UNIVERSITY OF TECHNOLOGY SYDNEY

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DEVELOPMENT OF EFFICIENT MEDIUM ACCESS CONTROL PROTOCOLS FOR WIRELESS BODY AREA NETWORKS

by

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Declaration

I certify that, to the best of my knowledge, the dissertation in this thesis has not previously been submitted for a degree nor as part of requirements for a degree except where otherwise acknowledged within the text.

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Abstract

Future healthcare systems aim to provide smart, unobtrusive, unconstrained, pervasive and proactive healthcare through affordable and accessible means. A key enabler towards achieving the above is through solutions, which provide timely and continuous monitoring and analysis of physiological parameters of the body. The parameters obtained through the remote monitoring systems are used to analyse, diagnose and develop treatments. This allows for early detection of symptoms or abnormalities and in turn, prevention of illnesses.

Wireless Body Area Networks (WBANs) are an essential part of future healthcare systems with the potential to seamlessly interconnect wearable and implantable sensors. In recent years, WBANs are expected to support various types of applications with datarates from a few Kbps up to 15 Mbps and satisfy heterogeneous requirements of both medical and consumer electronics.

WBANs have captured the attention of researchers and motivated them to develop strategies that can enable them to handle various types of applications. Unfortunately, existing wireless networks cannot meet the strict Quality of Service (QoS) requirements of these networks. Hence, novel communication protocols considering the limitations of these networks need to be developed to pave the way for optimum network efficiency and data transmission reliability.

The Medium Access Control (MAC) protocols have an important role in supporting the combination of reliability, quality of service, energy efficiency and scalability. The current IEEE 802.15.6 MAC protocol based on the latest WBANs standard is not optimised to maintain a balance between the energy limitation and QoS requirements for the diverse range of applications. Consequently, new research is required to explore the above issue and develop new enhancements for the IEEE 802.15.6 standard to better manage different applications over different conditions and scenarios better.

This research focuses on developing MAC protocols to improve the performance of WBANs specifically in the saturation condition. As in saturated networks all the nodes send packets continuously, high level of collisions occurs and the medium is poorly utilised. While the high percentage of the packets of the highest user priority are dropped which carries life-critical information, other user priorities are not able to access the medium. To this extent, this research considers these challenges to improve the network performance in saturated networking condition both for the highest user priority and the other user priorities at the same time.

Two IEEE 802.15.6-based MAC protocols, Saturation Aware for the User Priorities (SAUP) and Saturation Aware for the Highest User Priority (SAH) MAC protocols have been proposed to address these shortcomings for all the user priorities and enhance the channel access for different user/application priorities in saturated networks.

The simulations were performed in the MATLAB framework. The results indicate the proposed protocols achieve better network performance as well as reducing energy consumption compared to the IEEE 802.15.6 MAC protocol. The improvements in the network performance and energy efficiency are specificity, for the user priorities other than the highest one in the proposed SAUP MAC protocol. However, SAH proposed MAC protocol focuses on the network improvements for the highest user priority comparing with IEEE 802.15.6 MAC protocol in the saturated WBANs.

Acknowledgements

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Publications

1. S. Sadra, M. Abolhasan, ”On Improving the Saturation Performance of IEEE 802.15.6-based MAC Protocols in Wireless Body Area Networks”, the 13th International Wireless Communications and Mobile Computing Conference (IEEE IWCMC), 2017.

2. S. Sadra, M. Abolhasan, ”On Developments of MAC Protocols for Wireless Body Area Networks”, To be submitted to the Journal of Networks, 2017.

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Chapter 1

Research Overview and Objectives

1.1 Introduction to Wireless Body Area Networks

The IEEE 802 standard refers to the Institute of Electrical and Electronics Engineers (IEEE) standardisation for local and metropolitan area networks [1]. This standard has developed several international wireless communicating standards such as the IEEE 802.11 for Wireless Local Area Networks (WLANs) [2], the IEEE 802.15.1 for Wireless Personal Area Networks (WPANs) based on the Bluetooth Technology [3], the IEEE 802.15.4 for Low-rate Wireless Personal Area Networks (LR-WPANs) [4] and the IEEE 802.15.6 for Wireless Body Area Networks (WBANs) [5].

The task group six of IEEE 802.15 [6], first in November 2007 launched a new and impressive standard for short range, low power and low datarate wireless communications, named as wireless body area networks. This standard supports the variety of applications domains (medical and non-medical applications) in an immediate vicinity of the human body and even not only humans..

IEEE 802.15.6 standard utilises frequency bands of unlicensed Industrial Scientific Medical (ISM), the licensed Wireless Medical Telemetry Services (WMTS) spectrum as well as Medical Implant Communications Service (MICS) frequency band and Ultra-Wideband (UWB) for transmitting information through WBANs.

WBANs are the seamless networks comprise of variant types of smart, low-power, small-sized sensing devices positioned in the close neighbouring of the human body. These networks aim at gathering the vital physiological information of the body and provide straight off, timely-based, reliable and accurate feedback.

The sensing nodes include in the structure of WBANs are wearable, implantable or external biosensors with a single node as a central controller, which can be a Personal Digital Assistant (PDA), a smart-phone, a portable device or a micro-controller board [7].

A typical architecture of a WBAN is illustrated in Figure 1.1 [8]. There are two types of data transmission in WBANs; the first one is communicating the body's physiological signs from biosensor devices to the central controller. The second type is transferring the aggregated data from the controller either to the users themselves or an emergency server, professional medical staff and healthcare centres in medical applications or to corresponding gaming centres, fitness centres and etc. in consumer electronic applications.

In medical applications, corresponding measured data can be utilised in early detection and prevention of a life-threatening situation as well as diagnosing, monitoring and observing illnesses and managing the decision support. Accordingly, WBANs provide the solutions for the issues of surveillance and management of chronic illnesses, rehabilitation therapy, post-surgical patients, disable people and elderly populations.

However, in order to provide affordability as well as ensure flexibility and mobility

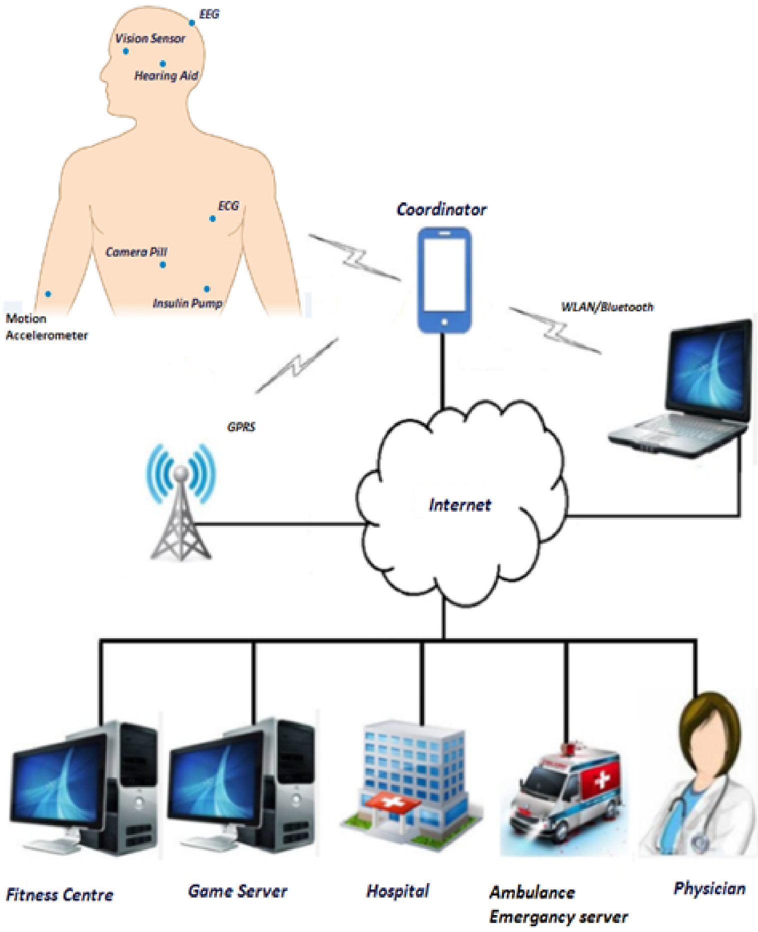

Figure 1.1: WBAN Structure for Medical and Non-Medical Applications

of the body, WBANs encounter hardware limitations. To improve impalpability, some constraining factors such as the weight or the size of the biosensors should be considered while attaching or implementing to the human body.

Furthermore, WBANs should comply with the issues of the communication complexities in the presence of the human body such as the effect of the body shape and movement as well as the radiation pattern and absorption rate factors.

Undoubtedly, such networks are expected to provide realtime information with maximum reliability and throughput and with the lowest acceptable amount of latency. As an obvious outgrowth, WBANs have strict Quality of Service (QoS) requirements while experiencing hardware constraints and environmental issues.

1.2 Research Motivation and Objectives

Achieving the unique set of QoS and providing the privacy and security requirements are the critical demands in WBANs. Hence, novel communication protocols that consider the limitations and requirements of these networks need to be developed to provide the optimum network efficiency and data transmission reliability.

The Medium Access Control (MAC) protocol has a major role in the determination of transition medium allocations to each component in wireless systems. Accordingly, one of the most important challenges in the field of developing optimum WBANs are designing proper MAC protocols to comply with the requirements of such networks.

To put it simply and clearly, MAC protocols have an important role in the determination of throughput, delay, collision, retransmission, energy consumption, reliability and scalability in each wireless network.

Unfortunately, existing MAC protocols are not able to support the combination of reliability, Quality of Service (QoS), energy efficiency and scalability to meet heterogeneous demands of medical and customer service applications of WBANs. Thus, this research focuses on challenges, consideration and developments of MAC protocols specifically for WBANs.

In WBANs, an emphasis is given to handling the emergency situation and giving priority to the traffic based on the data importance. This can be more critical in medical applications when the emergency data can be life-threatening information which need immediate attention. This scenario can be worse in the case the system is in the saturation condition, when data is overloaded in the network.

To this end, this research focuses on developing the MAC protocols for WBANs in saturated networking conditions to simultaneously provide reliable and efficient solutions considering the priority and emergency handling.

1.3 Research Contributions

Considering the shortcoming of current WBAN specific MAC protocols, this research provides a comprehensive review on the MAC protocols in Wireless Sensor Networks (WSNs) and WBANs as well as the comparison amongst them. More importantly, two IEEE 802.15.6-based MAC protocols have been proposed which both consider the issues of the network reliability under saturation condition. The contributions made in this paper are as follows:

- Study of the previously proposed MAC protocols for both WSNs and WBANs considering advantages and shortcomings of each protocol.
- Investigation of the MAC protocols for two IEEE standards, IEEE 802.15.4 and IEEE 802.15.6.
- Specification of the parameters as well as the assumptions for simulations.
- Implementation of the IEEE 802.15.4 and the IEEE 802.15.6 MAC protocols in both saturated and non-saturated networks and providing their performance.
- Proposition of two IEEE 802.15.6-based MAC protocols to improve the overall network performance in saturation condition for all user priorities specifically for the highest one.

- Investigation and simulation of the two proposed MAC protocols and discussion on the improvements and the comparison with the IEEE 802.15.6 MAC protocol.

1.4 Thesis Outline

Chapter 2 provides a comprehensive literature review on WBANs, defining its objective, requirements and challenges. It also provides a comparison of WBANs with the other wireless technologies and defines its architecture considering the topology being used, types of applications and data traffic. An overview on existing wireless MAC protocols as well as the previously proposed MAC protocols for WBANs and WSNs are discussed as well. In addition, this chapter discusses the MAC protocols for IEEE standards applicable in WBANs, the IEEE 802.15.4 and the IEEE 802.15.6.

While Chapter 3 describes the simulation results and discussion on IEEE 802.15.4 and IEEE 802.15.6 MAC protocols, Chapter 4 presents the proposed Saturation Aware for the User Priorities (SAUP) and Saturation Aware for the Highest user priority (SAH) MAC protocols and discusses the simulation results of implementing them as well as comparing these proposed protocols with the current IEEE 802.15.6 MAC protocol based on the simulation results.

Finally, Chapter 5 concludes the research carried out in this thesis and presents the future plan.

Chapter 2

Literature Review

In this chapter, firstly, the challenges in current healthcare systems are presented. This follows by the history of health monitoring systems and complete overviews on wireless body area networks and wireless medium access control protocols. The specific requirements of MAC protocols for WBANs and the challenges in designing these protocols for such networks are elaborated. Two IEEE standards applicable in WBANs are described including their architecture, topology and mechanism. Then, existing MAC protocols for WBANs are functionally described and the advantages and shortcoming of each protocol are presented. At the end, a comparison between current protocol for WBANs are provided based on different aspects of the network performance such as the priority and emergency handling, energy efficiency, scalability and adaptability.

2.1 Challenges in Healthcare Systems

Lately, healthcare systems face significant obstacles that clearly indicate urgent considerations. Chronic diseases outbreaks, growth in the population of elderly people and high health-related cost are considered to be the major challenges, need to be accounted for and constitute a new solution to address the issue of managing high demands for care services. Figure 2.1 points out some of the main challenges in healthcare systems which comprises of:

Figure 2.1: Challenges in Healthcare Systems

2.1.1 Increases in Aging Population

One of the utmost achievements of humankind is the expansion of life expectancy. In Australia, the average life span increased drastically from 71 years in 1970 to 82 years in 2013 and the range in the United States was from 70 years in 1970 to 79 years in 2013, regarding both genders [9].

By 2045-2050, life expectancy is estimated to reach 78 years in the less developed countries and 85 years in the more developed ones. Longer life expediency, obviously, results in world's aging population growth. On the other hand, the rapid progressive growth in numbers of elderly people is a repercussion of the higher birthrates in the early and middle years of the twentieth century as well as the influence of aging the baby boomer generation. The number of aged population in 2013 is four times greater than whom lived in 1950 and the population of elderly people will nearly triple by 2050 [10].

Elderly people require pervasive caring, and in consequence, they have an outstanding need for the healthcare services. Expectedly, increasing the population of aged people would overload the healthcare system and affect their quality of life.

2.1.2 Increases in Various Types of Diseases

The leading fatal burdens of illnesses are chronic diseases such as cancer, heart disease, cardiovascular disease, Parkinson's disease, asthma, obesity, diabetes and so on so forth. Millions of people are suffering from such diseases and in 2020 the number is expected to double in comparison with the current situation. However, most of these people, while developing the symptoms and experiencing the signs of their diseases, have their illnesses diagnosed when it is too late for treatments [11].

Aside from patients with chronic diseases, some post-procedural/surgical patients need observation during their recovery period as well as persons with special disabilities who have greater needs for healthcare.

2.1.3 Increases in Healthcare Expenditures

The healthcare services cannot satisfy the demand of patients and their capacity is overloaded although their cost is increasing year by year. The overall health care expenditures in Australia was 7.3 percent of Gross Domestic Product (GDP) in 1995 which have significantly raised to %9.4 in 2013.The total Health expenditure of United States was %13.2 in 1995 which raised to 17.1 percent of GDP in 2013 [12].

These statistics have introduced innovative challenges for healthcare industries which necessitate new and proactive means in the future generation of healthcare systems to provide basic human welfare rights at a lower cost and in turn to overcome the pressure on the healthcare systems.

2.2 Remote Health Status Monitoring

In the recent decade of the technological evolution, there is a growing intention in easy and wide access to every essential aspect of the life. The accessible and affordable healthcare is one of the most important expectations in everyone's life.

Ubiquitous healthcare has been at the forefront of the researchers in the scientific and healthcare industrial community for many years. Enhancements are achieved for eliminating wires in healthcare by the integration of miniaturised biosensors, intelligent textiles, micro-electronics and nano-electronics systems. This has triggered the theory of unconstrained and consistent patient health status monitoring and medical observation system through wearable sensor devices or implanted ones. In addition, advanced wireless communication techniques and its benefits have motivated the concept of developing seamless physiological sensing systems to be implemented in the healthcare activities related to humans. Remote health observation system can gather and forward the reliable biosignal measurements to the healthcare services in order to investigate a possible health threatening status, diagnose, analyse and develop treatments [13].

Figure 2.2 [14] illustrates that the utilisation of wireless, low-power, lightweight, small-

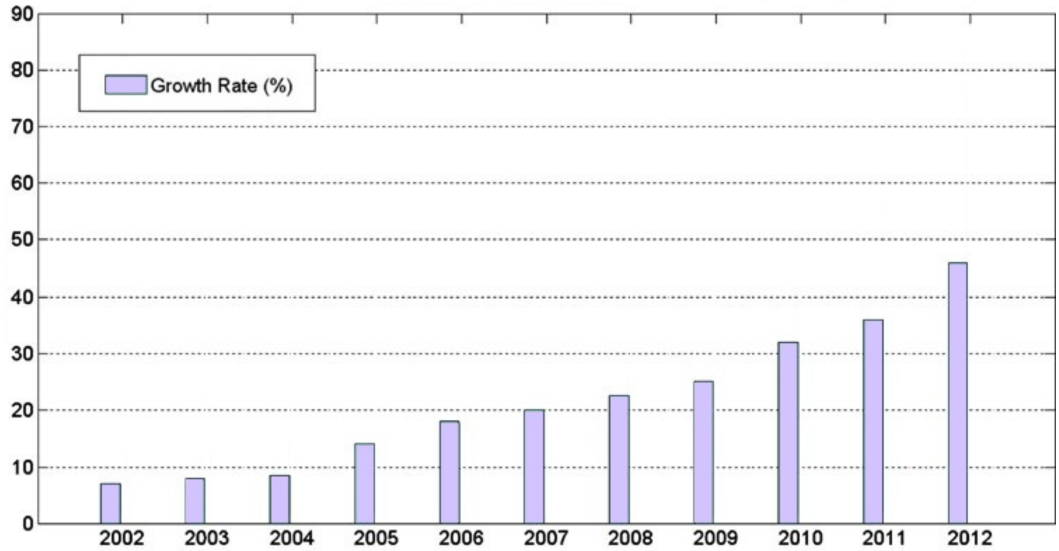

Figure 2.2: Growth of Utilising Wireless Sensors in Healthcare, Medical and Biometrics (World), 2002-2012

sized and smart sensor nodes in the healthcare had been increasing in recent years. The rapid growth marked a new beginning and deploying of application areas which are very critical to the human life. In meanwhile, the numerous corresponding researchers potentially have led to the formation of the wireless body area networks technology to implement pervasive personal health management [15].

