File Directory	c:\\temp\\

Figure 6.4: The user-defined attributes of the *wban_analyzer_node* node

6.4.3.2 wban_sensor_node

The hierarchical structure of the user-defined attributes of the wban_sensor_node node model follows.

Application data can be generated by the WBAN Coordinator or by the End Device, and are transmitted as a MAC Frame Payload. The details of the source attributes for Traffic Source and GTS traffic Source can be found in [98, 102]. Here we show a typical attributes of Emergency Node where the traffic type has been selected as ETS traffic and MSDU inter-arrival time has been chosen as 1 sec.

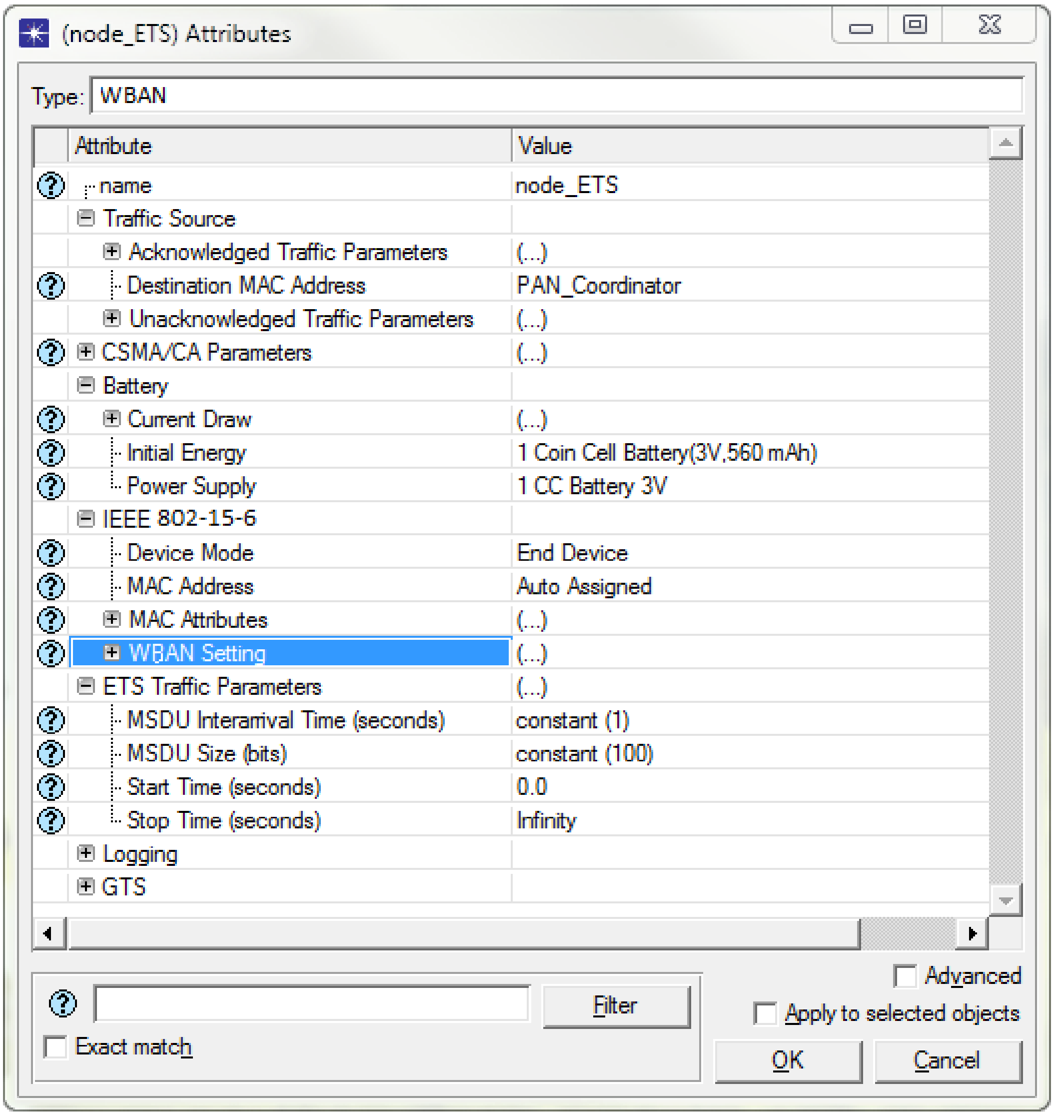


Figure 6.5: The user-defined attributes of the *wBan_sensor_node* node

Table 6.1 summarizes the various traffic parameters of *wBan_sensor_node* with their descriptions

Attribute Name	**Value**	**Description**
MSDU Interarrival Time	PDF [sec]	The inter-arrival time in seconds between two consecutive MSDUs
MSDU Size	PDF [bits]	The size of the generated data unit i.e. MSDU in bits
Start Time	[sec]	The absolute simulation time in seconds when the traffic source will start its data generation.
Stop Time	[sec]	The absolute simulation time in seconds when the traffic source will stop its traffic generation.

Table 6.1 : Traffic Parameters

Battery

The Battery module computes the consumed and the remaining energy levels during the active and inactive periods. The default values of the current draws are set to those of the Nordic mote specification [101].

Attribute Name	Description	Value
Receive Mode	The current draw of the device when the transceiver is in the receiving mode	13.8mA
Transmission Mode	The current draw of the device when the transceiver is in the transmitting mode	0 dBm = 11.3 mA (-6 dBm) = 9 mA (-12 dBm) = 7.5 mA (-18 dBm) = 7mA
Idle Mode	The current draw of the device when the transceiver is in idle mode and voltage regulator is on.	2.0 μ A
Sleep Mode	The current draw of the device when the transceiver is inactive and voltage regulator is off.	.9 μ A
Initial Energy	The initial amount of battery energy before any activity.	6,048 Joule
Power Supply	The battery voltage in Volts. There is 1 predefined option:	3V

Table 6.2 : Battery Module Parameters

6.4.4 Major Contributions:

In this section we will mainly highlight the major changes what we have made on IPP-HURRAY's IEEE 802.15.4 protocol. We use screenshots in this section to get a clear picture of our implementation.

Major Changes in our implementation:

1. Creating a new traffic class for emergency traffic.
2. Changing Superframe structure (along with changes in slot duration, number of time slots) according to specifications of IEEE 802.15.6 .

6.4.4.1 Emergency Traffic Creation:

We consider a separate traffic class for Emergency traffic as we know the IEEE 802.15.6 protocol has defined seven traffic categories based on the user priorities. Although we did not consider all of these traffic priorities in our module we distinguish the periodic medical traffic from emergency traffic type. As emergency situations can occur any time, assigning them into TDMA time slots on the next superframe will significantly delay the transmission. In our implementation, using the Emergency traffic class, emergency data can be created on any generation time with defined time interval. For periodic medical data GTS will be used.

To create the emergency traffic type in OPNET we have used the following steps:

1. Frame type creation :
   We define the frame type for emergency traffic (ETS_FRAME_TYPE) header in wban_params.h as shown in the following screenshot.

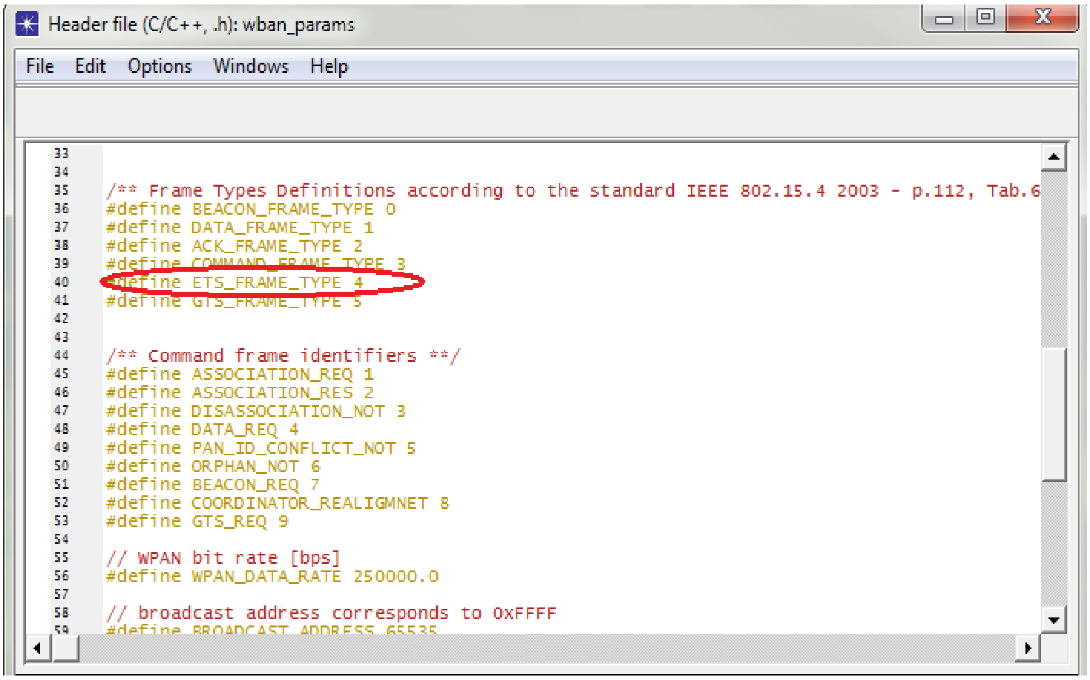


Figure 6.6: Insertion of Emergency Frame Type (screenshot)

2. Creating a node model and connecting with MAC:
   We create the emergency traffic node (ETS Traffic Source) using the node model editor and traffic stream (STRM_FROM_ETS_TO_MAC) to connect it with the MAC protocol. General steps for creating a traffic source can be found in [97]. Figure 6.7 shows and the node model and stream type for MEB MAC protocol.