In many cases, patients need to be kept under observation in hospitals or clinics for an extended period to detect certain medical conditions. This is quite resource intensive and leads to a restriction in both patients' lives and their normal activates. Remote health monitoring through WBANs has propelled by recent challenges in healthcare systems to provide ubiquitous and ambulatory healthcare in an inexpensive and affordable way which can release the capacity of healthcare centres.

2.3 Overview of Wireless Body Area Networks

In WBANs, wearable biosensing devices are qualified to sample, process, monitor and convey physiological vital signs of the human body within the proximity distance of it as well as delivering real-time feedback to physicians or related centres. The sensor nodes are placed on or within the proximity of a human body or even embedded inside the body. Electroencephalograms (EEG), Electrocardiogram (ECG), Electromyogram (EMG), Blood Pressure Sensor, Body Temperature Sensor, Glucose Monitoring Sensor, Pulse Oximeter, and Motion Accelerometer Sensor are some examples of different types of on-body or wearable sensor devices used in WBANs [16]. The examples of in-body biosensors are sensors implanted under the skin of patients or some are shaped as swallow pills such as capsule-sized cameras, as shown in Figure 2.3.

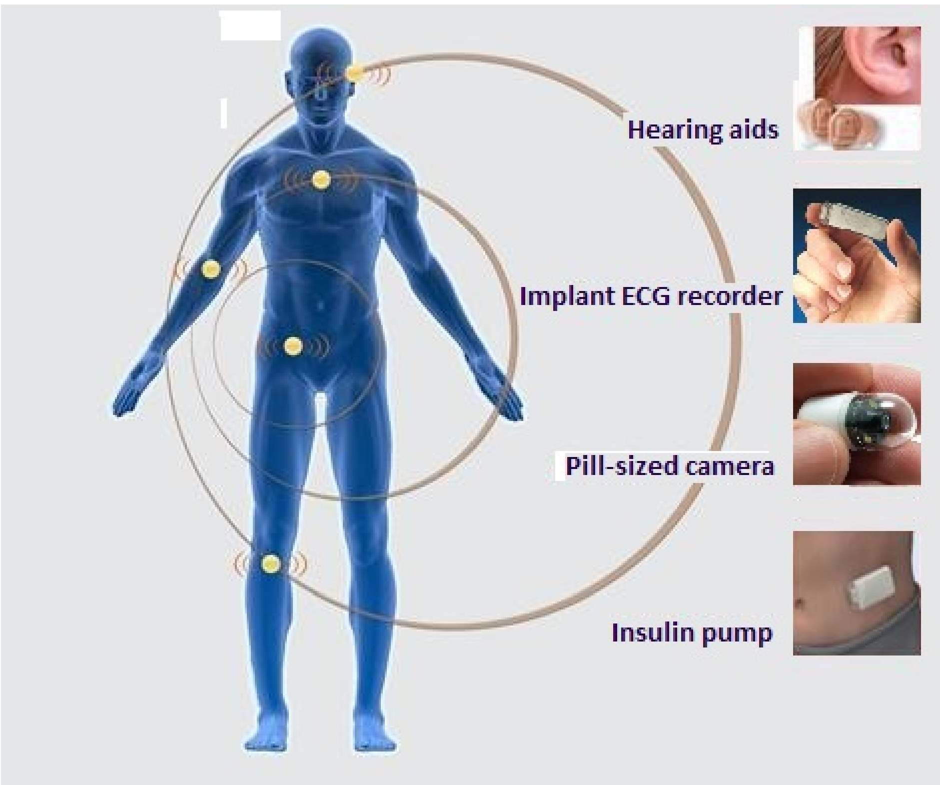

Figure 2.3: Sensors in Wireless Body Area Network

These biosensors obtain vital signs of a patient's body such as heartbeat, temperature, glucose level, blood pressure, breathing rate and thus, providing timely based information to hospitals for analysis, diagnosis and develop treatments through wireless networks [17].

Mainly, the location of a sensor depends on the function of the biosensor. Consequently, depending on the considered physiological parameters, different sensors can be used in the network, such as implanted nodes, body surface nodes or external nodes. The description of some biosensors using in WBANs and the specification of their measured data are presented in Table 2.1 [11].

2.3.1 Advantages of Wireless Body Area Networks in Healthcare

Mobile healthcare through WBANs improves the quality of life and has several benefits. It provides greater mobility and flexibility to patients without restricting or causing any discomfort in their lives. Thus, patients can engage in their normal activities instead of staying at hospitals or close to a specialised medical service.

WBANs provide early diagnosis through constant or periodic monitoring and reduce healthcare costs as well as increase healthcare centres availability for demanding treatments. As a result, a healthcare centre can be available for at-risk groups.

WBANs are expected to cause an impressive shift in the healthcare system and modernise the way people manage and think about their health, similar to the way the Internet has changed the way we get information or communicate with each other.

Type of Biosensor	Type of Application	Description	Priority	Energy Consumption
Electroencephalogram (EEG)	On-body Medical application	Scalp-placed electrodes measure the brain's electrical activity in the certain period of time and send the electrical signal as a pattern of waves.	High	Low
Electrocardiogram (ECG)	On-body Medical application	Sensors placed on the chest and measure the heart's electrical activity.	High	Low
Electromyogram (EMG)	On-body Medical application	Electrodes placed on the skin over the target muscle to measure the electrical activity of the muscle over contraction and during rest.	High	Low
Pacemaker	In-body Medical application	Abdomen-located device to control abnormal heart rhythms by prompting the heart using low power pulses.	High	Low
Blood Pressure Sensor	Wearable Medical application	A sensor usually placed on the left arm to measures the blood pressure and pulse rate.	High	High
Body Temperature Sensor	On-body Medical application	Skin surface sensors to measure the temperature of the body.	Medium	Low
Glucose Monitoring Sensor	In-body Medical application	Sensors inserted under the skin of the patients to provide the continuous record of level blood sugar.	High	Extremely low
Insulin Pump	Wearable Medical application	Wearable devices usually placed on the belt or in the pocket of diabetic patients to deliver continuous amount of insulin to keep the blood glucose on the track.	High	High
Endoscope Camera	In-body Medical application	A swallowable pill-shaped camera capable of taking videos while passes through the digestive organs.	High	Low
Pulse Oximeter	Wearable Medical application	A probe which is situated on the fingertips or ear-lopes to measure the oxygen saturation level of the blood.	High	Low
Motion Accelerometer	Wearable Medical application	A device located on the target place to detect a movement in different dimensional.	Medium	Low

Table 2.1: Biosensors and the Specifications of their Measured Data

2.3.2 Applications of Wireless Body Area Networks

Primarily, healthcare applications were the main objectives in integration of WBANs, however, these networks have been benefited in various and even conflict types of applications with diverse application domain such as sports, entertainments and military services and so on, so forth [18].

In recent years, state-of-the-art WBANs were expected to satisfy both medical strict criteria and consumer electronics heterogeneous requirements while experiencing hardware constraints and environmental issues.

WBAN applications are categorised into medical applications and non-medical (Consumer Electronics) ones, as illustrated in Figure 2.4.

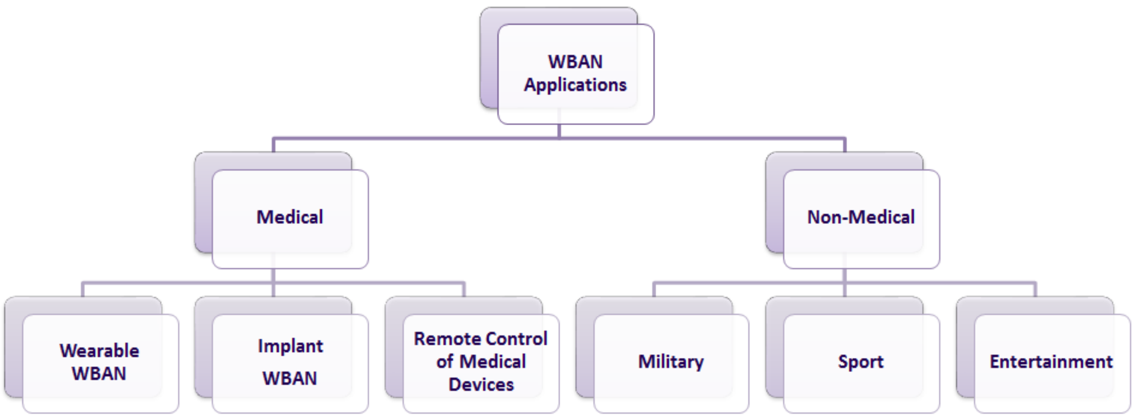

Figure 2.4: Wireless Body Area Networks Applications

WBANs are utilised in a wide range of applications in healthcare. As previously mentioned, health status monitoring through different biosensors are the main objectives in medical applications. Other example of a wearable WBAN is asthma controlling, to help asthma sufferers by having the capacity of recognising the substances in the air which a particular asthma penitent is allergic to and thus should avoid. Diabetes controlling is an instance of an implant WBAN which can reduce the risk of a diabetic patient fainting by means of auto injecting insulin whenever their insulin level is out of the range using insulin pump. Considering a patient with a heart problem, remote controlling can alert the hospitals or medical centres through measuring the risk factors, even before an emergency condition like hearth attack happens. Remote control of medical devices are achieved through WBANs, such as providing voice direction for a blind person or converting audio broadcast announcements to a text by having special eye-glasses for hearing disability people . Other example of medical application can be wireless hearing aids, muscle tension monitoring, artificial hands [19][20] [21].

Non-Medical applications utilise WBANs in several ranges of areas. WBANs provide new opportunities for battlefield defence and survivability in the military. In sports, the performance of an athlete can be monitored by a WBAN for improving purposes or can be used in fitness. In entertainment applications, WBANs can sense a body posture and provide current gesture of the body as an input in gaming or they can be used in connecting wireless headphones to a music streaming equipment with higher bandwidths. Consumer electronics applications are broadly used in communication of cell phones, music players, headphones, video streaming, forgotten thing monitoring and social networking [22][23][24].

2.3.3 Requirements of Wireless Body Area Networks

The objective in designing WBANs are providing a simple, accrue, reliable and high speed communication in the immediate proximity of a human body. Such networks have strict Quality of Service (QoS) requirements such as [25][26][27]:

- Supporting energy efficient real-time communication with low to medium transmission rate.

- Transmitting data with low delay and near zero packet loss.
- Handling emergency messages in a reliable manner and providing priority for medical applications.
- Efficient bandwidth utilisation.
- Supporting scalability for network configuration by adding or removing sensor nodes.

2.3.4 Network Topology in Wireless Body Area Networks

In particular, WBANs consist of several body sensor nodes together with a single central controller. Traditionally, WBANs have been designed to operate in a star topology, where a central node acts as a coordinator and manages data exchange to and from all the sensor nodes in the network. However, the IEEE 802.15.6 working group, the latest IEEE standard for WBANs has considered these networks to operate in either a one-hop or two-hop star topology, as shown in Figure 2.5 [11].

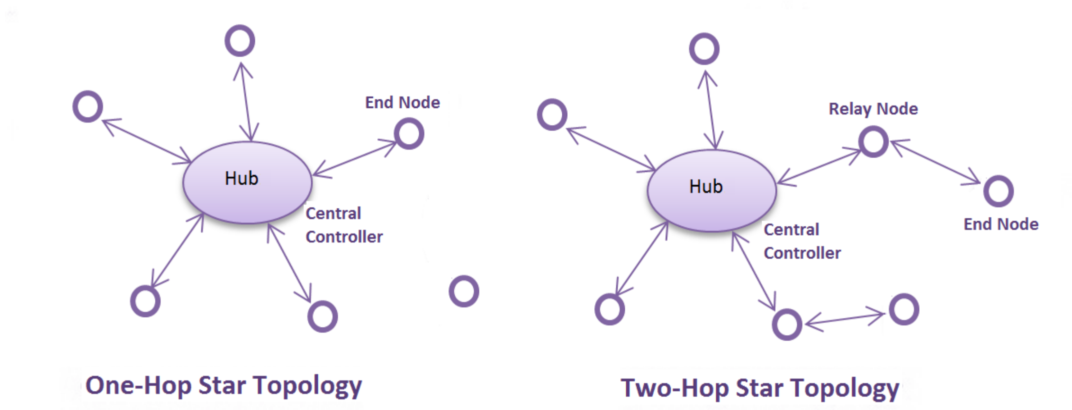

Figure 2.5: Network Topologies in Wireless body Area Networks

Each node is assigned a role based on its position in the network. The central node coordinates data to or from all the other nodes in the network and can provide an interface to other networks or medical centres. End nodes are biosensors inside, on or in an immediate vicinity of human body based on their embedded applications. Relay nodes are used in two-hop star topology and they are placed in between parent nodes and end nodes, capable of relaying data to and from other nodes [28].

2.3.5 Types of Data Traffic in Wireless Body Area Networks

WBANs deal with three types of traffic, that is, normal, on-demand and emergency traffic. Normal traffic is the regular traffic generated by sensors in a normal condition to transmit to the central controller which can be either periodic data or a bursty traffic.

Whenever a physician requests particular information from a patient, mostly for diagnostic purposes, the central node sends on-demand traffic to that certain node and asks for specific data. On-demand traffic can be continuous (in case of surgical events) or discontinuous (when occasional information is required).

Emergency traffic can be commenced by a node when it has life critical information to send or in situations that require urgent attention. Emergency traffic is unpredictable and has the highest priority to handle. Bear in mind that, in medical applications this type of traffic could be life threatening [29].

2.3.6 Wireless Body Area Networks Comparison to Wireless Networks

Wireless networks support different datarate and coverage and can be categorised based on these factors. WBANs may interact with the Internet and other existing wireless networks such as ZigBee, WSNs, Bluetooth, WLAN, WPAN, Wireless Metropolitan Area Network (MAN), video surveillance systems and cellular networks [30].

As illustrated in Figure 2.6 [11] , WBANs operate in a range of 2 to 5 meters of a

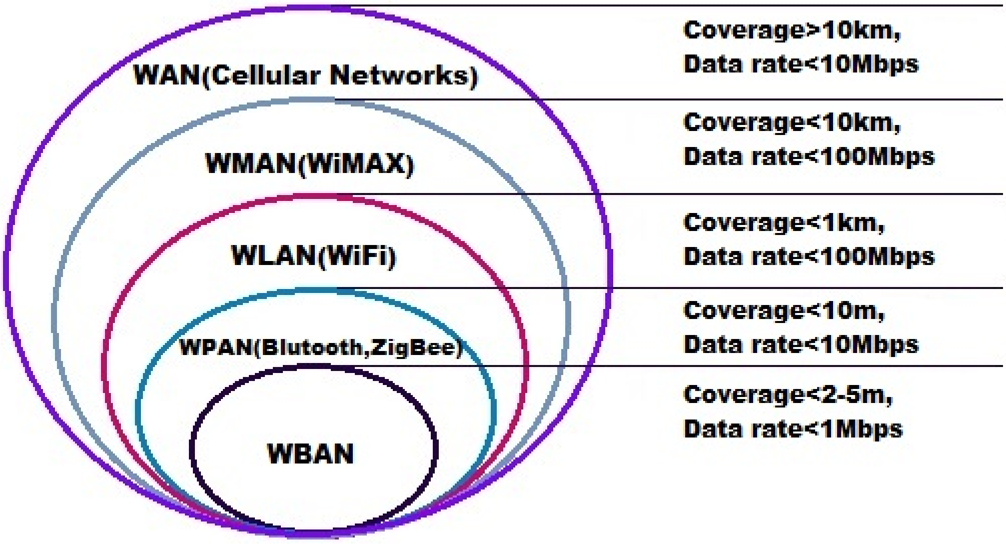

Figure 2.6: Interaction of WBANs and Existing Wireless Networks

human body but WPANs are such networks that operate by a 10 meter distance from a human body. WLANs and WMANs support higher datarate and coverage while WLAN can cover smaller areas like a campus. WPAN, on the other hand, covers a larger area like a city. In addition, Wide Area Networks (WANs) are data networks covering a wide geographical area, as big as the Planet [31].

2.3.7 Wireless Body Area Networks Comparison to Wireless Sensor Networks

Although, WBANs are considered as special purpose Wireless Sensor Networks (WSNs) with specific QoS requirements, there are several important differences between these two networks. Considering that WBANs are working in close distance of a human body, the transmitted signal can be absorbed by human tissue and movement and body shaping which cause's variable path loss. Firstly, due to redundancy of the nodes in WSNs, these networks focus on maximum throughput than reliability which is a must in WBANs where each node carries vital information. Thus, WBANs focus on reliability, emergency and priority regulations but WSNs focus on delivering information. Secondly, the number of nodes in WSNs is on a much larger scale than the number of nodes in WBAN, as patients cannot carry great number of sensors on their body. Thirdly, the energy efficiency in WSNs is not as strict as in WBANs because the nodes in WSNs probably have larger battery and battery changing is possible. However, the important contrast between these two wireless networks is WSNs are generally homogeneous networks which are application-specific networks and such networks focus on specific application only. In contrast, WBANs are heterogeneous networks with diverse range of applications and such networks focus on multiple applications. In summary, the WSN specific protocols are inadequate to be used in WBANs [32].

2.4 Overview of Medium Access Control (MAC) Protocol

The MAC layer coordinates interference-free data exchange in a shared transmission medium whilst maximising throughput and minimising latency. Thus, this protocol manages the access to the radio channel, allocation and de-allocation of data and control frames between the central controller and the other nodes [33]. Figure 2.7 shows the process of data transition.

Designing a proper medium access control protocol for WBANs is essential to ensure the application specific QoS and provide the combination of reliability, energy efficiency

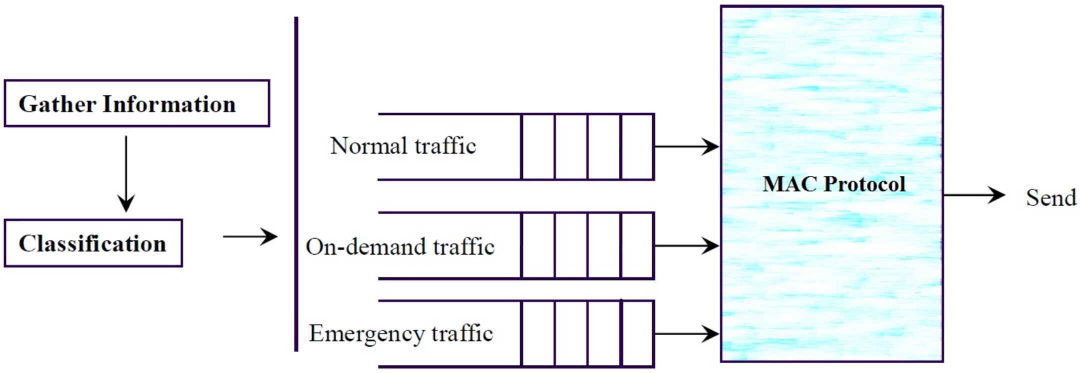

Figure 2.7: Medium Access Control Protocol and Data Transition Process

and scalability.

2.4.1 Challenges in MAC Protocol Design for WBANs

To fulfil the diverse requirements of both medical and consumer electronics applications, a very meticulous approach needs to be considered in the design of MAC protocols for WBANs. The challenges in designing a WBAN based MAC protocols are as follows [34][35][36]:

Energy Efficiency

Energy efficient wireless network is one of the main objectives in WBANs. As all sensors in WBANs are working on battery and battery charging and replacement can be quite uncomfortable especially for implanted ones, power consumption determines the lifetime of these networks. Hence, in order to prolong the operation of WBAN battery-driven sensors, it is critical to minimise the remarkable amount of power consumption in this network. Significant amount of energy is consumed in:

- Channel sensing

- Data transmission
- Signalling between nodes

On the other hand, a WBAN MAC should reduce major sources of energy wastage in WBANs such as, frame collision, overhearing, idle listening and control packet overhead. Whenever, two or more nodes transmit their data simultaneously, a collision takes place which results in corrupted packets. In such a situation, frame retransmission is required and more energy is exhausted. Overhearing is a consequence of receiving the packets which belong to another node which needs retransmission, as well. Idle listening happens under a condition in which a node listens to the possibility of collecting a data frame which has not been sent. Control packet overhead is essential in channel access handling. Remarkable amount of power is consumed in transmitting, collecting and listening to control traffic [37]. An energy efficient MAC protocol is a must to span the life time of wireless body area networks.

Traffic Correlation

Traffic correlation can introduce data overload which result is excessive collisions thus increasing the latency and power consumption in the network.

As physiological data in medical applications are dependent on each other, a small variation in physiological sign may trigger most of biosensors at the same time. For instance, the temperature of patients suffering from fever is much higher than its normal condition which increases their blood pressure and breath rate. In another example, when a patient is about to have a heart attack, the temperature will rise, blood pressure is changed and a lot more will happen. As nodes in the network simultaneously try to send their data, saturation condition will occur [38].

So, providing reliable communication under saturation condition is one of the major objectives in designing a WBANs MAC protocol.

Scalability

There is a possibility of changing the configuration of sensor nodes as a result of deploying new nodes, dead or faulty nodes as well as postural body movements. WBAN MAC protocol should support adaptability to traffic fluctuations and structure alterations in the network [39].

Priority Handling

Some data in WBANs have higher priority than others. In an emergency situation, life critical data needs to be transferred immediately and in a most reliable manner. Emergency handling is very critical in healthcare. And WBANs MAC should provide priority, based on traffic specifications [40].

2.4.2 Existing Wireless MAC Protocol Applicable for WBANs

Three categories of wireless MAC protocols which are applicable for WBANs [41][42]:

Fixed-assignment Protocols

In fixed-assignment proposals, the basic characteristic of communication resources such as time and frequency are allocated to nodes for data transmission. The allocated resources are fixed during packet transmission. Such class of protocols can reduce or eliminate collisions whilst requiring tight synchronisation via a centralised controller. Time Division

Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA) can be considered to be a part of this category of protocols. Among fixed-assignment protocols, TDMA is the best access technology for WBANs, where data transmission to and from the sensor nodes is performed in dedicated timeslots. This approach can completely avoid collision and reduce idle listening and overhearing issues. However, TDMA protocols have poor performance in terms of bandwidth utilisation as fixed-length timeslots are allocated to sensor nodes despite its traffic characteristics. Moreover, frequent synchronisation of the nodes causes severe energy wastage and scalability is not provided as changing frame length and timeslot assignment is not an easy task. FDMA and CDMA are not suitable to be used in WBANs due to hardware complexity in FDMA and high computational demands in CDMA.

Demand-assignment Protocols

In demand-assignment proposals, the transmission medium is allocated to transmitters for a short duration for instance a data burst. This category can be classified into centralised and distributed protocols. Polling protocol is an example of centralised protocols in this category where data transmission is coordinated through a central node. Although this protocol is scalable, it is not convenient for WBANs as it introduces a high level of signalling and energy wastages as well as requiring a complex central controller.

Random-assignment Protocols

In random access protocols, data is transmitted in a fully distributed mode. That is, no central coordinator is used; instead all the nodes coordinate their data transmission with each other instead. The nodes only gain access to the communication resources when they have actual data to send or receive. Therefore, these types of protocols are more suitable for bursty and non-periodic traffic. Some common random access protocols are ALOHA or slotted ALOHA (S-ALOHA), Carrier Sense Multiple Access (CSMA), and Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA).

The advantages of this class of protocols are their simplicity, scalability and freedom of synchronisation. However, they encounter heavy collision, idle listening and overhearing issues due to their out of order competition for medium access. Such issues have led to the introduction of a new MAC protocol which uses the combination of these protocols such as IEEE protocols.

Two IEEE standards applicable in WBANs and their related MAC protocols are presented in the next two sections.

2.5 IEEE 802.15.4 Standard

IEEE 802.15.4 [21] is considered a standard for Low Rate Wireless Personal Area Networks (LR-WPANs) to provide low-power, low-datarate, low-complex and low-cost wireless connection in the personal operating space (POS) of 10 meter of not specifically humans. Mentioning that restrained battery life, ease of implementation, reliable and relax throughput and affordable system while simultaneously maintaining protocols' simplicity and flexibility are the fundamental objectives to be achieved in such networks.

Specifications of the physical layer (PHY) and medium access control (MAC) sublayer are presented in IEEE 802.15.4 standard for seamless connectivity among fixed or portable even in motion sensor devices, typically, operating in comparatively short vicinity of the body of humans/nonhumans.

This standard defines several PHYs operating in a variety of frequency bands:

- 868–868.6 MHz (20 kbit/s)
- 902–928 MHz (40 kbit/s)
- 2400–2483.5 MHz (250 kbit/s)
- 314–316 MHz, 430–434 MHz, and 779–787 MHz in China
- 950–956 MHz in Japan

Regarding this standard, channel assignments are defined as follows; 16 channels are available in the 2450 MHz band, 10 in the 915 MHz band, 1 in the 868 MHz band, 22 channels across the 950 MHz band, and 8 channels across the 780 MHz band for data transmission.

2.5.1 Network Topologies

LR-WPAN systems adhering to this standard are composed of several constituents, at least one sensor device being the most basic as the WPAN coordinator and two or several sensor devices communicating on the same physical channel.

As illustrated in Figure 2.8, a WPAN operates either in the star topology or the peer-to-peer topology regrading to its application domain [43].

The star topology is direct communications between sensor nodes and a PAN coordinator without presenting any relay nodes as oppose to peer to peer topology, in which, the sensor nodes can communicate with the others if they are in range of each other.

Generally a sensor device can be either the commencement point or the termination node based on the nature of its associated applications. The central controller can be

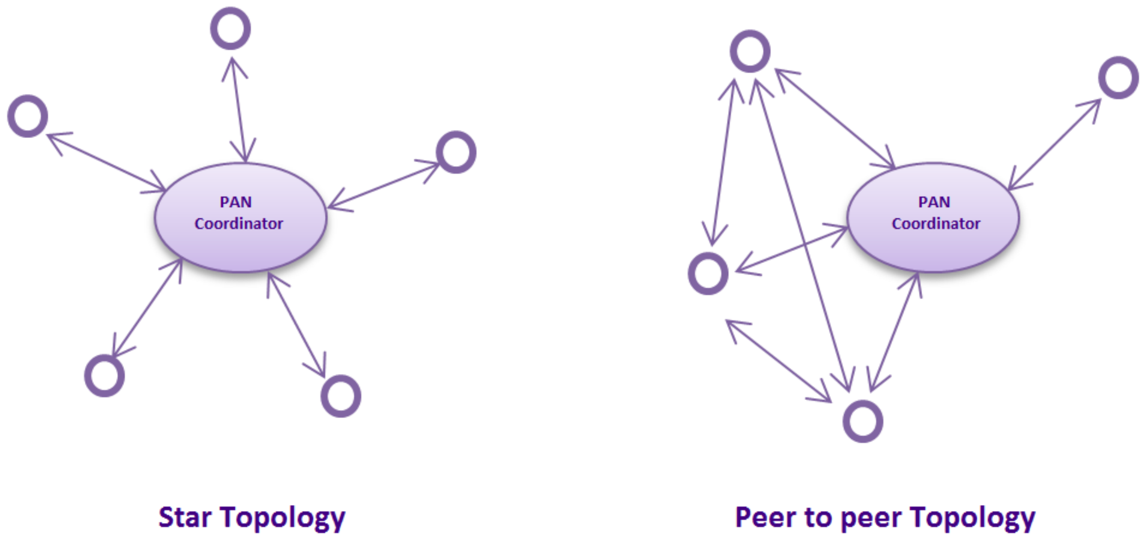

Figure 2.8: IEEE 802.15.4 Star and Peer-to-Peer Topology

employed as means of routing data communication over the whole network and, in fact, it is the primary controller of the WPAN. Although most devices in WPAN based on the power of the batteries, PAN coordinator has larger battery or is connected to the main power. As a consequence, personal healthcare, gaming, home automation and computer peripherals are the applications utilise star topology networks. However, a peer to peer topology is capable of implementing in more complex network, such as mesh networking topology.

2.5.2 IEEE 802.15.4 Architecture

The IEEE 802.15.4 architecture is determined in terms of the communication layers. Each layer takes charge of one part of the standard offering services to the higher layers.

Physical layer (PHY) comprises of the radio frequency transceiver and its control scheme, thus, at least one physical layer is included in a sensor device for WPAN. Some of the characteristics of the physical layer are activating the transmission radio selecting the physical channel, assessing the clear channel and communicating packets through the medium.

Nevertheless, access to the physical channel for all types of transmission and sharing the medium among network components are provided by a MAC sublayer. Some of the features of MAC sublayer are beacon management, medium access, guaranteed time slot (GTS) management, frame validation, acknowledged frame delivery, association, and disassociation. Although, there are no specifications for the upper layers, a network layer and application layer is defined in IEEE 802.15.4 standard, noteworthy, network configuration, data routing and manipulation are provided by network layer and application layer maintains the intended function of sensor nodes.

2.5.3 IEEE 802.15.4 MAC Protocol

This standard supports two different approaches for data transmission. Either using of a superframe structure in WPAN networks, in which a PAN coordinator bounds the channel by means of broadcasting beacons refers to beacon-enable mode or non-beacon mode, in which, no beacon is transmitted.

The structure of the superframe is specified by the coordinator and a superframe in a WPAN, optionally, can be divided to an active portion and an inactive portion, as illustrated in Figure 2.9 [1].

Beacon frames are broadcasted at the start of each superframe by the PAN coordinator. The beacons are utilised as a means of synchronisation of network components as well as the network and the superframe identification.

As defined in the standard, three parts are forming an active part, a beacon, a contention

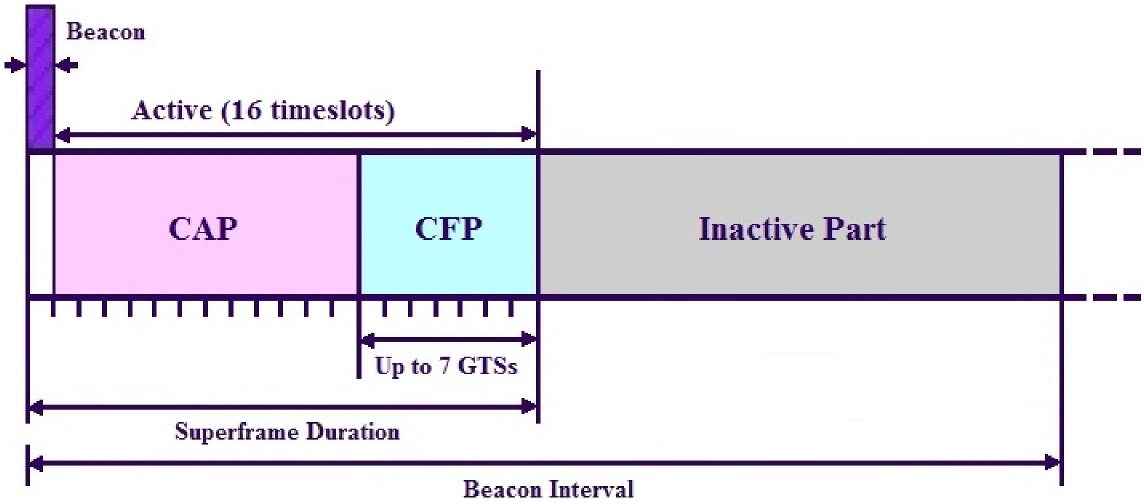

Figure 2.9: Superframe Structure of IEEE 802.15.4 MAC Protocol

access period (CAP) and a contention-free period (CFP). At the beginning of slot 0, the beacon frame is transmitted which is immediately follows by CAP interval and CFP interval respectively, in a presence of any CFP interval. In this case, any allocated GTSs are placed within the CFP till the end of the active part of the superframe. However no data is transmitted within inactive portion of the superframe, and due to extending the sensors' battery life, the sensors enter to a sleep mode during the inactive part [44].

IEEE 802.15.4 standard utilises either CSMA/CA or ALOHA protocols to allocate packets during the CAP interval during each superframe. Obviously, each sensor node contents with others nodes in the network using these protocols to get allocation in the physical medium for transmitting its data. While sensors communicate through dedicated time slots using TDMA protocol during CFP intervals.

Channel allocation either in CAP or CFP period is based on the application domain in each sensor devices which is determined by PAN coordinator depends on the priority of traffic and acceptable latency in an application or certain bandwidth requirement.

As defined in the standard maximum up to seven GTSs are dedicated to sensor nodes within CFP, although, each GTS can comprise of more than a time slot. This is because of the fact that, enough timeslot should remain in the CAP interval for contention access of other sensor devices or new sensors attempting to join the WPAN. Thus, there is minimum interval dedicated to the CAP as per the standard. Bear in mind that within the CAP in each superframe, all contention-based transmissions should be completed and frame transaction in a GTS should be done before commencing next GTS or ending the current CFP.

Contention Access Period (CAP)

A mentioned before the CAP period commences subsequent to the beacon frame in the active interval of the superframe boundary and extends till the end of it with the zero CFP length or ends at the beginning of the CFP period when any GTS dedicated in the system. Considering the standard, the least value for CAP is a *MinCAPLength*, that is, the minimum number of symbols forming the CAP which equals to 440 symbols.

The frames of MAC commands always delivered during the CAP interval. As a sensor device should complete its data transmission and get the relevant acknowledgement at least an Interframe spacing (IFS) interval before the end of the current CAP period, there should be enough time slots before the CAP finishes, otherwise, the packet waits till the start of CAP period in the next superframe ahead.

It is worth mentioning that, all types of data frames and MAC control frames convey during the CAP interval utilising slotted CSMA/CA scheme other than acknowledgement or any packet pursues the acknowledgement of a data request command.