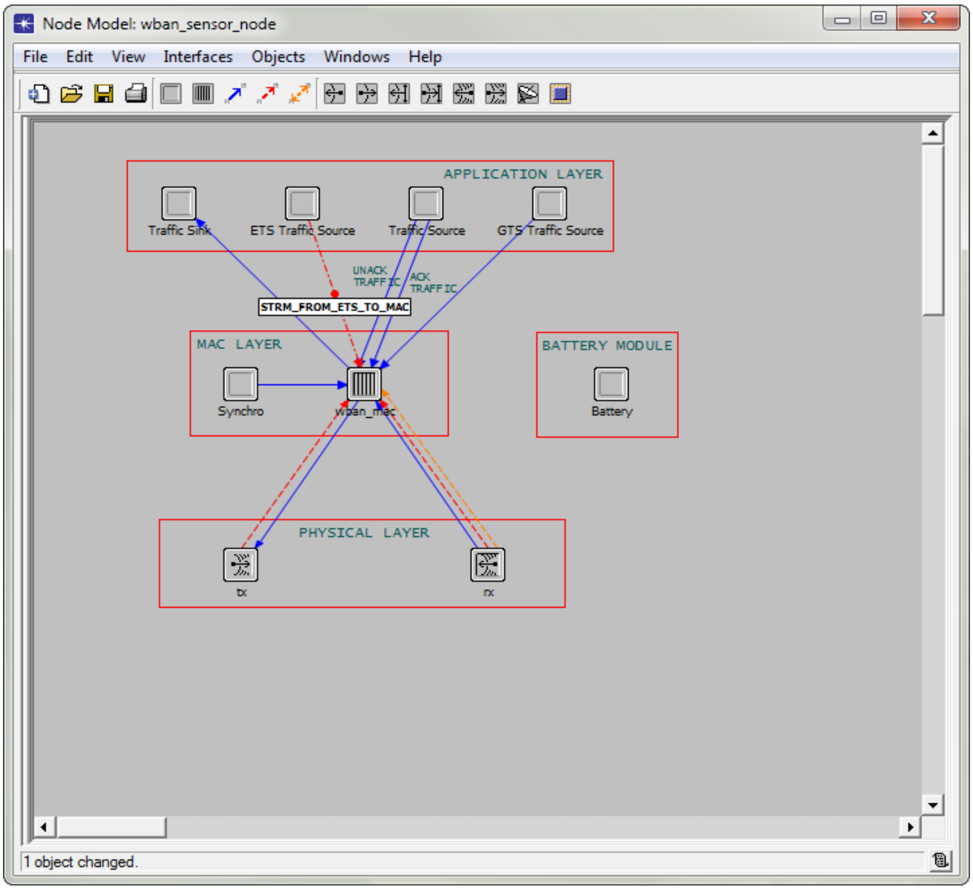


Figure 6.7: Node Model

3. Define the process model

In the process model(wban_ETS_packet_source_process) we define 2 forced states and 3 unforced states as shown in figure 6.9 and after that we define the two functions which are shown in Table 6.3.

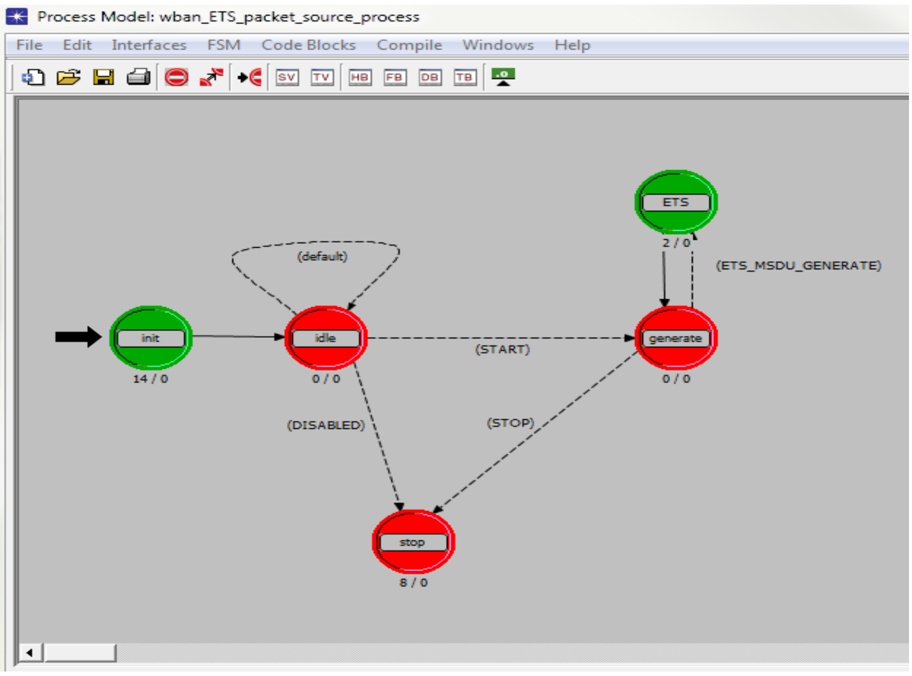


Figure 6.8: Process Model for Emergency Traffic

Function	Where	Purpose
wban_source_init	In Init State	▪ To read the read the values of source attributes ▪ To schedule a self interrupt that will indicate start time for MSDU generation
wban_ets_traffic_generate	In ETS State	▪ To create a MSDU requiring acknowledge based on the MSDU generation specifications of the source model and sending it to the lower layer.

Table 6.3: Functions used in the Process Model

4. <u>Define the Function Block in wban ETS Packet Source Process</u>
   a. Define wpan_ets_traffic_generate() and assign variables (MSDU Size, inter-arrival-time) so that they can capture the input data from ETS Traffic Source Attributes.
   b. Send the MSDU via the stream (STRM_FROM_ETS_TO_MAC) to the lower layer.
5. <u>Coding in MAC.cc</u>
   a. In wban_parse_incoming_frame() check from what input stream (STRM_FROM_ETS_TO_MAC) the packet is received.
   b. If input stream is STRM_FROM_ETS_TO_MAC send the fame for encapsulation and enqueue and invoke wban_encapsulate_and_enqueue_ETS_frame().
   c. In wban_encapsulate_and_enqueue_ETS_frame(),

      → create a MAC frame by using op_pk_create_fmt(),

      → generate the sequence number for the packet, lastly

      → Bind ETS_FRAME_TYPE, sequence no, source address and destination address with MAC frame by using op_pk_nfd_set()

      → transmit the packet checking the queue condition.

6. <u>Define frame type in Analyzer</u>

   ETS frame has to be defined in analyzer to collect the packet level performance of ETS traffic.

7. <u>Define the Source Attributes :</u>

   Finally before beginning simulation the ETS source attributes need to be set which is shown in 6.9.