Interframe spacing (IFS)

Interframe spacing is an interval required by MAC sublayer to process the collected frames from physical layer. The IFS is necessary among the two successful transmissions from a single node and among acknowledgement and following transmitting frame. However, the length of the IFS interval is related to the packet size of the previous data transaction. Based on IEEE 802.15.4 standard, the data frame size up to *MaxSIFSFrameSize* will be pursued by a short interfame space (SIFS) interval with a minimum *macSIFSPeriod* length, otherwise, followed by a long interfame spacing (LIFS) interval with a minimum *macLIFSPeriod* length.

The value of the *MaxSIFSFrameSize* and minimum LIFS and SIFS periods are specified in the standard for Narrowband PHY as follows:

- *MaxSIFSFrameSize* = 18 Bytes
- *MACLIFSPeriod* = 40 symbols
- *MACSIFSPeriod* = 12 symbols

Contention Free Period (CFP)

As mentioned earlier, the CFT interval is located in the active portion straight after the CAP contains the GTSs dedicated to certain nodes. The PAN coordinator assigns each GTS to sensor nodes within the CFP inhabiting continuous slots. Due to the 16 fixed slots of the superframe of IEEE 802.15.4, the length of CFP can vary depends of number of GTSs allocated in the system.

Accessing physical medium in CFP interval is conducted through TDMA method without any need for contention. However, the transmission during the CFP period should end at least an IFS interval prior to termination of its GTS.

2.5.4 Superframe Structure

The values of *MACBeaconOrder* (BO) and *MACSuperframeOrder* (SO) define the structure of IEEE 802.15.4 MAC superframe [45]. The BO defines the period beacons are transmitted. The value of *MACBeaconOrder* and the *BeaconInterval* (BI) are calculated as follows:

$$\text{BI} = \textit{BaseSuperframeDuration} \times 2^{BO}$$

$$\text{for } 0 \leq \text{BO} \leq 14 \text{ ,}$$

If BO equals to 15, no beacon is sent during the superframe, the exception being on receipt of a beacon request command. So, the value of SO is neglected whenever the value of BO is 15.

Furthermore, the value of SO reveals the duration of the active part in the superframe, consisting of the beacon frame. The value of SO, and the superframe duration are obtained based on the below equation:

$$\text{SD} = \textit{BaseSuperframeDuration} \times 2^{SO}$$

$$\text{for } 0 \leq \text{SO} \leq 14 \text{ [45]}$$

If SO equals to 15, just a beacon frame is transmitted during the superframe. In this case, no superframe is considered other than the beacon.

Any WPAN using beacon enable mechanism sets BO to a number between zero and 14 and relatively, SO to a number between zero to BO, both inclusive.

2.5.5 IEEE 802.15.4 Channel Access Mechanism

The MAC protocol takes on permitting access to the physical channel supporting the functions of WPAN association and disassociation, handling beacon transmission as well of system synchronisation, security and reliability and contention access and GTS access employment.

The methods in accessing the physical radio are presented in IEEE 802.15.4 standard, based on the network configuration, either ALOHA or CSMA- CA mechanism. In the beacon enabled method the slotted version is utilised while the unslotted ones are used in non-beacon method. Note that, only the CSMA/CA approach is considered and analysed in this research.

2.5.6 IEEE 802.15.4 CSMA/CA Mechanism

As an unslotted CSMA/CA channel access scheme is utilised in non-beacon method without superframes, before intending to transfer any data packet or MAC command, a sensor delays the transmission for a predefined random duration. The sensor node starts transmission whenever the channel becomes idle, immediately after the random backoff units. Otherwise, if it finds the busy channel after the backup, delays the transmission for another random period before attempting to access the channel repeatedly. Noting that, there is no need to use a CSMA/CA access to send acknowledgement and beacon.

On the other hand, in beacon broadcasting method, using slotted CSMA/CA access scheme, the backoff intervals of all nodes are aligned with the superframe slot boundaries of the PAN coordinator. As a result, the start of the first backoff period of each device is regulated with the beginning of the beacon frames to the PAN controller. In fact, the

MAC sublayer in beacon broadcasting mode guarantees that the physical layer starts all transactions on the boundary of a backoff interval.

Whenever a sensor intends to send data within the CAP period, does detecting the boundary of the coming backoff slots, delays the transmission for accidental times of backoff slots. If the channel is found to be idle, data transaction starts on the coming backoff period boundary. However, given that the channel was busy, pursuing previous backoff, awaits for random backoff units before intending to access the channel again.

2.5.7 IEEE 802.15.4 CSMA/CA Algorithm

As already described, earlier than the transmission of data packet and MAC frames only during the CAP interval, the CSMA/CA algorithm should be employed. Noteworthy, this algorithm is not utilised in sending beacons, acknowledgement frames, or even packets during the CFP period.

Within use of regular beacons in the superframes, the slotted CSMA/CA access method is considered by means of a MAC sublayer or unslotted one in non-beacon case. However, it should be borne in mind that, in either method, the algorithm is carried out by means of some time slots known as backoff intervals, equal to *UnitBackoffPeriod*, which is defined to be 20 symbols in the standard.

Number of Backoff (NB), (Contention window) CW, and (Backoff exponent) BE are the elements should be implemented before trying to send any data in the physical medium.

NB counts the times the algorithm needs to backoff in the existing effort for getting the channel access. After the completion of the successful transmission or failure the value of NB is reset to zero for further attempt.

CW counts the number of backoff intervals, the algorithm should find the idle medium before begin to send packets. Again, the value of CW is reset to CW0 earlier to try to send data and failure due to busy channel. Noteworthy, the contention window is only considered to be utilise for slotted CSMA/CA.

BE counts the number of backoff intervals a device delays to begin the transmission. The value of BE is reset to *macMinBE*. Note that, in a case *macMinBE* value is zero, collision will be unavoidable during the first iteration of CSMA/CA algorithm.

The value of *macMinBE* and *macMaxBE* are defined in the standard as:

$$macMinBE = 3, macMaxBE = 5$$

While the CSMA/CA algorithm is assessing clear channel assessment (CCA) mechanism, the sensor nodes do not process any new data frame although their radio is active.

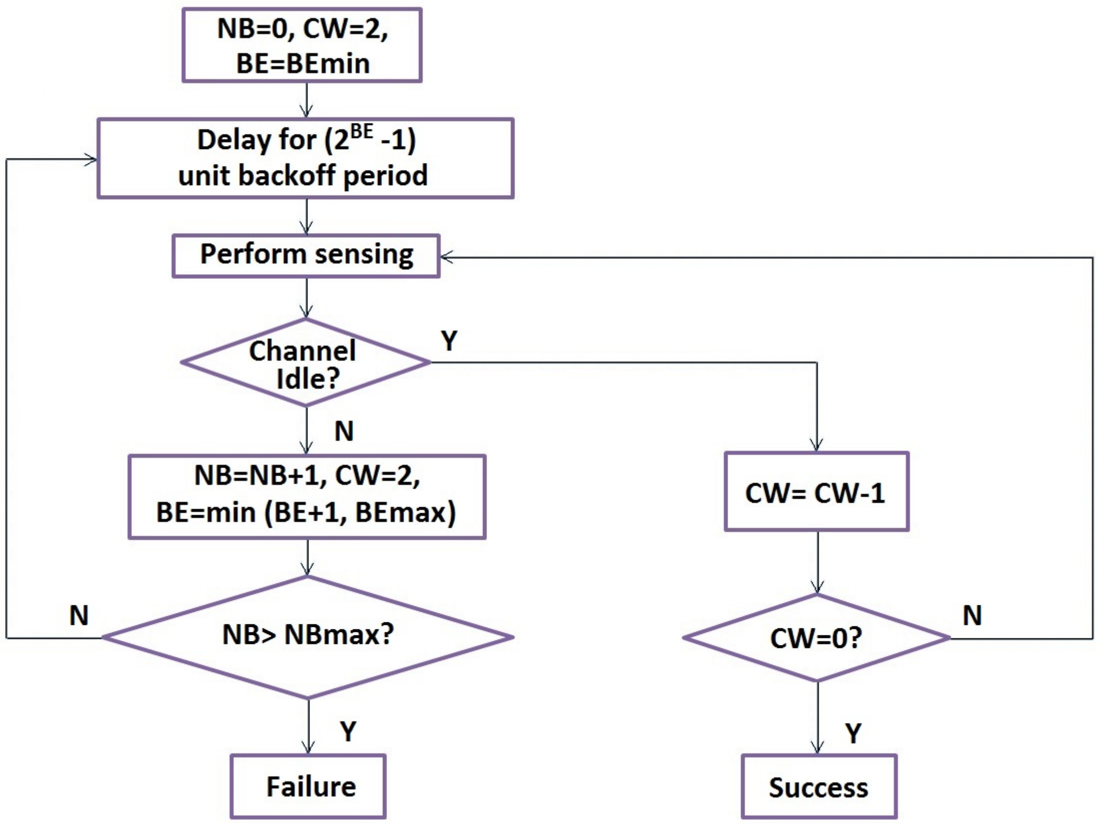

Figure 2.10: IEEE 802.15.4 CSMA/CA Algorithm

Figure 2.10 reveals each stage of the CSMA/CA algorithm. In a condition CSMA/CA algorithm gets success, MAC protocol allows the communication. In the other case with failure the MAC terminates the channel access.

MAC protocol manages the transmission mechanism using CSMA/CA algorithm to ensure that there is enough space remains in the superframe for delivering slots related to the algorithm and the data itself within the CAP period. In this regard, in a condition that the backoff slots is larger than the remaining number of backoff periods during contention access phase, MAC protocol stops the counter of backoff countdown and continue it during the coming CAP interval.

Reversely, in a case the number of backoff slots is same as or smaller than the remaining number of backoff periods contention access phase, MAC protocol employs the backoff waiting and afterward check the check whether it can proceed.

In fact, MAC protocol can proceed in a case all the CSMA/CA mechanism slots including the number of CW for idle channel assessment plus the traffic slots and its acknowledgement frames can be proceed within the current CAP phase. Otherwise, the protocol do not allows the CCA procedure by physical layer and delays it till the beginning of the next CAP interval with the further random backoff before examining the availability again [46].

2.6 IEEE 802.15.6 Standard

The cutting edge standard for WBANs, IEEE 802.15.6, endeavours to offer an international standard for low power, low to medium rate, low cost, short range about 2 to 5 meter (in human tissue area), and intensively reliable wireless connectivity to be used in an immediate distance from, or inside body of humans/non-humans.

Stringent QoS maintaining, extreme reliability, power efficiency, datarates from a few Kbps in narrowband and up to 10 Mbps in ultra wideband as well as complying with severe non-interference procedure can be given to meet the regulations of such networks to be broadly utilised in both medical and non-medical services.

Low power communication in this standard paves the way for sensor devices in order to save energy, span the life of their limited battery power and more importantly reduce the specific absorption rate (SAR) into the body for safety purposes.

The standard utilises frequency bands of unlicensed Industrial Scientific Medical (ISM) as well as the supported frequency spectrum by the national medical or regulatory authorities such as the licensed Wireless Medical Telemetry Services (WMTS) spectrum and Medical Implant Communications Service (MICS) frequency band for transmitting information through wireless network. Among these frequency bands, WMTS is the preferable band by The Federal Communication Commission (FCC) for medical applications considering less interfering possibilities with other wireless technologies.

As present short range wireless networks even personal area network system cannot appease the simultaneous medical and entrainment or consumer electronic application domains, the IEEE 802.15.6 standard aims to provide an aggregate solution to meet the demands of such networks and support the diverse requirements considering variety of application environments.

2.6.1 IEEE 802.15.6 Network Topology

The standard of IEEE 802.15.6, considering network topology, accepts one-hop star topology as well as two-hop star networks, both with only one hub in the system, as demonstrated in figure 2.11.

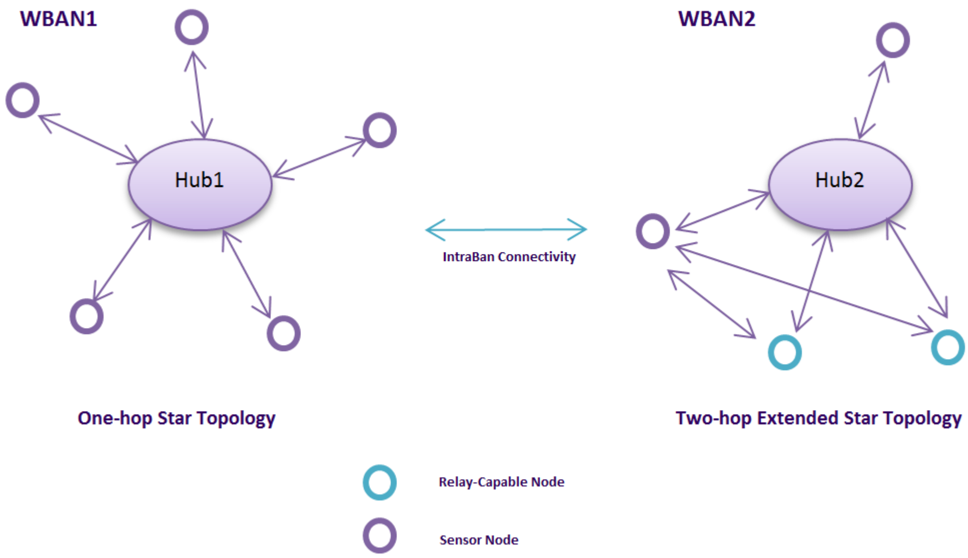

Figure 2.11: IEEE 802.15.6 Network topology

A hub or central controller performs the coordination on the respective nodes as a means of accessing physical channel and managing the transmit power. In a one-hop star WBAN, data frame transmissions are supposed to take place directly between nodes and the hub. However, given a two-hop extended star WBAN, the hub and a node can exchange data packets using optional relay nodes.

One hub would suffice in a WBAN, whereas the number of nodes can vary up to *MaxBANSize*; which is defined to be 64 in the IEEE 802.15.6 standard due to limitations in transmission strategy.

This standard specifies that straight connection between a single sensor node and a hub take place at the PHY layer and MAC sub-layer. It is worth to note that only one operating channel at any given time is to be utilised by the PHY layer and MAC sub-layer of a hub or sensor devices.

2.6.2 IEEE 802.15.6 Access and Allocation Classifications

A sensor device or the coordinator gains one or more time intervals (allocation) utilising an access scheme in order to start off transmissions [28]. Different types of allocation and access methods are specified in this standard and definition of them are as follows:

Contended Allocation

Utilising random access, contended allocation is considered as uplink non-reoccurring time intervals that a sensor device gains within RAP or CAP period, based on CSMA/CA or slotted Aloha method, in order to start off transmissions. It can be proper for assigning uplink unpredictable frames.

Bilink Allocation

Bilink allocation is considered as time intervals the coordinator or a sensor device starts transmissions to covey data and management traffic to a sensor device or the coordinator, correspondingly. Optionally there would be an acknowledgement frame in a response. It is worth mentioning that in such allocation, only after receiving a polling message from the central controller, a sensor device can start off a transmission.

Unscheduled Bilink Allocation

Utilising unscheduled access, unscheduled bilink allocation is considered as reoccurring time intervals that a sensor device or the coordinator gains for starting off transmissions, based on aggregate best effort scheduling and polling scheme. It is a bilink allocation on a best effort basis which is proper for assigning uplink/downlink periodic (low or high duty-cycle) or quasi periodic frames.

Scheduled Allocation

Utilising scheduled access, scheduled allocation is considered as reoccurring time intervals that a sensor device or the coordinator gains for starting off transmissions, based on advance reservation and committed scheduled scheme. It can be an uplink/downlink or a bilink allocation, which is proper for assigning uplink/downlink periodic (low or high duty-cycle) or quasi periodic frames.

Polled Allocation

Utilising polling access, polled allocation is considered as uplink non-reoccurring time intervals which are assigned to sensor nodes by the central controller, based on impromptu or scheduled polling scheme, for starting off transmissions by sensor nodes. It can be proper for assigning uplink ordinary, unexpected or extra frames.

Posted Allocation

Utilising posting access, posted allocation is considered as downlink non-reoccurring time intervals that the coordinator assigns to itself, based on impromptu or scheduled posting scheme, for starting off transmissions by the central controller. It can be proper for assigning downlink unexpected or extra packets.

Type-I polled Allocation

The breadth of a polled allocation which is defined with regards to the time intervals admitted for frame transaction.

Type-II polled Allocation

The breadth of a polled allocation which is defined with regards to the number of frames admitted for transaction.

2.6.3 IEEE 802.15.6 MAC Protocol

Given the medium access is to be time scheduled, the central coordinator and the entire corresponding sensor nodes are supposed to support time reference based allocation intervals where the time axis is splitted into superframe boundaries without considering beacon frames transmissions during beacon periods.

The IEEE 802.15.6 standard supports three different approaches for data transmission as follows.

- Beacon mode with superframes
- Non-beacon mode with superframes
- Non-beacon mode without superframes.

In superframed beacon enabled access method, exception being in inactive superframes, the coordinator sends regular beacon frames in each beacon interval in order to provide timely based allocations in its WBAN. In superframed non-beacon enabled access method, no beacon frames is sent during beacon period boundries. In non-superframed access method without beacon, no timely based allocation is provided in the channel.

In the other words, to be able to provide time referenced allocation, a WBAN operates either in beacon mode and beacon frames is broadcasted in superframe boundaries apart from inactive superframes or in superframed non-beacon mode, without implementing beacon frames. In a case the system does not operate on timely basis, without superframes and allocation slots, no beacon frame is broadcasting while channel allocation in its WBAN is assigned without time referencing.

Beacon Mode with Beacon Periods (Superframes)

In this mode, regarding each active superframe, a dedicated access phases is assigned by the central coordinator as illustrated in Figure 2.12 [5].

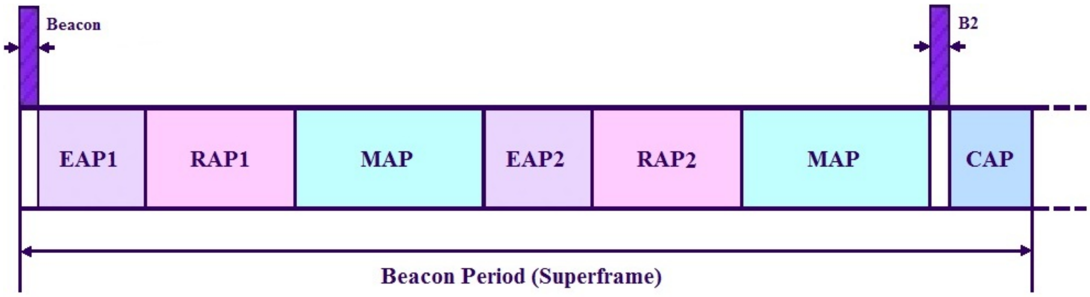

Figure 2.12: Layout of IEEE 802.15.6 Access Phases in a Beacon Period (Superframe) for the Beacon Mode

Given that there is no allocation and data transmission is performed in inactive superframes, an integer number of inactive beacon period can be scheduled by the central controller following each active one.

Stated above, exclusive access phase 1 (EAP1), random access phase 1 (RAP1), managed access phase (MAP), exclusive access phase 2 (EAP2), random access phase 2 (RAP2), another managed access phase (MAP), and contention access phase (CAP) are placed in the active superframe.

Exception being the RAP1, all the above access phases can have the length of zero during corresponding beacon period as defined in the standard. Note that, a preceding B2 frame is transmitted by the coordinator, in a presence of any CAP access phase in relevant superframe. The access methods during EAP1, RAP1, EAP2, RAP2, and CAP are either

CSMA/CA or slotted Aloha based random, for setting up any frame exchange in any active beacon interval.

The following allocation intervals can be implemented only in MAP access phase by use of the coordinator:

- Scheduled uplink allocation intervals, scheduled downlink allocation intervals, and scheduled bilink allocation intervals
- Unscheduled bilink allocation intervals
- Type-I, but not type-II, immediate polled allocation intervals and posted allocation intervals initiating in this MAP as well as future polls or posts starting and ending in the MAP.
- Non-Beacon Mode with Superframes

Non-Beacon Mode with Superframes

Only a MAP access phase can be implemented in any superframe regarding this mode, as illustrated in Figure 2.13 [5].

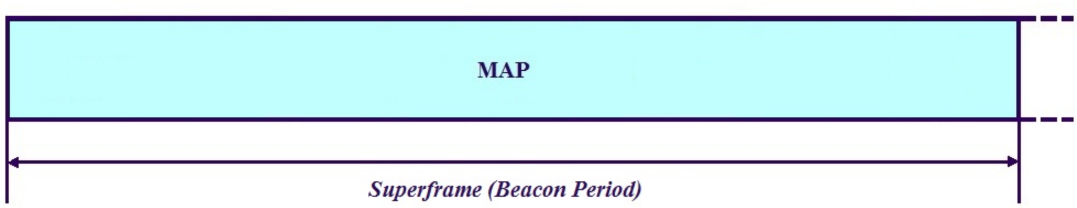

Figure 2.13: Layout of IEEE 802.15.6 Access Phases in a Superframe (Beacon Period) for Non-Beacon Mode

Non-Beacon Mode without Superframes

Unscheduled bilink allocation, type-II polled/posted allocations are implemented by use of the coordinator regarding this mode. Subject to this method, the central controller initiates frame transactions by considering the medium as a part of the EAP1 or RAP1 access phases and thus utilising random access allocation, performs the data exchange.

2.6.4 IEEE 802.15.6 Channel Access Mechanism

Only contented allocations are employed during the EAP1, RAP1, EAP2, RAP2, and CAP intervals by utilising random access method which is either CSMA/CA or slotted Aloha access mechanisms based on the IEEE 802.15.6 standard.

Urgency type data transaction of the highest user priority is performed by the coordinator or sensor nodes, obtaining contended allocations in either EAP1 or EAP2 access intervals. The hub gets such a contended allocation with a pSIFS (75 µs in narrowband PHY) delay after the start of these access phases without implementing random access procedure. Only sensor nodes can get contended allocations during RAP1, RAP2, and CAP intervals in order to carry on other user priorities' management or data transaction.

Based on IEEE 802.15.6 standard, the coordinator broadcasts beacons to perform synchronisation and determine the specification of the length and beginning and ending of EAP1, RAP1, EAP2, or RAP2 access phases in beacon mode with superframe boundaries. Upon receiving a beacon in any superframe, contended allocations can be implemented in the relevant access phases.

In a case of transmitting highest user priority data frames by utilising CSMA/CA access method, the EAP1 and RAP1 access phases can be combined into a single unified EAP1, the EAP2 and RAP2 access phases can be combined into a single unified EAP2 to obtain continuous allocation and enhance the bandwidth utilisation. However, in transmitting by means of slotted Aloha access method, the RAP1 can consider as another EAP1, and RAP2 as another separate EAP2 but not combined or continuing access phase.

In order to support prioritised method for data transmission of differing user priorities (UPs), Table 2.2 illustrates the relevance between maximum and minimum contention windows (CW) in the CSMA/CA access scheme, maximum and minimum contention probability (CP) for slotted Aloha access. However, only the CSMA/CA approach is considered in this research.

UP	Traffic Designation	CWmin	CWmax	CPmin	CPmax
0	Background (BK)	16	64	1/8	1/16
1	Best Effort (BE)	16	32	1/8	3/32
2	Excellent Effort (EE)	8	32	1/4	3/32
3	Controlled Load (CL)	8	16	1/4	1/8
4	Video (VI)	4	16	3/8	1/8
5	Voice (VO)	4	8	3/8	3/16
6	Media Data or Network Control	2	8	1/2	3/16
7	Emergency or Medical Report	1	4	1	1/4

Table 2.2: Contention Window Bounds for CSMA/CA (WBAN User Priority Mapping)

2.6.5 IEEE 802.15.6 CSMA/CA Mechanism

Using the CSMA/CA access mechanism, a contented allocation can be implemented by means of a backoff counter and a contention window. However, the minimum and maximum values are defined for contention window in the standard.

Employing CSMA/CA method [47], the backoff counter is setup to zero at the initialisation. To perform a contended allocation anytime the sensor node has at least one frame to exchange, the backoff counter is changed from zero to any random integer value which is spread over [1, CW] gap. However the contention window can get different values based on network transmission status in and determines based on what is specified in the standard.

The sensor node sets the contention window to CWmin for relevant user priority, in the case of no contented allocation previously or gaining expected acknowledgement frame for its last transaction. However, if there is not a need for receiving acknowledgement frame, the sensor node does not change the value of contention window.

In the failure of a frame transmission or not obtaining the acknowledgement to the last, the sensor node doubles the contention window for even numbers of consecutive failure or keeps it unchanged for odd numbers of failure. In a case of exceeding the maximum value of contention window for relevant user priority by doubling, the sensor node picks the value of CWmax for each user priority.

2.6.6 IEEE 802.15.6 CSMA/CA Algorithm

Employing prioritised CSMA/CA access method, a sensor node sets up the backoff counter to zero. For initiating a frame transmission, the backoff counter gains any random integer between one and the value of contention window and starts decrementing concerning each idle CSMA slot that follows. By approaching the value of backoff counter to zero during the present CSMA slot, the contented allocation will be assigned at the end of the present CSMA slot and can be spread at or by the end of the present RAP or CAP access phases. The structure of CSMA slot is presented in Figure 2.14.

The length of IEEE 802.15.6 CSMA slot is a fixed period of *pCSMASlotLength* specified as follows:

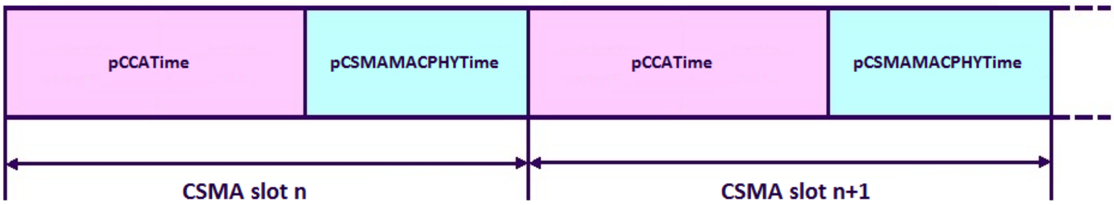

Figure 2.14: IEEE 802.15.6 CSMA Slot Structure

$$pCSMASlotLength = pCCATime + pCSMAMACPHYTime$$

Where *pCSMAMACPHYTime* is 40 μs and *pCCATime* is determined to be 63/symbol rate in narrowband PHY.

Based on the standard, a CSMA slot can be considered idle for detecting an idle physical medium during the start of CSMA slot plus the length of *pCCATime*. Upon unlocking the backoff counter, the decrementing is started for each idle CSMA slot.

Sensor nodes maintain locking and unlocking and decrementing their backoff counter to obtain the contended allocation for frame exchange. The backoff counter is locked given to any of the later circumstances:

- Upon the cutback to value of zero, the sensor node resets the backoff counter.
- Whenever a sensor node notices the transmission and busy medium, it would consider busy till the end of its transaction with no need for channel re-sensing.
- Whenever a sensor node notices the transmission is not during the EAP, RAP, or CAP interval for highest user priority (UP7) or is not during RAP or CAP for the other user priorities (UP<7).
- Whenever a sensor node notices there is not enough interval remains for frame

transaction by end of the current CSMA slot and the end of the EAP, RAP, or CAP periods.

The backoff counter can be unlocked given that both later conditions are guaranteed:

- Having idle transmission channel for the length of *pSIFS* during the EAP, RAP, or CAP for highest user priority (UP7)or during the RAP or CAP access intervals for the other user priorities (UP<7).
- Having enough time intervals within the present access phase either EAP, Rap or CAP phases for entire frame exchange moreover a CSMA slot.

2.7 WSNs MAC Protocol Applicable in WBANs

In this section, some WSNs specific MAC protocols which can be used in WBANs are presented in details. The advantages and disadvantage s of utilising these protocols in WBANs are provided as well.

2.7.1 Sensor MAC S-MAC Protocol

Sensor MAC (S-MAC) [48] is a scheduled-contention MAC protocol aims to improve energy efficiency by means of reducing idle listening, collision and overhearing while providing scalability. S-MAC adopts a synchronised duty cycle schedule to cut the energy waste during idle listening. The timing structure of the protocol consists of periodic fixed-length active and sleep intervals. A single active interval and sleep interval forms a S-MAC frame, in which, the nodes exchange data in active periods and turn off their transmitter during sleep periods to save energy. The structure of S-MAC protocol is revealed in figure 2.15 [48].

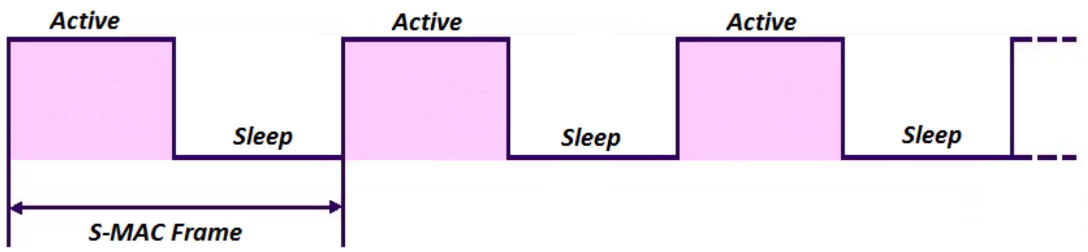

Figure 2.15: S-MAC Protocol Structure

The length of active and sleep interval is decided based on the requirement of the application in the network. The active portion is further splitted into synchronisation part and data communication part. The MAC structure of a sender and receiver communication is shown in figure 2.16 [48].

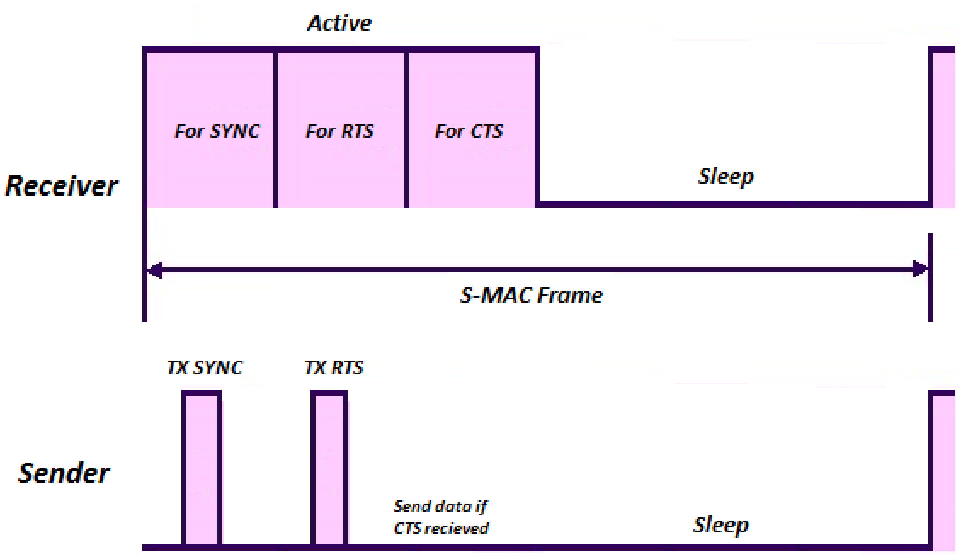

Figure 2.16: S-MAC Sender Receiver Communication

The nodes receive SYNC packet within the synchronisation part that contains sensor address, clock alignment and sleep schedule information. If the sensor cannot receive the SYNC packet, it may set its own sleep schedule. The access mechanism within each active part is based on CSMA/CA approach which uses RTS (Request to send)/CTS (Clear to send) technique to avoid collision. The exception is in broadcast messages which are transmitted without using the RTS/CTS method. For solving the overhearing problem, whenever a node finds a medium busy, goes back to sleep and sets the timer for a value of Network Allocation Vector (NAV) to wake up and sense the medium again. In this protocol the long data packets is divided to small messages and transmitted in burst, which increases the delay as each burst packet needs to have separate RTC/CTS procedure.

Comparing with TDMA access scheme, S-MAC utilises medium efficiently and consumes less energy because TDMA protocol has small timeslots and duty cycle while S-MAC has broader duty cycle and requires more relaxed synchronisation. Furthermore, utilising CSMA/CA mechanism for data transmission, S-MAC protocol supports scalability for the expense of longer delay compared to TDMA scheme. The S-MAC protocol trades off energy consumption for throughput and latency [49].

Because of fix-length duty-cycle of this protocol, the sensor nodes remain awake even after the completion of transmissions, thus, waste energy. Besides, the synchronisation is an extra overhead.

Considering utilising in WBANs, S-MAC does not meet the QoS requirements of these networks. It is not energy efficient as some nodes do not need to wake up regularly and exchange data. Latency is not acceptable in real-time monitoring in medical applications. It does not support priority or critical data delivery.

2.7.2 Timeout MAC T-MAC Protocol

Time-out MAC (T-MAC) [50] is a scheduled-contention MAC protocol that improves S-MAC protocol by means of the adaptive duty cycle. T-MAC maintains the dynamic active periods according to the applications and traffic demands. Same as in S-MAC protocol, a frame in T-MAC is divided to an active part and an inactive part and aggregated frames form the MAC structure with different size active and sleep intervals.

In T-MAC protocol, the node goes to the sleep mode after being idle for the duration of adaptive timeout (TA). The value of TA should be large enough to receive the beginning of the CTS packet. As a consequence, TA interval is greater than sum of the length of contention interval, the length of the RTS packet and the interval between the end of the RTS packet and start of the CTS packet [51]. Figure 2.17 [50] determines the differences between S-MAC and T-MAC protocol.

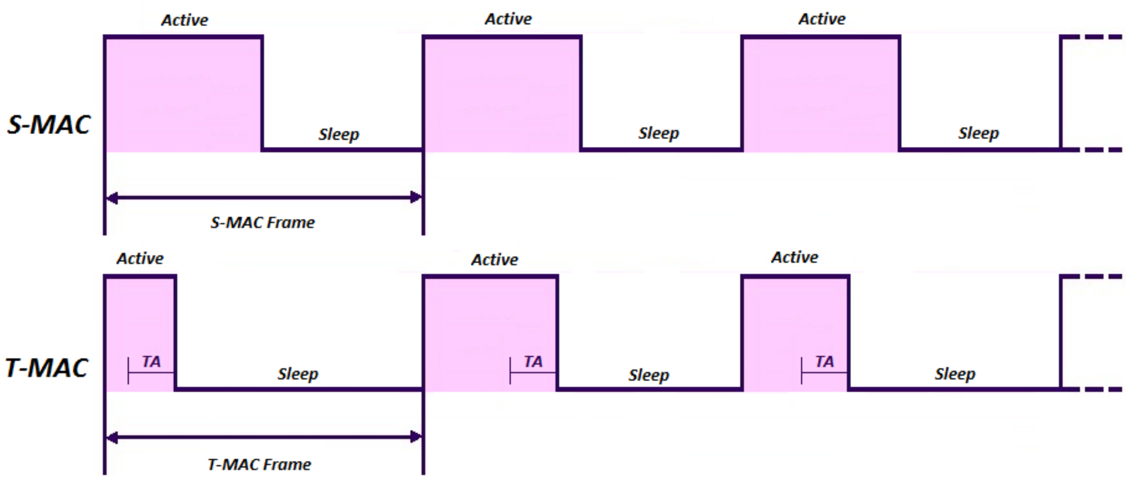

Figure 2.17: The Frame Structure of S-MAC & T-MAC Protocols

T-MAC improve the network performance compared to S-MAC considering energy efficacy and latency. However, synchronisation is still an overhead consumes extra power. Considering using in WBANs, even though the T-MAC protocol is adaptive and scalable, it is not suitable approach as does not support throughput, delay and energy requirements of these networks. Besides, no mechanism is available for emergency and priority handling.