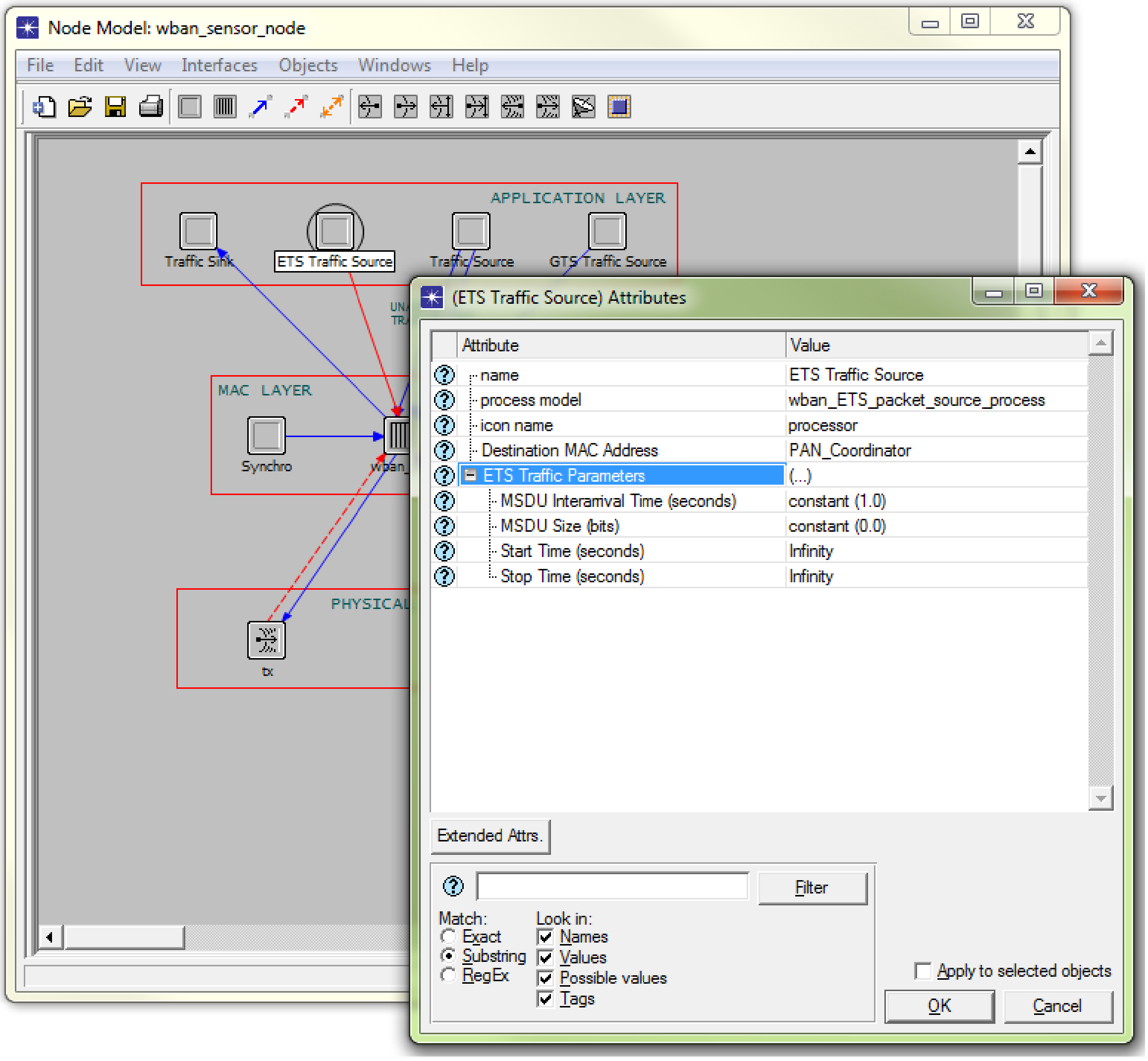


Figure 6.9: Source Attributes

6.4.4.2 Creating Superframe Structure of IEEE 802.15.6

As we know the superframe format of IEEE 802.15.6 MAC is completely different than IEEE 802.15.4. MAC, to implement this, we follow the following steps :

1. Change the superframe duration and slot duration in wban_pramas.cc

Variables	**Attributes**	**Value**
aNumSuperframeSlots	No of slots in Superframe	256
aBaseSlotDuration	Slot Duration	16000 ms
aBaseSuperframeDuration	Superframe Duration	65536 ms

Table 6.4: Variables Related to Superframe

2. Assign length of the Access Phase in time slot & assign variables to mark the start and end of different access phases

   Figure 6.10 shows the screenshot of different access phase length and start time of the particular access phase.

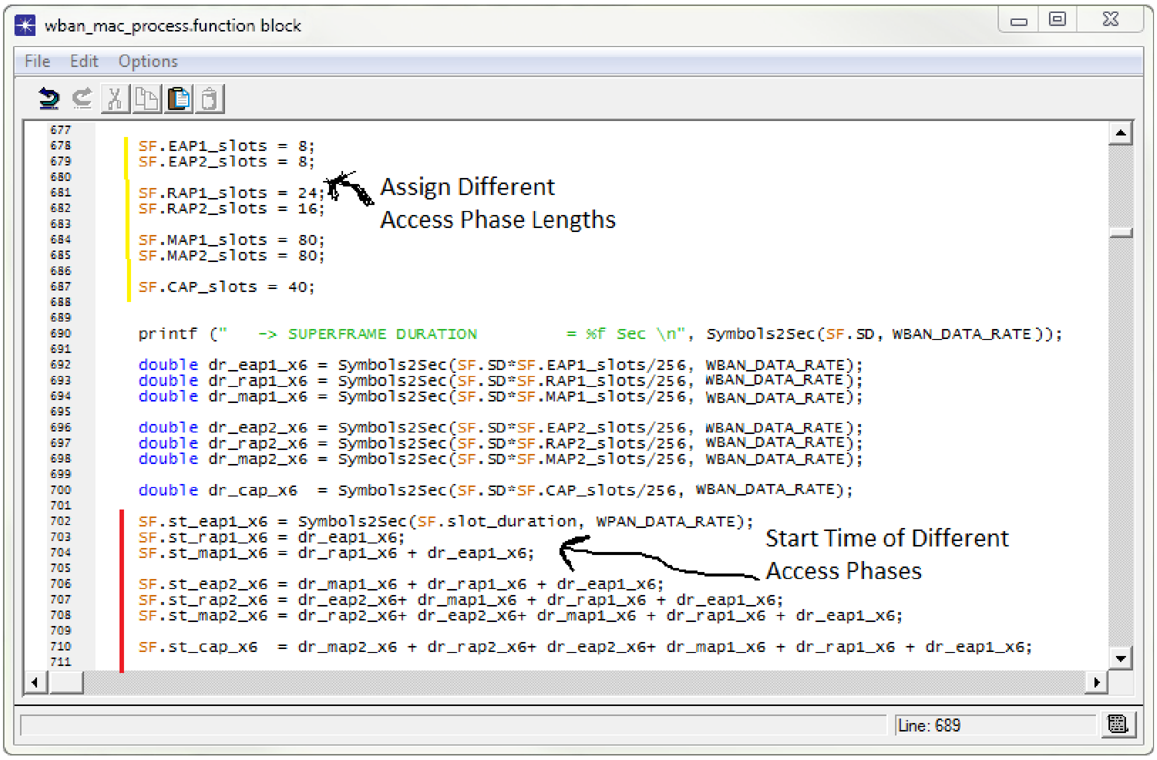


Figure 6.10: Access Phases Length for IEEE 802.15.6 MAC

3. Scheduling an interrupt to call these access phases after sending beacon

   The start time of the different access phases needs to be scheduled by using op_intrpt_schedule_self function. The screenshot is attached in figure-6.11

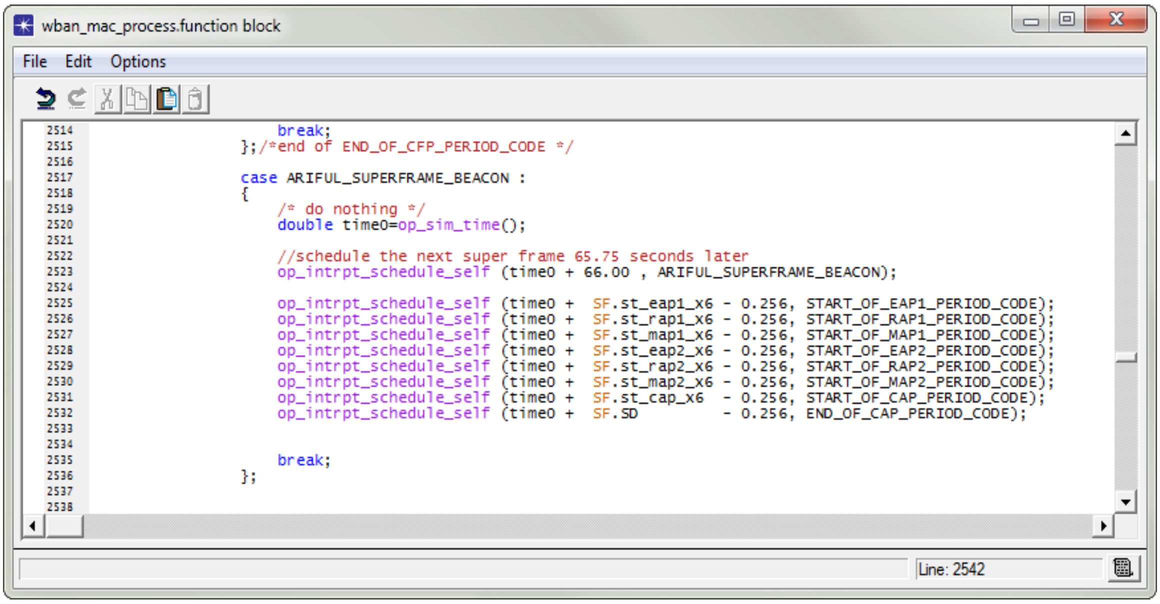


Figure 6.11: Scheduling interrupt for invoking Channel Access Phases

4. Invoking Appropriate Channel Access Schemes

As EAP1, RAP1, EAP2, RAP2 are based on CSMA/CA. To invoke CSMA we use the following conditions :

CAP_ACTIVE = OPC_TRUE,

CFP_ACTIVE = OPC_FALSE,

GTS_ACTIVE = OPC_FALSE;

To invoke TDMA in MAP we use these conditions

CAP_ACTIVE = OPC_FALSE;

CFP_ACTIVE = OPC_TRUE;

6.4.5 Obtaining Results

Here we insert some screenshots which will help to understand the results collection procedure for OPNET. For example, if we want to plot the energy consumption trace of the coordinator the steps that will be required are shown Figure 6.12. Select the Coordinator Node and choose Individual DES Statistics by right clicking and select the Consumed Energy attributes from the Battery module.