2.7.3 Berkley MAC B-MAC Protocol

The Berkley MAC (B-MAC) protocol is a low power listening (LPL) MAC protocol proposed in [52] to achieve efficient channel utilisation. This protocol aims to reduce the power consumption with efficient channel utilisation and collision avoidance. The superframe structure of this prortocl is provided in Figure 2.18 [52].

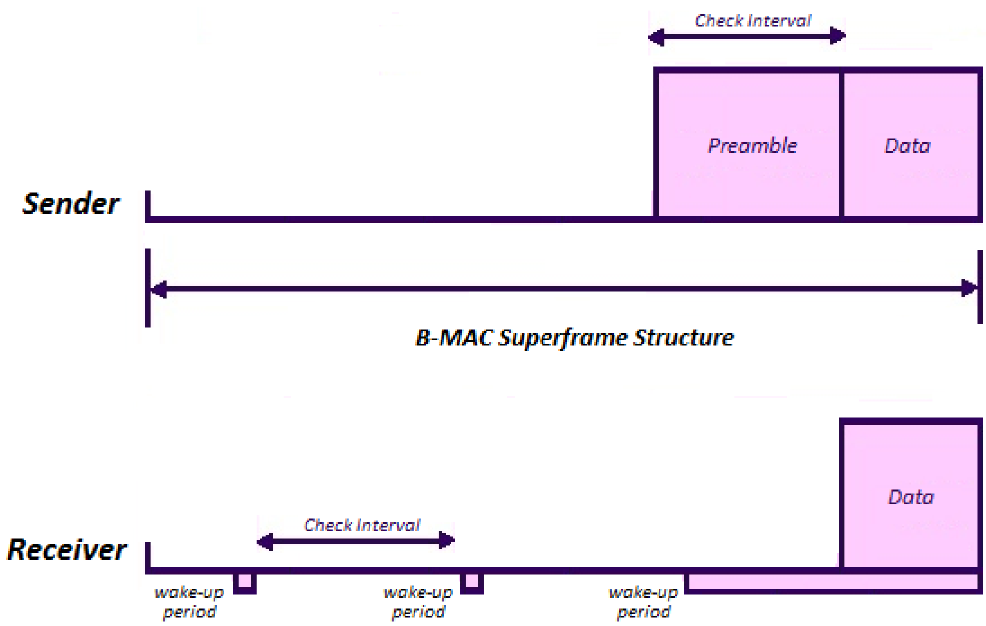

Figure 2.18: Superframe Structure of B-MAC Protocol

In LPL mechanism, the preamble sampling technique as well as the channel polling is utilised to reduce the wastage of energy during idle listening. The sender transmits a preamble just before data traffic to inform nodes to stay awake to receive the packet. The sensor nodes listen to the medium regularly regardless of synchronisation. If the medium is busy, they continue listening to receive data otherwise they go back to sleep.

B-MAC protocol samples the medium at the fixed time intervals and the preamble with greater than a sampling period is added to every data frame. The best result for B-MAC protocol is achieved when the channel is idle [53].

B-MAC protocol performs well for periodic traffic or when the data traffic is high but it does not handle emergency situation nor not provide any priority for traffic. Considering using in WBANs, it is not efficient for low datarate applications specifically in-body biosensors. Although it is scalable but it does not adoptive to the traffic changes because of it fixed sampling intervals and preamble size.

2.7.4 Wise-MAC Protocol

Wise-MAC [54] is another power-efficient MAC protocol uses LPL mechanism and non-persistent CSMA protocol for resource allocation. This protocol aims to reduce the preamble size and as a result reduce the wake-up period and the throughput limitation.

Regular sampling of the channel activity, the channel polling, is implemented for each node receiver. However, at the sender side, the protocol starts with a default preamble size but minimise the size of the preamble for upcoming frames based on the interval between communications and the timing frequency. Consequently, Wise-MAC protocol is adaptive to data traffic and the preamble size becomes smaller in a high traffic condition and the packet overhead is reduced by increasing in data traffic [55].

Compared to B-MAC protocol Wise-MAC is more energy efficient to use in WBANs but it still suffers to prioritise the traffic nor reliable in an emergency situation. However, this protocol is scalable and adaptive to the data traffic.

2.8 Review of MAC Protocols for WBANs

2.8.1 IEEE 802.15.4 MAC protocol

The complete description of IEEE 802.15.4 MAC protocol is provided in section 2.5. As per standard [4], multiple physical layers with variety of frequency bands are used in IEEE 802.15.4 protocol which assigns 16 channels in 2.4GHz, 10 channels in 915MHz, 22 in 950MHz, 8 in 780MHzand one channel in 868MHz. Spreading parameters as well as data parameters of aforementioned frequency bands are presented in Table 2.3.

PHY (MHz)	Frequency Band (MHz)	Channels	Spreading Parameters		Data Parameters		
			Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
780	779-787	8	1000	MPSK	250	62.5	16-ary orthogonal
868	868–868.6	1	300	BPSK	20	20	Binary
915	902–928	10	600	BPSK	40	40	Binary
950	950–956	22	300	BPSK	20	20	Binary
2450	2400–2483.5	15	2000	OQPSK	250	62.5	16-ary orthogonal

Table 2.3: Spreading Parameters and Data Parameters of IEEE 802.15.4 Frequency Bands

The beacon enabled method of the IEEE 802.15.4 with superframe boundaries are widely utilised in the application related to WBANs in the recent years. Providing low rate, low power and inexpensive seamless connectivity in an approximate 10 meters of the humans are the features make it possible to capture the attention of researchers to analyse these networks in both medical and on- medical applications in WBANs. The most important features of this protocol is hybrid superframe structure which provides both contention access and dedicated slots access through the same superframe and can be used in handling emergency data as it is critical in medical applications [56].

As discussed earlier, the typical superframe structure of an IEEE 802.15.4 protocol is composed of 2 portions, active portion and inactive one. The whole network is coordinated by central controller which sends regular beacons for synchronisation, providing information about current superframe and association control. Theoretically, three functional parts have made the active period, the beacon, the CAP period and the CFP interval. Beacon is the part dedicated for transferring the beacon frames to deliver the information regarding current superframe and for synchronisation purposes. The CAP interval is for sending data traffic and MAC commands frames. Note that, the acknowledgement frame and traffic do not compete for an access through the CAP. Based on the IEEE 802.15.4 standard, although the whole superframe is divided to 16 equal length timeslots, up to seven time slots can be allocated for dedicated transmission in the CFP part called guaranteed time slots, GTSs. However, each GTS can have more than a slot length depending on the application requirement. The superframe length and active interval length are calculated as follows:

Beacon Interval = *BaseSuperframeDuration* × $2^{macBeaconOrder}$

Superframe Duration = *BaseSuperframeDuration* × $2^{macSuperframeOrder}$

While $0 \leq$ *macSuperframeOrde*r $\leq$ *macBeaconOrder* ≤ 14

Since the length of *BaseSlotDuration* is specified as 60 symbols in the standard and the constant 16 timeslots are defined per each superframe, *BaseSuperframeDuration* is:

BaseSuperframeDuration= 16 × *BaseSlotDuration* = 960 symbols

Whereas, the symbol rate is defined as 62.5 ksymbol/s in 2.4 GHz frequency spectrum, as a consequence the symbol period is 16 µs. Thus, the length of *BaseSuperframeDuration* is calculated as:

$$BaseSuperframeDuration = 960 \text{ symbols} = 960 \times 16\ \mu s = 15.36\ s$$

The issues regarding the IEEE 802.15.4 are mentioned in literature. Scalability problem is the one which is not supported by this protocol. During the communication process, based on the network's plan and configuration, there is a need for adding or removing some sensors. The overall performance of the system is decreased by increasing the number of nodes.

Even though there are 7 GTSs for emergency situation handling, the protocol does not provide priority allocation to the traffic. Although the fixed number of timeslots is another challenge in data transmission. In addition, the IEEE 802.15.4 MAC protocol does not support high datarate applications [57].

2.8.2 IEEE 802.15.6 MAC Protocol

Details regarding the standard [5] and the algorithm of IEEE 802.15.6 are provided in section 2.6. Because of the unique and strict requirements of WBANs, a new protocol was required to help address the challenges in such networks. In this regard, the task group 6 of IEEE 802.15 in November 2007 published a standard specifically to be used in wireless body area networks and provided the detailed specifications of MAC and PHY protocols to be used in both medical and non-medical consumer electronic applications.

As previously mentioned WBANs use ISM, WMTS, MICS and UWB bands for data communication. While licenced 402-405 MHz MICS band is assigned to implanted data transmission, other types of medical applications use unlicensed 2400 MHz ISM band. However, unlicensed ISM bandwidth is employed by other short range wireless networks such as Zigbee, Bluetooth and WiFi, the interference is highly possible. Whereas, WMTS band is a licenced frequency band and can be utilised by authorised physicians and trained technicians. Yet, high datarate application such as video and voice data cannot be supported by restricted 14MHz WMTS band [58].

Same as IEEE 802.15.4, superframe boundaries structure with broadcasting beacons is preferable. In Figure 2.19 the superframe structure of both IEEE 802.15.4 MAC protocol and IEEE 802.15.6 MAC protocol are depicted.

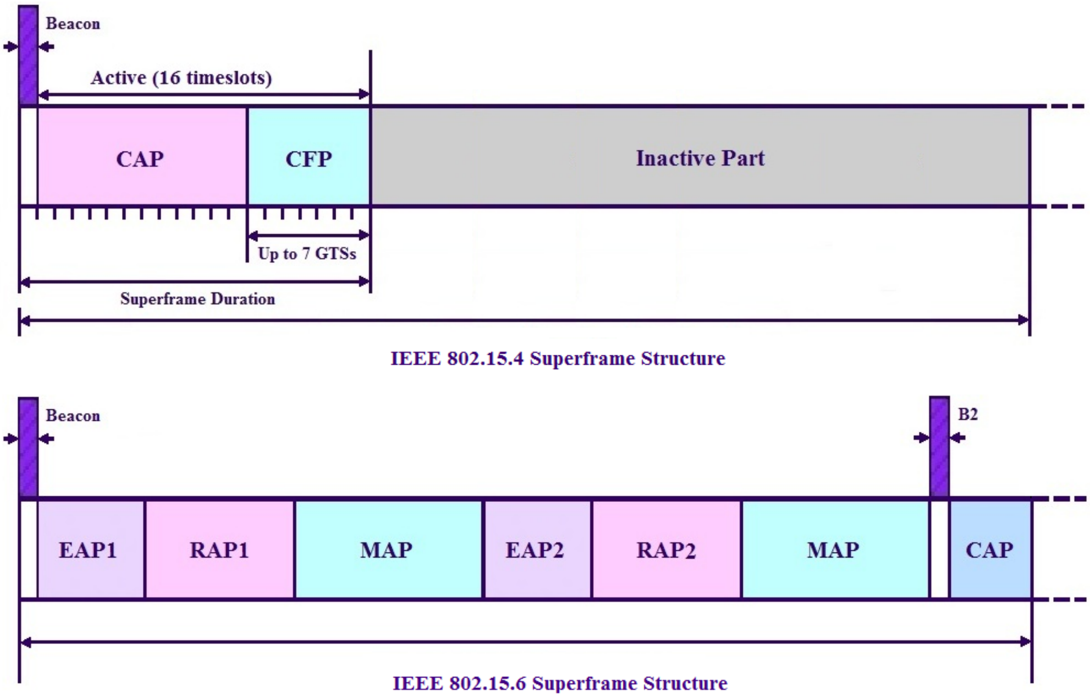

Figure 2.19: Superframe Structure of IEEE 802.15.4 MAC and IEEE 802.15.6 MAC Protocols

As shown in the picture and mentioned before, the superframe structure is divided to different functional access phases. Among these access phases the EAP1 and EAP2 is dedicated for the transmission of highest user priority traffic, although all other traffic are transmitting during RAP1, RAP2 and CAP intervals. Despite that beacon frames are broadcasting at the beginning of the superframe in both protocols, B2 is an indicator which represents the existence of CAP phase during the current superframe. MAP is for blink uplink and downlink transactions.

Mentioning that, the key feature of IEEE 802.15.6 protocols are priority and emergency handling [59]. As described before, the protocol supports 8 user priorities based on the traffic type it carries along physical channel either in uplink or downlink transmissions. In this respect, the highest user priority, UP7, is assigned to medical applications. Due to high sensitivity of the clinical application, the structure of its superframe made it possible to provide access phases specifically for highest user priority traffic.

Moreover, by implementing special algorithm of IEEE 802.15.6 CSMA/CA and utilising lowest contention window for UP7, the access precedence is doubled.

The standard of IEEE 802.15.6 is not finalised yet and there are issues and challenges in providing the QoS requirements of WBANs which have extensively reviewed by researchers all around the world and in this research some of the MAC protocol issue will be investigated and solutions will be presented.

2.8.3 Heartbeat Driven MAC Protocol (H-MAC)

The idea to cut back on the high power consumption due to regular synchronisation in TDMA scheme has motivated the authors in [60] to propose the novel heart beat driven MAC protocol. In H-MAC, the extra energy usage for the clock alignment of the network components is eliminated by utilising the alternative heart rate rhythm of the human body for synchronism purposes. The star topology is used in this protocol and the network is coordinated by the central controller to maintain timeslot assignment and superframe structure. The central coordinator and biosensors drew out the characteristics of the heart rate from their sensory data and set their internal clock by detecting the peak waves as the source, the heart rate rhythm data, is unique. The peak intervals of the heart beat wave can be scaled for synchronisation by means of the ECG QRS complex detection [61] and the automatic beat detection [62] algorithms extracting peaks from the inherent heart beat pulse. However, the resynchronisation recovery method is used in the cases of peak extraction failure or information loss due to the interference. For resynchronisation, the sensor turns on its radio to receive the accurate peak interval of the controller broadcasting in each frame.

H-MAC protocol supports reliability through dedicated time slots by utilising TDMA method which minimises the collision, overhearing and idle listening and as a consequence the energy wastage is reduced. Moreover, the energy efficiency of the WBAN networks is enhanced by omitting the further power usage for broadcasting beacon frames. Simulation results conducted by the authors in [60] prove the system improvement in terms of energy comparing to Sensor MAC (S-MAC) [48] and Lightweight MAC (L-MAC) [63] protocols. However, this protocol by means of TDMA method does not support scalability, emergency and priority handling. Furthermore, due to the heterogeneous characteristic of the applications in WBANs using same length and non-traffic adaptive timeslots leads to inefficient bandwidth usage especially in a case of lower traffic. Additionally, the issue of peak interval overlapping is addressed by utilising guard bands which in turn leads to resource wastage.

Even though exploiting heart beat peaks and have benefited from them instead of TDMA synchronisation leads to overall power consumption reduction and prolong the lifetime of the network, there are some issues worth to be considered here. Some biosensors cannot access to heartbeat through their sensory information such as motion accelerometer and there is a need for facilitated and more complex biosensors instead. In a case of emergency or saturated condition due to sever traffic correlation as described in section 2.4.1, the heart rate can be changed dramatically and thus considering synchronism source, reliability cannot be guaranteed [64].

2.8.4 Body-MAC Protocol

The authors in [65] propose a TDMA based MAC protocol and a star topology structure to achieve energy efficiency and improve network performance. The body-MAC protocol aims to support various types of applications inclusive of ultra-low rate, high datarate medical or multimedia applications and even life critical medical applications simultaneously. Concerning this, Body-MAC employs adaptive resource allocation and flexible sleep period management based on the requirements and features of the applications utilising the WBAN.

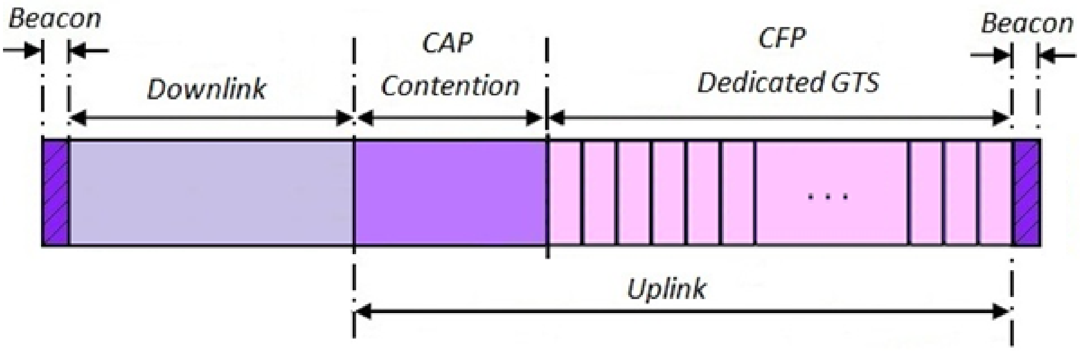

Figure 2.20: Superframe Structure of Body- MAC Protocol

As illustrated in Figure 2.20, the superframe structure of Body-MAC consists of three main subframes including asymmetric but adaptive uplink and downlink intervals and the beacon. The allocation interval and configuration details of upcoming MAC frame structure are predefined and transmitted along with the synchronisation and network data through the beacon frames. The downlink period is utilised for accommodating the on-demand and broadcasting data either to a single node or group nodes. The uplink interval is further divided into CAP and CFP portions for transmitting regular traffic, thus, have larger size compared to downlink interval. While each GTS in the CFP is utilised for frame transaction of one sensor node, MAC control frames or small sized data traffic can be transmitted during CAP using CSMA/CA method.

In this protocol, the central coordinator predefines the duration of both downlink and uplink intervals, including the CAP and CFP periods, based on system's current traffic pattern to maintain the adaptive allocations and efficient sleep mechanism for nodes.

Upon a node's allocation request on CAP period, the novel dynamic bandwidth allocation procedure is decided by the central controller to accommodate Burst Bandwidth, Periodic Bandwidth or Adjust Bandwidth based on the types of transmission traffic. While Burst Bandwidth is temporary allocation lasts during a few MAC frames, Periodic Bandwidth provides regular distributions for a dedicated node. Both can be removed by the coordinator based on need. However, the length of Periodic Bandwidth can be altered by utilising the Adjust Bandwidth assigned to the particular node upon its request by the gateway.

Furthermore, this protocol introduces the traffic adaptive sleep mechanism motivated by the idea of energy wastage in some low-duty-cycle nodes which do not require receiving beacon frames or be active during uplink and downlink intervals in each superframe .On the other hand, idle listening to obtain potential traffic wastes the power resources, and the sleep mechanism forces the nodes to sleep and turns their radio off. However, the sleep method should provide the balance between accessibility and power efficiency in the network.

Body-MAC sleep process has three stages to perform such as sleep-mode request, sleep-mode grant, and sleep-mode wakeup. Subject to the specification and the QoS requirement of the application, each node determines the sleep parameters and sends the sleep-mode request during CAP. The coordinator sends back an acknowledgement upon receiving it and sends back the sleep-mode grant in the following downlink interval to indicate the acceptance or rejection and determines the sleep parameters according to the traffic associated with that particular node. The coordinator sends a wake-up command whenever there is a need to send data or broadcast information.

The Body-MAC protocol in comparing to the IEEE802.15.4 MAC protocol proves the improvement concerning energy consumption and delay considering the adap sleeping scheme and three bandwidth allocation factors as well as dynamic Uplink and Downlink intervals resulting in the reduction of radio switching state. However, more control packets exchange is occurred during bandwidth and sleep procedure requests and allocations results in energy wastage. The bandwidth usage is not optimised due to the exclusive downlink interval as the downlink traffic is not sequential.

Although the protocol accommodates on-demand traffic, no specific procedure is defined for emergency traffic and priority handling. On the other hand, random sleep process requires resynchronisation which results in extra energy wastage. In the case of a saturated network, the protocol cannot be reliable due to the collision in CAP and packet drop.

2.8.5 Med-MAC Protocol

The MED-MAC protocol proposed in [66] is an adaptive and energy efficient MAC protocol which is specifically suitable for low to medium datarate medical applications. The protocol approach is non-contention medium access through dynamically modifiable TDMA scheme and traffic adaptive timeslots. Optionally, the contention portion can be employed in the MAC frame structure to accommodate low datarate traffic and more importantly it is utilised in emergency handling and initiation process. The superframe structure of a typical Med-MAC protocol is shown in figure 2.21.

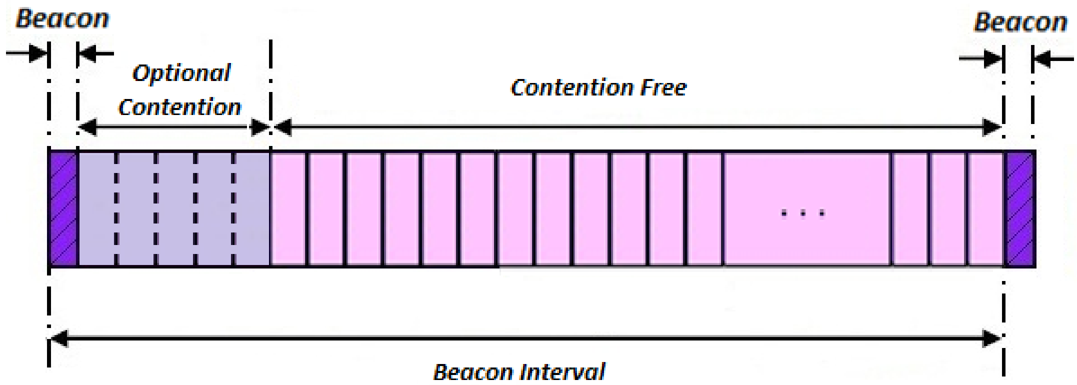

Figure 2.21: Superframe Structure of Med- MAC protocol

The structure of its superframe and even the length of its single time slot can be altered based on the current traffic, upcoming traffic and application's QoS requirements. The main feature of the MED-MAC protocol is maintaining unique synchronisation mechanism to eliminate the extra power wastage for clock adjustments in each beacon interval. In a case of having regular downlink messages the synchronisation is implemented through an updated timestamp field. An Adaptive Guard Band Algorithm (AGBA) maintains the clock alignment by means of inserting the adjustable guard bands to track the time drafts in the case of interrupted downlink packets or in very low duty cycle applications. The Drift Adjustment Factor (DAF) alters the guard bands to improve the bandwidth usability.

The topology used in this protocol is a point to multipoint star topology with a central gateway manages the synchronisation, traffic analysis, structure adjustments and channel allocations.

Three different classes of slot reservation are facilitated by a MED-MAC frame structure; low datarate traffic such as temperature and pulse information is accommodated as class 0. While class 1 is utilised in allocating medium datarate traffic such as blood pressure, EEG, ECG and oximeter data, class 2 is allocated to high datarate applications in medical imaging, Capsule, EMG and video traffic.

The simulation results show that the MED-MAC protocol consumes less energy in class 0 and class 1 applications compared to IEEE802.15.4 MAC protocol due to the adjustable GTS. However, it does not support higher datarate class 2 applications which are life-critical in medical applications. In addition, the protocol is not suitable for higher datarate consumer electronic applications either.

In this protocol, adaptive and dynamic multi-superframes and adjustable timeslots provide efficient bandwidth usage, scalability and reliability by eliminating collision, idle listening and overhearing. Even though, using the novel scheme for synchronisation reduces the power wastage, the guard bands degrade the efficiency of bandwidth utilisation. In addition, for network configuration, the protocol requires more complex coordinator and more energy is wasted for controlling messages.isotretinoin

An optional CAP is utilised to accommodate emergency traffic but the protocol does not support priority. Thus, in the saturation condition, the MED-MAC protocol encounters severe collisions and packet drops during CAP and is not suitable to deliver life-critical data.

2.8.6 Master-Slave MAC Protocol

Authors in [67] proposed a master-slave MAC protocol, where a central master controller handles all the transmissions to and from slave nodes. The network topology is star where a single node connects the network at a time. The channel access is TDMA along with the clear channel assessment to avoid collision. The central master links all the slave sensor nodes to the network and initiates all the communications. Maximum of 8 salve nodes is considered in each cluster refers to a single master-slave network. For employing more than 8 nodes, the slotting management should be implemented outside of the protocol. The protocol facilitates the inter-connection of clusters.

The communication in master-slave MAC is initiated by link establishment procedure. The master node is enabled and starts to connect the unattached slave nodes by forwarding the unique address and structure data to a single node on each vacant channel. When a node tries to join the network, it starts scanning for the first available channel and remains on the channel for a predefine period of time. If the channel is idle, the node hops on the other available channel, otherwise remains on the channel to receive the broadcasting beacon and sleep scheme information. Upon receiving the beacon, the node sends acknowledgement and goes to a sleep. During the communication during each wake up period, the sleeping scheme is changed and optionally synchronisation is processed for the time drifting alignment. For accommodate the critical emergency data, the transmission is performed out of the normal wake up process by activation the alarm mode. Whenever a node cannot access the medium due to the alarm condition of other nodes, the Wakeup Fall-back Time (WFT) factor sets the sleep time for that particular node. Both slave and master has the same parameters for WFT and simultaneously wake up to communicate with each other, rebuilding the schedule. In addition, the protocol facilitates the transmission of large data frames by means of transmitting fragmented packets one at a time.

The Authors in [67] provide the comparison regarding power consumption to Zigbee, Bluetooth and LAN networks which are not energy efficient networks.

Despite that the collision, idle listening and overhearing problems is mitigated by means of master-slave TDMA approach, the control signalling, beacon broadcasting and synchronisation consume energy. Utilising WFT, the protocol reduces collision and energy wastage due to the access failure in an alarm condition. Reliability and scalability is achieved by centrally management mechanism, however, too much control overhead is associated with it. The protocol considers up to 8 sensor nodes in each cluster and accommodating more nodes requires exterior time slotting management which leads to the hardware complexity. Data priority is not supported in this protocol and there is not reliable procedure available to maintain sporadic alarm events in a case of saturated network condition.

2.8.7 Battery Dynamics Driven MAC Protocol

The protocol proposed in [68] considers the cross layer design scheme, the battery's discharge dynamics and electrochemical features, the packet scheduling in the MAC layer and the channel quality in the physical layer. The topology is star with TDMA access scheme. Figure 2.22 demonstrates the superframe structure of the protocol which is divided to 3 intervals; beacon, active TDMA interval and inactive interval.

The length of the beacon interval is adaptive to the QoS requirement of the WBANs applications which is broadcasted in the beacon at the beginning of each superframe. Synchronisation information along with the Channel State Information (CSI) is transmitted

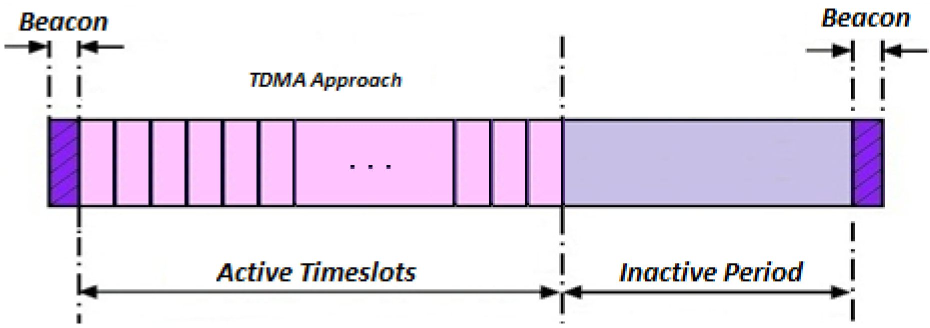

Figure 2.22: Superframe Structure of Battery-Dynamics Driven MAC Protocol

during the beacon as well. A fixed and same-length timeslot is dedicated to each node in the active part while all the nodes go to the sleep mode during inactive period. However, due to the adaptive superframe characteristic, the central node decides whether to allocate a time slot to the specific node in each frame or keep it in the buffer. The packet queuing scheme and time varying fading channels are the influence factors for buffering the data packets instead of sending them promptly.

The battery dynamic driven MAC protocol aims to improve the lifespan of the batteries and in turn, increasing the network's life while providing the reliability, timely delivery of information and latency requirement of WBANs.

Refer to [69] and [70], the capacity of the batteries can be recovered during the particular idle period. In consequence, by extending the duration of the idle or sleep period, the battery for each node lasts longer. In this regard, the scheduling method in this protocol allows acceptable packets buffering to optimise the balance between energy and latency. In a case of the overloading buffer, traffic is delivered if the quality of the channel is satisfactory otherwise the incoming packets are dropped.

The analytical model along with the simulation results shows that the battery dynamic driven MAC protocol performs better for low datarate applications in term of delay compared to traditional TDMA. However, by increasing the number of the arrival rate for high datarate applications, the latency is extended. Comparing with IEEE 802.15.4 MAC protocol, the protocol enhanced the network performance regarding average packet delay by increasing the number of nodes.

The trade-off between the reliability and latency should be provided because gathering the data in the buffer, reduce the timely conveyance of packet data. In other words, in this protocol, the reliability is not guaranteed utilising scheduling and queuing mechanism. It is adaptive and scalable but does not support priority or life critical information delivery. In a saturated network, the packet drop is occurred because of high traffic in the buffer and emergency data is not delivered either.

2.8.8 A Low-Duty-Cycle MAC Protocol

Utilising the static characteristics of WBANs, Authors in [59] introduce a low duty cycle MAC protocol with a modified TDMA access technique to achieve the energy efficiency. In this protocol, the superframe is divided to small portions of communication intervals with guard bands in between.

Figure 2.23 exposes the frame structure of the superframe. The network control packets are transmitted at the end of the MAC superframe to broadcast synchronism information or any network commands.

Communication is performed utilising multiple time slots. While, time slots S1 to Sn are dedicated to the 1^{st} node to n^{th} node respectively for the data transaction, timeslots RS1 to RSk are reserved for retransmissions of dropped packets for redundancy purposes. The number of reserved slots is predefined in relation to the number of system nodes, packet loss rate and BER. In the presence of a single-transceiver central node, the rest of

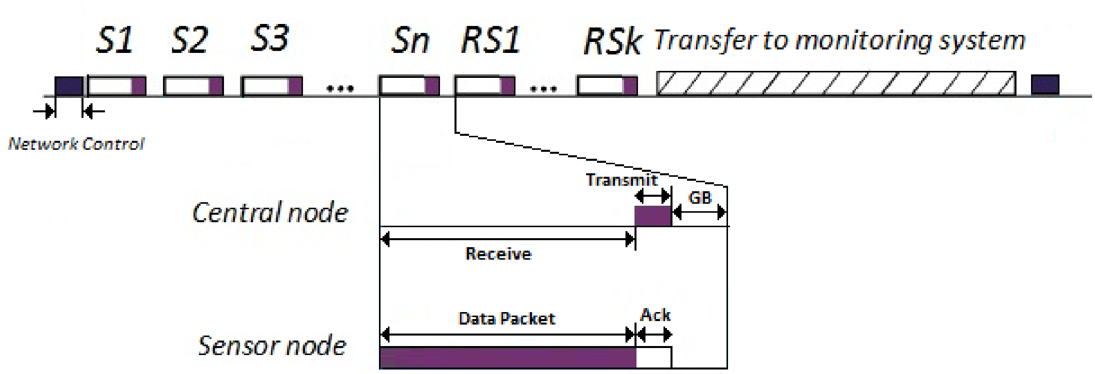

Figure 2.23: Superframe Structure of Low-Duty-Cycle MAC Protocol

the superframe remains for the packet transmission to the monitoring system. The central node with two transceivers can communicate simultaneously with the sensor nodes as well as the monitoring system. Thus, the extra period during the superframe is not necessary any more, and Bluetooth or Wi-Fi systems maintain the data transmission to the tracking system.

The protocol minimises the duty cycle to enhance energy efficiency, still, more power is required for the clock synchronisation. In the MAC superframe, the guard bands are used to avoid packet overlapping. Inserting extra guard times and having the same sized time slots wastes the bandwidth. Furthermore, the protocol is not flexible and adaptive to network change and not scalable either. Priority or emergency handling is not supported in low duty cycle MAC protocol due to the static configurations of the TDMA method.

2.8.9 Comparison Between the MAC Protocols Applicable in WBANs

The comparison between MAC protocols is made based on the key aspect of the network and QoS provisioning specifically for WBANs such as emergency and priority handling, energy efficiency, scalability and adaptability to the network traffic.

Table 2.4 provides the analytical differences between these MAC protocols.

MAC Protocol	**Approach**	**Synchronisation**	**Emergency Handling**	**Priority Handling**	**Energy Efficiency**	**Scalability**	**Adaptability**
S-MAC	Scheduled-Contention	Essential	NO	NO	LOW	NO	NO
T-MAC	Scheduled-Contention	Essential	NO	NO	MEDIUM	YES	YES
B-MAC	LPL	NO	NO	NO	LOW	YES	NO
Wise-MAC	LPL-CSMA	NO	NO	NO	MEDIUM	YES	YES
H-MAC	TDMA	Essential (Unique)	NO	NO	HIGH	NO	NO
Body-MAC	TDMA	Essential	NO	NO	MEDIUM	NO	YES
MED-MAC	TDMA	Essential (Novel)	NO	NO	HIGH	YES	YES
Master-Slave MAC	TDMA	Optional	YES	NO	LOW	YES	YES
Battery Dynamic Driven MAC	TDMA	Essential	NO	NO	MEDIUM	YES	YES
Low Duty Cycle MAC	TDMA	Essential	NO	NO	MEDIUM	NO	NO

Table 2.4: Comparison Between the MAC Protocols Applicable in WBANs

Chapter 3

Simulation Results and Discussion on IEEE 802.15.4 and IEEE 802.15.6 MAC Protocols

In this chapter, the performance of IEEE 802.15.4 and IEEE 802.15.6 MAC protocols on different aspect of network such as throughput, delay, power consumption, drop probability and successful transmission probability are evaluated using the MATLAB simulation framework. The simulation parameters and assumptions for each simulation are presented which comply with the IEEE standards. In the following, the advantages and shortcomings of each protocol are discussed in details based on the simulation results.