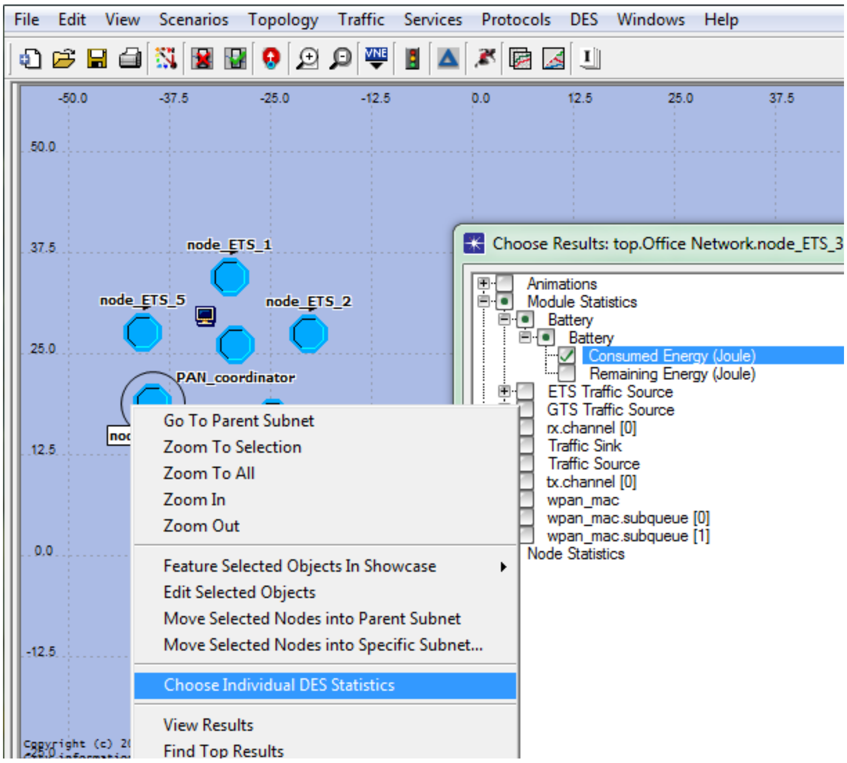


Figure 6.12: Choosing Statistics

The output can be seen in the Result Browser by clicking on the Show Button. The result is shown in Figure 6.13. To see the throughput we have to select Network Output Load in

Global statistics and the sample graph of throughput for the 5nodes scenario is shown in Figure 6.14.

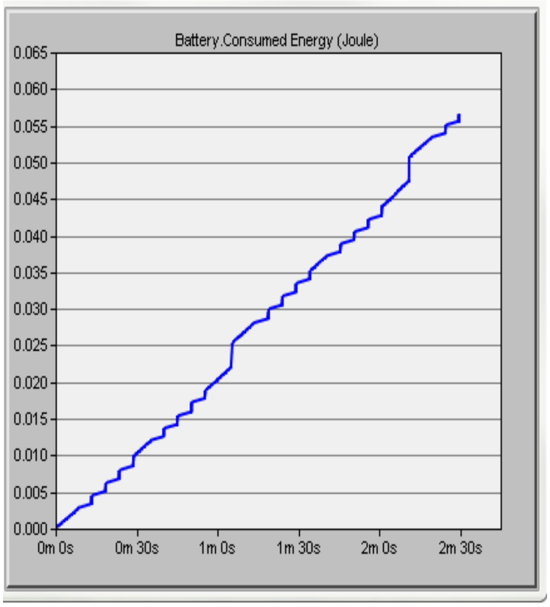


Figure 6.13: Battery Consumed Energy

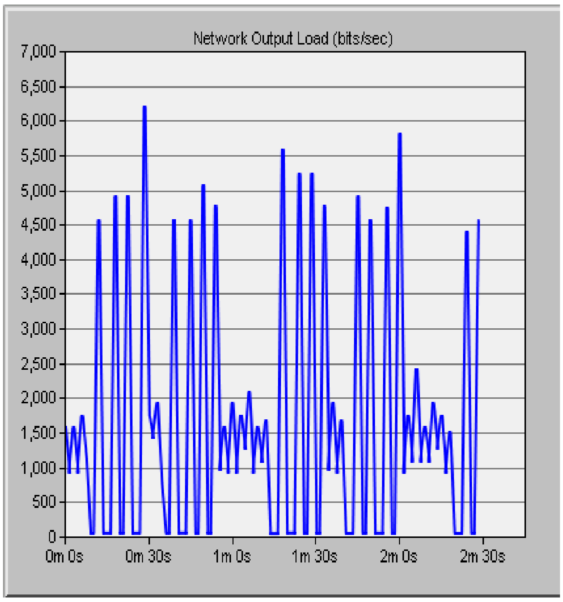


Figure 6.14: Throughput

6.5 Implementation of MEB protocol in OPNET

The major difference between the MEB MAC and the IEEE 802.15.6 protocol is in two aspects: 1. Superframe structure and 2. Listening window Insertion in MAP. Here we describe these two aspects :

<u>Assigning Channel Access Phases</u>

Since in MEB MAC protocol, EAP is not considered, we allocate the slots in the following way what we described in chapter -5, as shown in the following screenshot.

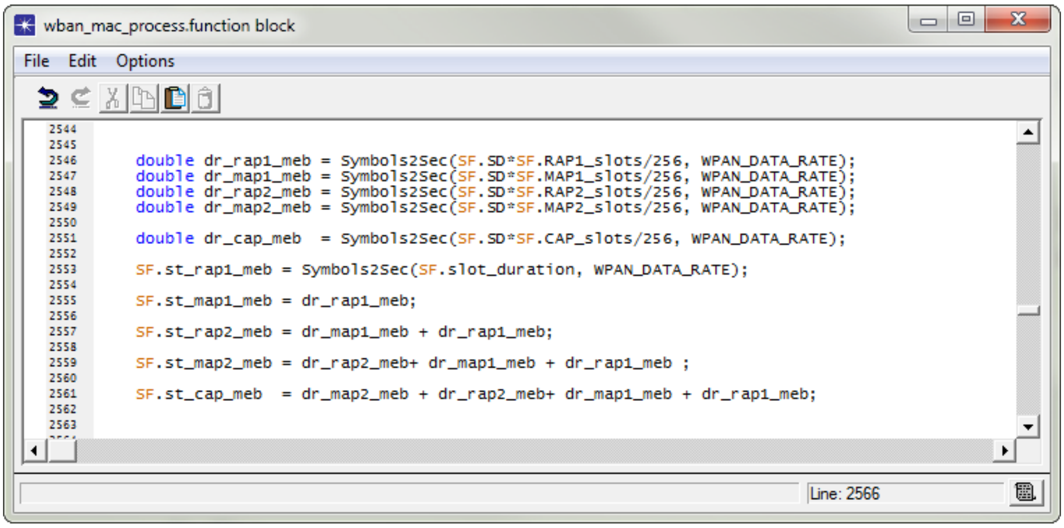


Figure 6.15: Access phase length for MEB MAC

Inserting Listening Windows

We define LWs in the function wban_encapsulate_and_enqueue_ETS_frame() and check the simulation time whether it falls in the MAP1 or MAP2 period. Lws are inserted in the superframe by using Algorithm 5.1. The code for LWs insertion is shown in figure 6.15.

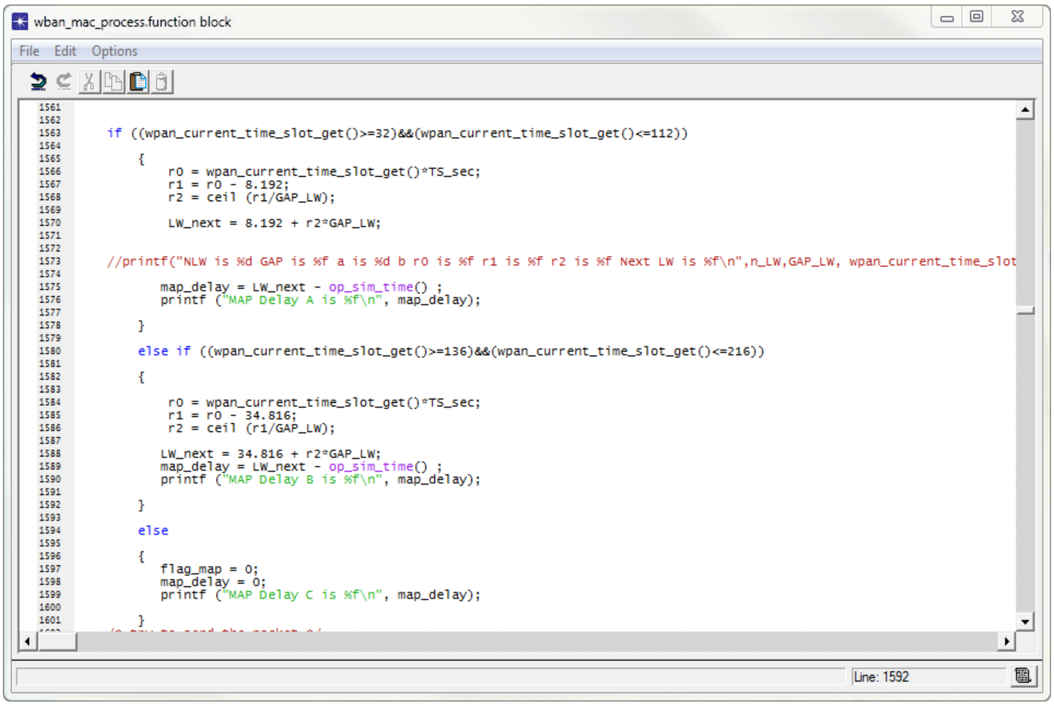


Figure 6.16: LWs Insertion in MEB MAC

6.6 Performance Analysis

6.6.1 Simulation Scenario and Parameters

In our simulation we first consider two types of scenarios where we consider single and multiple emergency nodes. Figure 6.17 shows the considered scenarios in our simulation. Here emergency nodes are attached with a co-coordinator. The MSDU size was considered as 100 bytes and the number of slots in the superframe is set to 256 and the superframe duration is 65.536 sec.

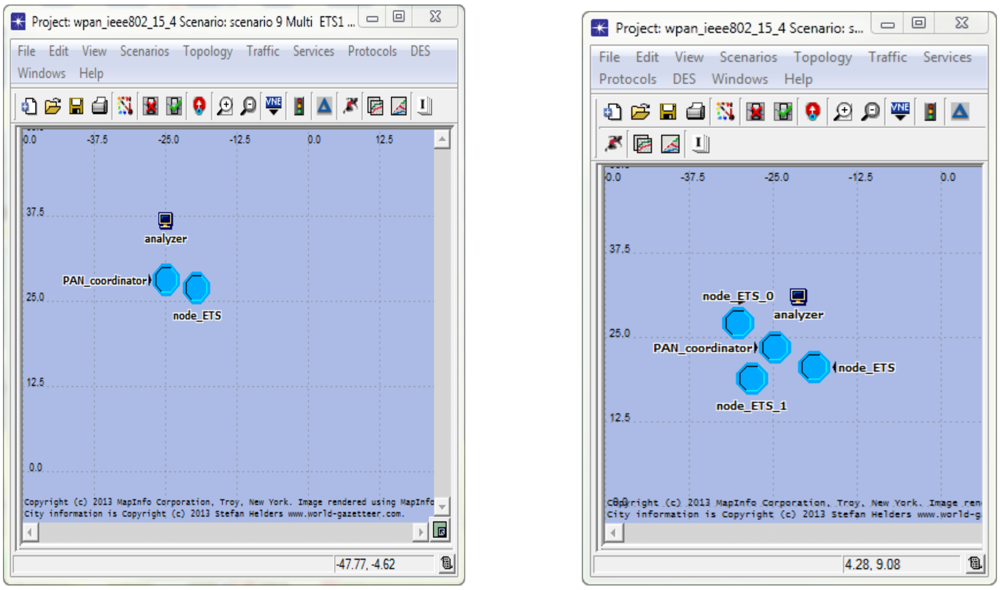


Figure 6.17: Considered Scenarios

6.6.2 Channel Access Delay and Throughput Comparison

The channel-access-delay results for a single emergency node and multiple emergency nodes are plotted in Figure 6.18 and Figure 6.19. Emergency Traffic is generated for 6 inter-arrival times (0.5 sec, 1 sec, 2 sec, 3 sec, 4 sec, 5 sec) in 65.53 sec long superframe duration.

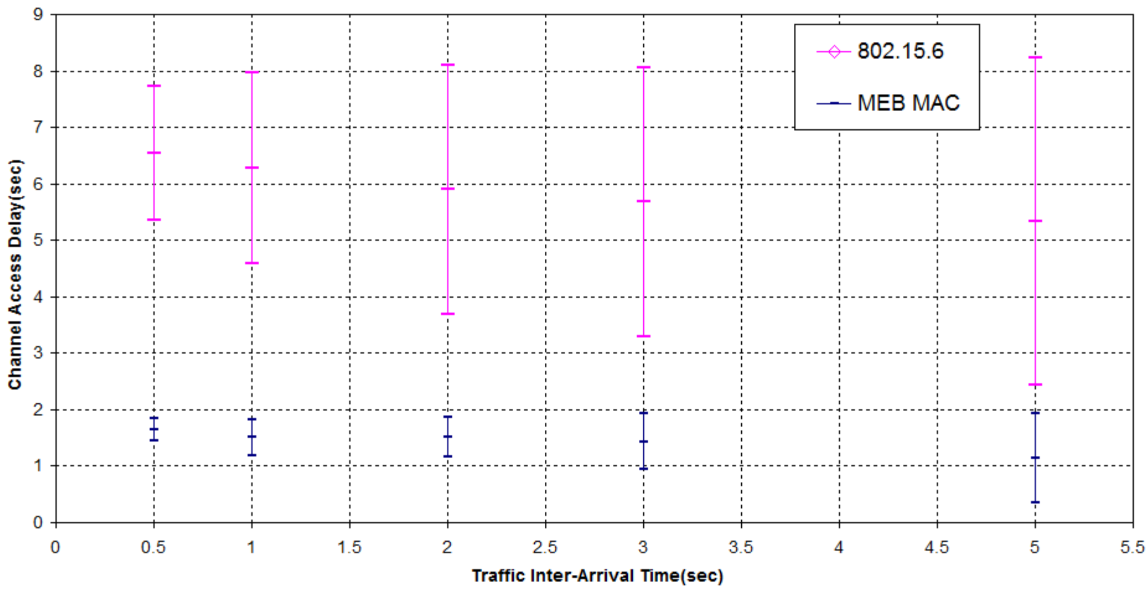


Figure 6.18: Channel Access Delay comparison for Single Node Scenario

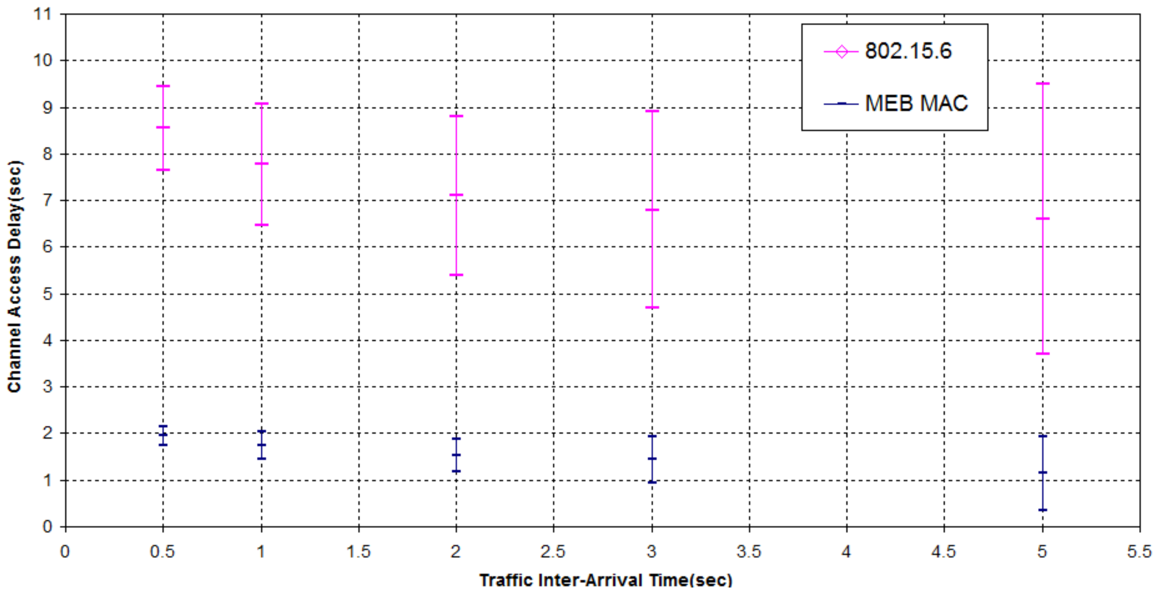


Figure 6.19: Channel Access Delay comparison for Multiple Nodes Scenario

From the above figures we can see that, the average channel-access-delay for IEEE 802.15.6 lies between 5.5 sec to 8.7 sec whereas the average channel-access-delay for MEB MAC falls between 1.1 sec to 2 sec. It can be seen that channel access delay for both protocols in both scenarios has been reduced with the increase in the traffic inter-arrival time. It is evident that channel-access-delay of MEB MAC is much smaller than IEEE 802.15.6 under any condition. In longer time intervals (from 2 sec to 5 sec) the average channel-access-delay for IEEE 802.15.6 slightly decreased for both of the scenarios. But for heavy traffic conditions (inter-arrival time .5 sec to 1 sec) the average channel-access-delay reaches approximately 6.7 sec., (for single node scenario) and this value is approximately 8.6 sec for multiple node scenario. In MEB MAC, the smallest channel-access-delay occurs with 5 sec traffic inter-arrival time for both of the scenarios. The similar trend is found in for other inter-arrival times for both of the scenarios. These figures also demonstrate the validity of Matlab results that were shown in Figure 5.3.

Figure 6.20 and 6.21 show the total throughput for the scenarios considered in the above section. As expected, throughput for both protocols is decreased with the increasing inter-arrival time and the difference between the throughput values also reduces as traffic inter-arrival time increases. In Figure 6.20 we can see for 0.5 sec inter-arrival time the throughput values for IEEE 802.15.6 MAC and MEB MAC are 449.2 bits/sec and 222.63 bits/sec respectively. On the other hand, for the same inter-arrival time these values are 481.59 bits/sec and 1377.59 bits/sec respectively for the 3 node scenario.

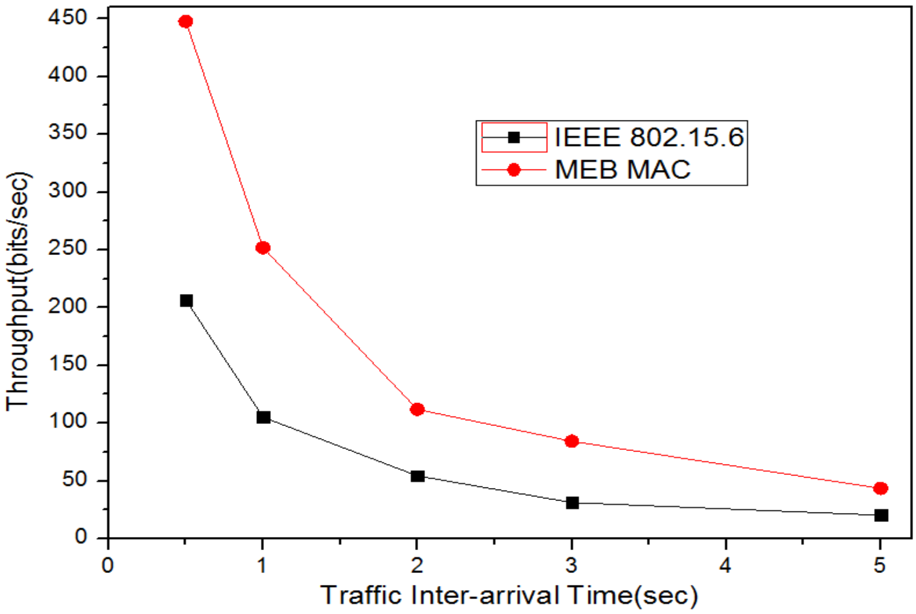


Figure 6.20: Throughput comparison for Single Node Scenario

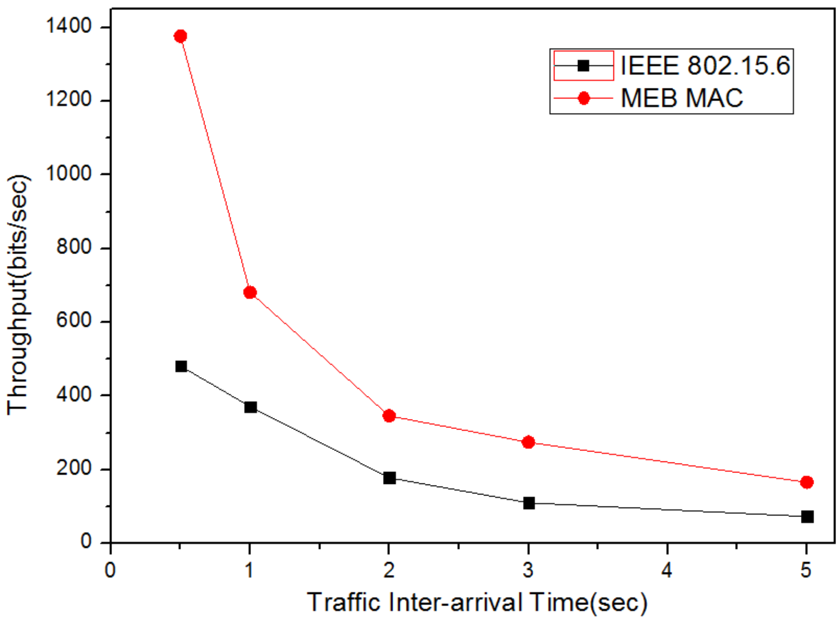


Figure 6.21: Throughput comparison for Multiple Nodes Scenario

From these above figures it is obvious that MEB MAC outperforms IEEE 802.15.6 MAC protocol significantly under any situation and for high traffic load and multiple nodes scenarios MEB achieves considerable performance gain as compared to IEEE 802.15.6 protocol.

6.6.3 Performance Comparison with Varying Nodes

Figure 6.22 and 6.23 show the total throughput, power consumption when varying the number of WBAN nodes in the network. The inter-arrival time is considered as 1 sec.

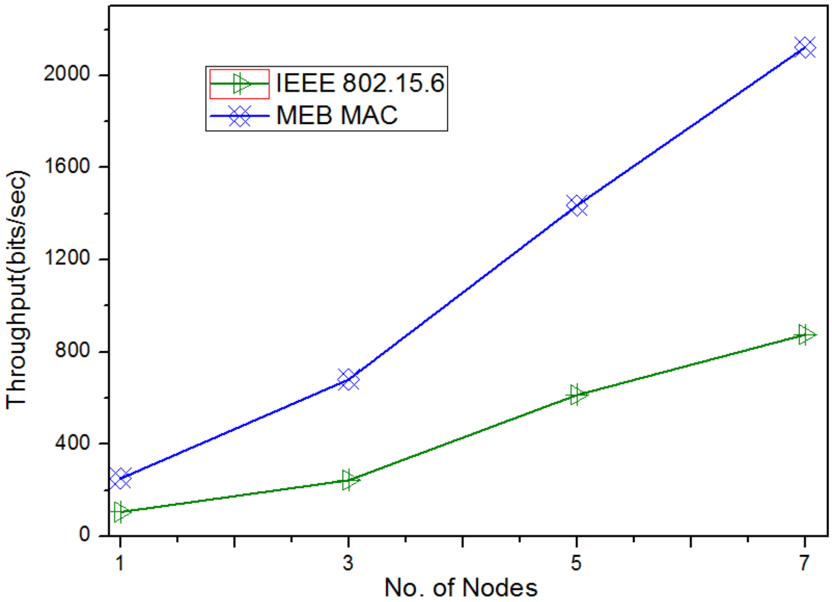


Figure 6.22: Throughput comparison for Varying Nodes

We can see from Figure 6.22 that MEB MAC has better throughput than IEEE 802.15.6 MAC in all cases. Although in the single node scenario the difference between throughput values is not so large but with increasing number of nodes the throughput for MEB MAC has increased significantly compared to IEEE 802.15.6 MAC. In the 7 node scenario, the throughput values for MEB MAC and IEEE 802.15.6 reach 875.41 bits/sec and 2122.35 bits/sec respectively.

The performance of energy per bit for IEEE 802.15.6 MAC and MEB MAC is shown in Figure 6.23, The parameter of energy per bit is defined as

$$E_b = \frac{E_{avg}}{Thr_{avg} \times T_{total}}$$

where E_{avg} is the average energy consumption within a certain time interval T_{total}, Thr_{avg} is the average achieved throughput in T_{total}.

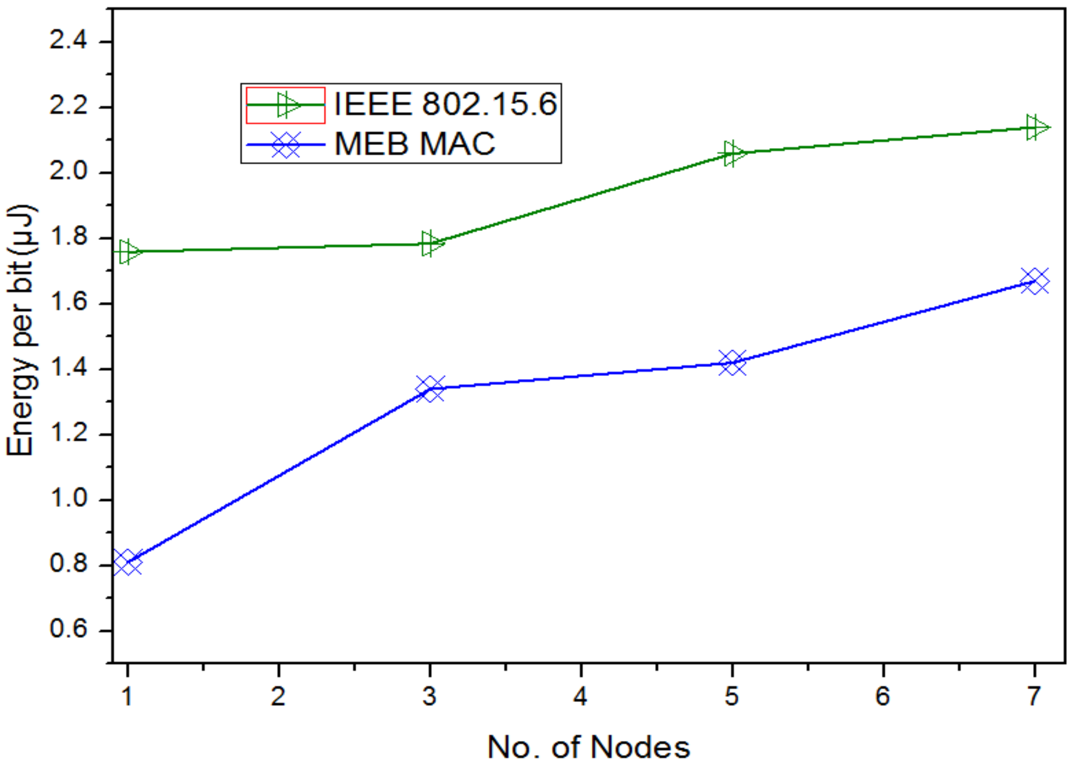


Figure 6.23: Required energy for Varying Nodes

Here we can observe that in the single node scenario, MEB MAC uses the lowest energy such as .81 µJ for transmitting packets whereas this value was 1.78 µJ for IEEE 802.15.6. As the number of node increases, the energy consumption for both of the protocol enlarges steadily. This linearity of energy consumption is not limited to small scale collisions and retransmissions only. We can see MEB MAC shows better performance than IEEE 802.15.6 MAC under any number of nodes. Hence, we can conclude that MEB MAC is much more energy efficient than IEEE 802.15.6 under various traffic conditions.

6.7 Summary

In this chapter we presented the implementation details of IEEE 802.15.6 MAC protocol in OPNET. Present simulators have strong limitations to handle the WBANs simulations. To the best of our knowledge this is the first discrete event based simulator for WBANs where the exact superframe format and appropriate traffic classes have been considered. We compared IEEE 802.15.6 MAC protocol with our proposed MEB MAC protocol. Various performance metrics such as channel-access-delay, throughput, and power consumption have been compared to justify the effectiveness of MEB MAC protocol.

Chapter 7

Conclusions

7.1 Conclusions

The main contribution of this thesis was to implement energy efficient MAC protocol and suitable discrete event based simulator development for WBANs. We started our work based on IEEE 802.15.4 MAC before the WBANs' standardization process was initiated. Firstly, we focused on IEEE 802.15.4 MAC's applicability for implant WBANs and then IEEE 802.15.6's standardization. We considered emergency channel access procedures for medical emergency traffic. We proposed MEB protocol in this regard, which is a novel energy-efficient MAC protocol for WBANs and strongly capable of reducing the channel access delay for emergency traffic. Initially we used MATLAB for MEB MAC's implementation but due to its limitation in handling scheduling and physical layer attributes, later, we concentrated on building a correct simulation tool in OPNET. Subsequently, we have implemented IEEE 802.15.6 and MEB MAC in OPNET and validated their correctness. The important results of this research work are summarized as follows:

Typically, the performance of WBANs devices depend on their placement i.e on-body, in-body or near the body surface. The complexity of the human tissues and body shape further make it difficult to obtain a simple path loss model for WBAN systems. IEEE 802.15.4 cannot be considered for implant WBANs in its unmodified form, because it does not achieve the level of power required for in-body nodes. Therefore, a channel model is necessary for the design and evaluation of the signalling techniques employed at the physical layer. TG-6 has suggested 7 scenarios with 4 channel models for WBANs system. To analyze an implant WBANs' behavior, firstly we implemented channel models between the implant to implant and implant-to-body surface in the MICS frequency band (402 – 405 MHz). We developed implant channel models and changed the power parameters of IEEE 802.15.4 protocol in NS-2 so that it become compatible for implant WBANs. The simulation results in NS-2, successfully confirmed the feasibility of the modified 802.15.4 for WBANs. Our results show that the implant to implant has less path loss, lower energy consumption and smaller packet delivery ratio as compared to implant to body surface.

Although emergency data is unpredictable and non-periodic but immediate delivery is very important, otherwise it can cause life-threatening events. We proposed MEB MAC, as a novel traffic adaptive MAC protocol in which we have mainly focused on the channel access delay reduction for medical emergency traffic of WBANs. We addressed IEEE 802.15.6 MAC and other protocols' limitations to handle emergency traffic. MEB MAC exploits the idea of a hybrid MAC approach where opportunities have been created to allow channel access for emergency traffic in scheduled access phases by inserting *LWs*. MEB MAC utilizes the unused bandwidth in scheduled access periods to create more scope for emergency traffic to get immediate access to the channel. MEB Protocol was also compared with two other recently reported protocols and our results show that our proposed MEB MAC protocol outperforms all the other protocols in long superframe duration. MATLAB codes for MEB MAC protocol are included in Appendix.

Lastly, we developed a discrete event based simulator in OPNET for WBANs. We presented the detailed description of the implementation by showing the module attributes and scenarios. Lastly we compared the IEEE 802.15.6 and MEB MAC for various types of scenarios. Our results showed strong agreement between the Matlab and OPNET simulations for channel access delay. The main contributions of this work are : implementing accurate superframe structure as suggested in standard, supporting large superframe duration with long time slot and creating a new traffic class for emergency applications.

7.2 Future Work

The study presented in this thesis leads to new avenues for future work. In this section, we outline some issues that we would like to investigate in our future research

The work in this thesis can be extended to include investigations of MEB MAC performance in the presence of other types of traffic and we will incorporate with it realistic channel models and interference from nearby networks. A WBAN MAC should also support dynamic resource allocation according to variable traffic nature. Dynamic superframe adjustment based on traffic demand can make the protocol more energy efficient. The duty cycle of the superframe structure can be investigated according to the channel opportunity and collision ratio. Future work will concentrate on further development of the OPNET model and enhancement of the Hybrid protocol. In our current work we have considered simple scenario. In future, more complex scenarios will be considered where the effectiveness of MEB MAC will be determined for the congested situation. In OPNET we have just concentrated on the development of MAC layer based protocol for IEEE 802.15.6. This work can be further developed by implementing appropriate channel models and PHY layers where the implant WBANs can be targeted to analyze the simulation based behavior.

Appendix

```
% MATLAB CODE for MEB MAC - ariful.huq@mq.edu.au
% Features :
%     1. IEEE 802.15.6 Superframe Structure,
%     2. Access Phases Allocation
%     3. Channel Access Delay Calculation Based on Random Arrival
%     4. Packet Loss Rate Calculation
%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                            Packet Arrival with
Collision                                       %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
no_of_slots = 256;
SuperframeDuration = 20;
slot_duration = SuperframeDuration/no_of_slots;

node_no = 7;

N1 = 20;            % How many times the 3 nodes congestion will occur
in 1 Superframe
N2 = 170;           % Number of non congested Traffic in 1 Superframe

R1 = 0 + (SuperframeDuration-0).*rand(N1,1);
R2  = [R1,R1,R1,R1,R1,R1,R1];
R3 = reshape(R2,1,length(R1)*node_no);



% R2  = [R1,R1,R1,R1,R1,R1,R1];          % For 7 nodes congestion
% R3 = reshape(R2,1,length(R1)*7);       % For 7 nodes congestion

R4 = 0 + (SuperframeDuration-0).*rand(N2,1);
R5 = [R3 R4'];
R6 = sort(R5);
R7=R6;

% R2  = [R1,R1,R1,R1,R1,R1,R1];          % For 7 nodes congestion
% R3 = reshape(R2,1,length(R1)*7);       % For 7 nodes congestion

% VVI ----  Adjusting arrival time with Slot Boundary
LK = slot_duration:slot_duration:SuperframeDuration;
for i = 1: length(R6)

    ss = find(LK>R6(i));
    R6(i) = LK(ss(1));

end
A = R6;
len = length(A);
%--------------------------------------------------------------------------%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%                               Algorithm 1: LW
Allocation                                  %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
requested_map = 166;
LSI_param = .9;  % based on highest delay tolernce....it is Application
dependent


%disp('Entering Loop');

%  Considered Slots for the Different Access Phases
    rap1 = 24;
    map1 = 88;

    rap2 = 16;
    map2 = 88;

    cap  = 40;

    dr_rap1 = SuperframeDuration*rap1/256;
    dr_map1 = SuperframeDuration*map1/256;
    dr_rap2 = SuperframeDuration*rap2/256;
    dr_map2 = SuperframeDuration*map2/256;
    dr_cap  = SuperframeDuration*cap/256;

    st_rap1 = slot_duration;   % 1st time slot is for 1st LW RAP will
start after that
    st_map1 = dr_rap1+slot_duration;
    st_rap2 = dr_map1 + dr_rap1+slot_duration;
    st_map2 = dr_rap2+ dr_map1 + dr_rap1+slot_duration;
    st_cap  = dr_map2 + dr_rap2+ dr_map1 + dr_rap1+slot_duration;


    map = map1 + map2;
    dr_map  = dr_map1+dr_map2;   % Duration of total MAP
    NLWmin = dr_map/LSI_param;   % Minimum No of LW

    GAP = map - requested_map;
    %GS = GAP*slot_duration;

    if (GAP<NLWmin)
        LSI = LSI_param;
    else LSI = dr_map/GAP;
    end

    N_LW = dr_map/LSI;


    LW1 = st_map1:LSI:st_rap2;     % Insertion of LW in MAP1
    LW2 = st_map2:LSI:st_cap;      % Insertion of LW in MAP2

    LW = [LW1, LW2];
    l = length(LW1);
    m = length(LW2);
    n=length(LW);

    occupied_slot = 256 - GAP;
%-----------------------------------------------------------------------
--------------%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
%                         Algorithm-2 : Collision 
Resolution                                    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
i = 1;

B  = A;
D = zeros(len,1);
Lost = 0;
len_B = length(B);
SimiFlag = 0;
IncFlag = 0;


while(i<len)
    IncFlag = 0;

       if(A(i)==A(i+1))              % With Same Arrival time

        simi = find(A==A(i));
        simi_cnt = length(simi);    % How many nodes with Same Arrival 
time


     for j = 1:simi_cnt

      fprintf ('match found for %.2f\n',A(i));

      ColDelay = 0;
      LoopLen = 1;
      flag = 1;

      cnt = 0;

      while LoopLen~=0

      if ((A(i)> st_map1) && (A(i)< st_rap2))     % Collision in MAP1

          ss3 = find(LW1>A(i));    % Searching Next LW
          cur_LW1 = LW1(ss3(1));  % Position of the next LW
          CWL = length(ss3);       % Number of Remaining LW
          RXS = 0 + (.5-0).*rand(1,1);% Pick a Random No within 0 to .5
          RIS = ceil(CWL*RXS);        % Choose the Desired LW
          Throw  = LW1(ss3(RIS)); % Transmit in the Next LW
          RTS = Throw - A(i);

      elseif ((A(i)> st_map2) && (A(i)< st_cap))    % Collision in MAP2

          ss4 = find(LW2>A(i));
          cur_LW2 = LW2(ss4(1));
          CWL = length(ss4);
          RXS = 0 + (.5-0).*rand(1,1);% Pick a Random No to choose the 
LW
          RIS = ceil(CWL*RXS);
          Throw  = LW2(ss4(RIS));
          RTS = Throw - A(i);
```

```
      else                                              % Collision in
RAP1,RAP2,CAP

      RTS = 0 + (6*slot_duration-0).*rand(1,1);

      ColDelay = ColDelay + RTS;
      Throw  = A(i)+ RTS;

      if( Throw > SuperframeDuration)
          Throw = 65.5;
      end
      end

           ss2 = find(LK>Throw);
           Throw = LK(ss2(1));

          Ys1 = find(B==Throw);
          LoopLen = length(Ys1);
          cnt = cnt + 1;

          Ys2 = find(B>Throw);
          Ys2Len = length(Ys2);


      if(cnt>4)             %Discard the packet if Collision Counter
reaches 4

          D(i) = 99;        % Value 99 will be indicated as lost packet
          B(i) = 98;
          LoopLen  = 0;
         Lost = Lost + 1;
      else

       if(Ys2Len==0)             % Vector B will  store the congested
traffic
            B(len_B+1)= Throw;
            len_B = len_B + 1;
         else
            a = B(1:i-1);
           a1 = 0;
            b = B(i+1:Ys2(1)-1);
            c = Throw;
            d = B(Ys2(1):len_B);
            B = [a,a1,b,c,d];
        len_B = len_B + 1;
        D(i)= Throw;

       end
      end

      end
       i = i+1;
       IncFlag = 1;
     end

       end


  if(IncFlag==0)
```

```
        D(i)=A(i);
        i = i+1;
    end
end
%-----------------------------------------------------------------------
--------------%
E = D;
%E = sort(D);
disp('SORTED ARRAY ELEMENT');
disp(E);

n_ET= length(E);
    delay = 0;
    cnt = 1;
    j= 1;
    k = m;
    total_delay = 0;
    take = 0;

for i = 1:n_ET

    DTS = E(i)-A(i);

             if ((E(i)==0))
                delay(i)=0;
                continue;
            end

            if(E(i)- st_rap1 < slot_duration)

                    delay(i)=0+DTS;
                    total_delay = total_delay + delay(i);
                    continue;
            end


            if ((E(i)>st_rap1) && (E(i)< st_map1))

                Col_Py = ceil(9*rand)/10;
                Rem = st_map1-E(i);
                delay(i)= Rem/(1-Col_Py)+DTS;
              total_delay = total_delay + delay(i);
             continue;
           end


               if ((E(i)> st_map1) && (E(i)< st_rap2))
                for j= j:l

                    if(((LW(j)-E(i)) > 0))
                         delay(i) = LW(j)-E(i)+DTS;
                             take = LW(j);
                             j = j+1; % to avoid next repeatation
                        total_delay = total_delay + delay(i);
                        break;
                    end
                end
                continue;
              end
```

```
            if((E(i)> st_rap2) && (E(i)< st_map2))

                Col_Py = ceil(9*rand)/10;
                Rem = st_map2-E(i);
                delay(i)= Rem/(1-Col_Py)+DTS;
                total_delay = total_delay + delay(i);
                 continue;
            end



            if ((E(i)> st_map2) && (E(i)< st_cap))
                 for k = k : n
                   if((LW(k)-E(i))>0)
                              delay(i) = LW(k)-E(i)+DTS;
                              k = k + 1;
                        total_delay = total_delay + delay(i);
                        break;
                    end

                 end
                continue;
              end

            if ((E(i)>st_cap)&& (E(i)< SuperframeDuration))
                 delay(i) = SuperframeDuration-E(i)+DTS;
              total_delay = total_delay + delay(i);
               continue;
            end

            if ((E(i) > SuperframeDuration))    % For collided traffic
                 delay(i) = 0;
              total_delay = total_delay + delay(i);
               continue;
             end


end
 %plot(delay);

 disp('NO OF LW')
 disp(N_LW);
 disp('Total Delay for EB MAC');
 disp(total_delay);

 avg_delayEBM = total_delay/n_ET;

fprintf('Average Delay  = %f sec\n',avg_delayEBM);


data_rate = 250;
thr1  = (occupied_slot/no_of_slots)*slot_duration/.256*data_rate;
disp(thr1);
thr2  =
(occupied_slotN_LW+n_ET)/no_of_slots*slot_duration/.256*data_rate;
disp(thr2);
thr3  = (N_LW+n_ET)/no_of_slots*slot_duration/.256*data_rate ;
disp(thr3);
```

```
 d1 = sort(delay);


 theory1 =
(rap1*dr_rap1/2+map1*dr_map1/2/N_LW++rap2*dr_rap2/2+map2*dr_map2/2/N_LW+
cap*dr_cap/2)/256;

fprintf('Number of Arrived Packet in 1 Superframe = %d\n',len);
fprintf('Number of Lost Packet = %d\n',Lost);
fprintf('Packet Loss Ratio = %f\n',Lost/len*100);
```

Bibliography

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