3.1 Simulation Parameters and Assumptions for IEEE-802.15.4 MAC Protocol

The assumption is made considering the frequency band of 2.45 GHz. The corresponding datarate for 2.45 GHz ISM band is 250 Kbps and symbol rate of 62.5 ksymbol/s in the IEEE 802.15.4 standard. Thus, the duration of a symbol is calculated as below:

Symbol Duration = $\frac{1}{62.5 \times 10^3}$ =$16 \mu s$

Some parameters are directly defined in the standard and presented in Table 3.1. Some other parameters should be calculated.

Parameter	**Value**
Base Slot Duration	60 Symbols
Num of Superframe Slots	16
BaseSuperframeDuration	Base Slot Duration × Num of Superframe Slots
Max GTS Num	7
Min CAP Length	440 Symbols
Unit Backoff Period	20 Symbols
MAC Max BE	3-8, defult 5
MAC Min BE	0-MAC Max BE, defult 3
MAC Max CSMA Backoffs	0-5, defult 4
MAC Max Frame Retries	0-7, defult 3
Max PHY Packet Size	127 Bytes
Min MPDU Overhead	9 Bytes
Max MPDU Overhead	25 Bytes
Max MAC Safe Payload Size	Max PHY Packet Size − Max MPDU Overhead
Max SIFS Frame Size	18 Bytes
MAC LIFS Period	40 Symbols
MAC SIFS Period	12 Symbols

Table 3.1: Pre-defined Parameters in IEEE802.15.4 Standard

As per the standard, each superframe is divided into 16 fixed time slots. Thus, a base superframe is equal to 960 symbols.

Base Superframe = Base Slot Duration $\times$ Num of Superframe Slots

= 60 Symbols × 16 = 960 Symbol

So, the BaseSuperframeDuration is calculated to be 15.36 ms.

BaseSuperframeDuration = 960 $\times 16 \mu s$

= 15.35 ms

There is a minimum interval defined for CAP period which is equals to 440 symbols and the duration is calculated as 7.04 ms.

Minimum CAP = 440 Symbol

= 440 $\times 16 \mu s$ = 7.04 ms

The maximum MAC payload size is calculated to be 102 bytes as below:

Max PHY packet size = 127 bytes

MAC frame size = 9-25 bytes

Max MAC payload size = Max PHY packet size - MAC frame size

= 127-25 = 102 bytes

In the simulation, the payload in GTS is considered to be 60 bytes and the payload in CAP to be 100 bytes.

As defined in the standard, the value of beacon interval and superframe are calculated by:

BI = BaseSuperframeDuration × 2MAC Beacon Order

SD = BaseSuperframeDuration × 2MAC Superframe Order

BI = 960 × 2BO, SD = 960 × 2SO, Whereas: $0 \leq SO \leq BO \leq 14$

In this work, four different scenarios are simulated in MATLAB framework [71].

1. Full duty cycle without GTS

2. Full duty cycle with employing 7 GTSs

3. 50% of duty cycle without GTS

4. 50% of duty cycle with employing 7 GTSs

Whereas in full duty cycle scenarios, BO = SO = 2, and in %50 duty cycle scenarios, BO = 3 and SO = 2 are implemented. Three types of traffic are considered in the simulation. Medical traffic, Constant bit rate traffic (CBR) and burst traffic. Medical traffic is sent through GTS in CFP while CBR and burst traffic are transmitted in CAP. While IEEE 802.15.4 CSMA/CA access mechanism with two stages of CCA is used in CAP interval for traffic contention, the medical data is transmitted exclusively in GTSs. The length of each GTS is considered the same length as a superframe slot.

The below lines of the MATLAB code are presented for a better clarification on the assumptions and simulation parameters.

- *aUnitBackoffPeriod=20; %symbol*
- *BitPerSymbol=2; % bit*
- *aBaseSlotDuration=3; % 60 symbols = 3*aUnitBackoffPeriod*
- *aNumSuperframeSlots=16;*
- *aBaseSuperframeDuration=aBaseSlotDuration*aNumSuperframeSlots;*
- *BeaconInterval=aBaseSuperframeDuration*2^(macBeaconOrder);*
- *SuperframeDuration=aBaseSuperframeDuration*2^(macSuperFrameOrder);*
- *aSuperframeSlot=superframeDuration/aNumSuperframeSlots;*
- *macMaxFrameRetries=7;*
- *macMaxCSMABackoffs=4;*
- *macMaxBE=5;*
- *macMinBE=3;*
- *macAckWaitDuration=2;*

- *macSIFSPeriod=1;*
- *phyCCADuration=2;*
- *DataRate=250; % kbit/sec*
- *AckLength=2;*
- *BER=2e-5;*
- *BeaconLength=aSuperframeSlot;*
- *Payload=[60 100 100]*8; % ECG CBR Bursty*
- *MaxSimTime=10^5; % Backoff Slot*
- *TrafficLoad =[0.005 0.06 0.06]; % packet/slot*
- *BufferSize=[10 10 10];*
- *MaxNumOfTrial=5;*

3.2 Simulation Results and Discussion of IEEE 802.15.4 MAC Protocol

The simulations are conducted for a single WBAN which refers to one patient. The effect of increasing number of the nodes on three key aspects of networks; throughput, delay and energy consumption are investigated. The results of simulations are illustrated in Figure 3.1.

As shown in the first and second graphs, by increase in number of nodes, the overall performance of the network decrease as the throughput will decrease and the frame delay will increase for all four scenarios.

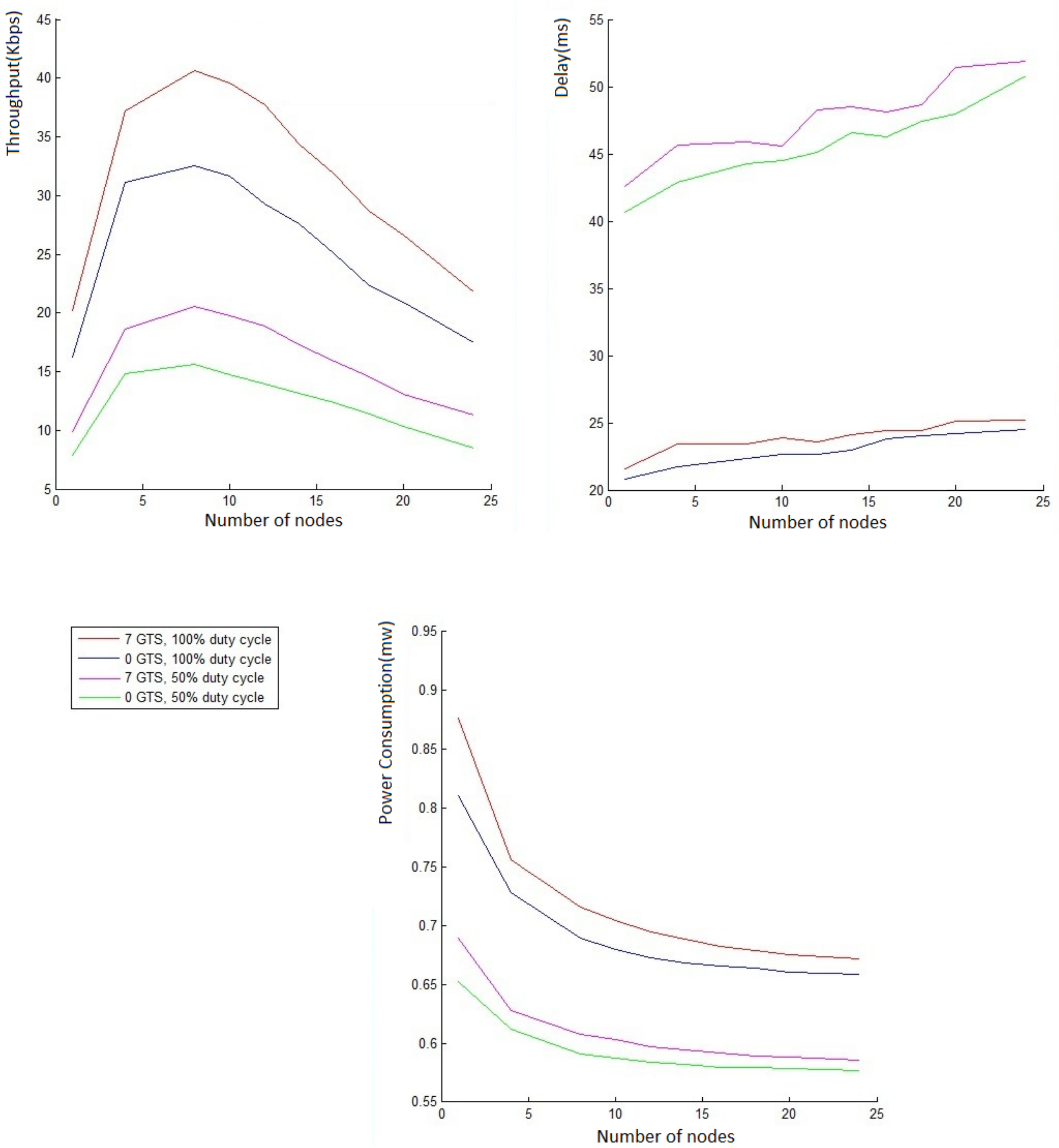

Figure 3.1: IEEE 802.15.4 MAC Protocol Simulation Results

The reason is by adding more nodes to the network, more collision occurs in CAP because of the increasing contention. Red and blue lines represent higher duty cycle mode which gives better results for throughput and delay at the expense of higher power consumption. Because higher duty cycle results in larger CAP length in which nodes have more time to send their data. Pink and red lines represent deploying 7 GTSs in our system which improves the throughput of network at the cost of higher power consumption. This is due to dedicated time slots for the nodes to send their packets but more power will consumed for synchronisation [72]. Furthermore, as a result of fixed superframe duration, using GTSs leads to lower CAP period and this will increase the delay. Hence, the issues of IEEE 802.15.4 MAC Protocol are as follows [73]:

- Do not support high datarate application.
- Do not support priority.
- May handle up to maximum 7 GTSs for emergency data.
- Do not support scalability; increase in number of nodes reduces the overall network performance.
- Using fixed 16 time slots in superframes, decreases the overall network performance.

3.3 Simulation Parameters and Assumptions for IEEE-802.15.6 MAC Protocol

Same as IEEE 802.15.4 MAC protocol, the assumption is made considering the frequency band of 2.45 GHz. The correlated datarate for 2.45 GHz ISM band is 971.4 Kbps and symbol rate of 600 ksymbol/s defined in the IEEE802.15.6 standard. Table 3.2 have illustrated some of the MAC parameters which have been determined in the standard.

Parameter	**Value**
Max BAN Size	64
CCA Time	63/ Symbol Rate
CSMA MAC PHY Time	40 μs
CSMA Slot Length	CCA Time + CSMA MAC PHY Time
MIFS	20 μs
SIFS	75 μs
Random Access	CSMA/CA

Table 3.2: Pre-defined Parameters in IEEE802.15.6 Standard

In the simulation, the IEEE 802.15.6-based CSMA/CA is an access method which supports traffic prioritisation based on the parameters mentioned in Table 1. Each CSMA slot length is defined to be CCA Time + CSMA MAC PHY Time and is calculated as:

CCA Time = 63 / Symbol Rate

= 63 / 600 ×103 = 105μs

CSMA Slot Length = CCA Time + CSMA MAC PHY Time

= 105μs + 40μs = 145 μs

The assumptions made in the simulation are as follows:

- A single WBAN consists of a central coordinator and 16 sensor nodes which are categorised to 2 nodes of each user priority.
- MAPs, EAP2, RAP2 and CAP length is set to zero.
- Differentiation parameters of CWmin and CWmax are implemented for each user priority.
- Payload Size is considered to be 60 bytes for highest user priority (UP7) and 100 bytes for other user priorities.

- Traffic load is 2 packets per slot for all user priorities.
- The maximum MAC frame retry is assumed to be 7.
- Bit Error Rate (BER) is considered to be 2×10^{-5}.

The below lines of the MATLAB code are presented for a better clarification on the assumptions and simulation parameters.

- *NodeCount=[2 2 2 2 2 2 2 2]; % LOW to HIGH*
- *Payload=[100 100 100 100 100 100 100 100 60]*8; %bit (low to High)*
- *TrafficLoad=10* [2 2 2 2 2 2 2 2]*pCSMASlotLength*10^(-3); % packet per slot*
- *DataRate=971.6; % kbit/sec*
- *HeaderRate=91.4;*
- *SymbolRate=600; % ksyb/sec*
- *pCSMAMACPHYTime=0.04; % msec*
- *pCCATime=63/SymbolRate;*
- *pCSMASlotLength=pCCATime+pCSMAMACPHYTime; %msec*
- *pSIFS=0.075/pCSMASlotLength; % slot*
- *macMaxFrameRetries=7;*
- *CWmax=[64 32 32 16 16 16 8 8 4];*
- *CWmin=[16 16 8 8 4 4 4 2 1];*
- *BER=2e-5;*
- *MaxSimTime=10^5; % Backoff Slot*
- *BufferSize=10;*
- *MaxNumOfTrial=5;*

3.4 Simulation Results and Discussion of IEEE 802.15.6 MAC Protocol

In this section, the simulations are implemented in both non-saturated and saturated network condition where each node has data to send every time and the buffer is full. The discussion is made and the issues of IEEE 802.15.6 protocol is highlighted.

3.4.1 Non-saturated Condition

Two scenarios [74] on non-saturated condition are considered in the simulations. A WBAN consists of the sensor nodes capable of investigating the behaviour of all user priorities. In the first scenario, the length of EAP1 is assumed to be constant and the length of RAP1 is dynamic. Network performance on the frame delay is investigated. The effect of increasing RAP1 length from 0.2 seconds to 1 second while the EAP1 phase is fixed to 0.05 seconds, is illustrated in Figure 3.2.

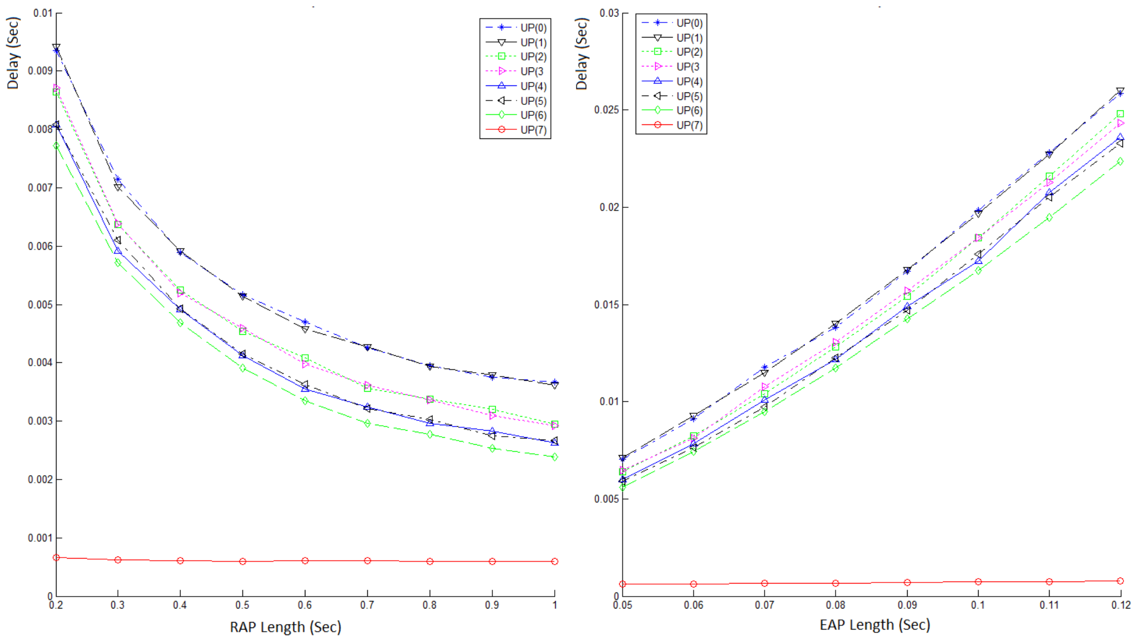

Figure 3.2: Frame Delay of IEEE 802.15.6 MAC Protocol in Non-Saturation Condition

As shown in the result, increasing the length of RAP1 while the EAP1 length is constant improves the frame delay for all the user priorities UP<7 but the delay frame of the highest one UP7 is unchanged. The reason here is larger RAP1, increases the phase which is used by all the other user priorities UP<7 that leads to reducing the collision probability and more nodes can transfer their packets and as a result, latency is decreased.

In the second scenario, the length of RAP1 is fixed to 0.03 seconds, while EAP1 is increasing from 0.05 seconds to 0.12 seconds. As shown in Figure 3.2, by an increase in the length of EAP1 with fixed RAP1 phase, the delay frame for all UP$<$7 is increased but for UP7. As the network is in non-saturated condition and UP7 is prioritised both on having dedicated phase in the EAP phase and the shortest CW in the RAP period, the increase in the EAP length does not affect the frame delay for UP7. Moreover, the highest user priority does not have data to send all the time in the non-saturated network and adopting larger EAP1 wastes the available bandwidth which leads to inefficient use of transmission medium.

Hence, the issues of IEEE 802.15.6 MAC Protocol in non-saturated condition are as follows [75]:

- Increasing EAP1 with fixed RAP1 increases the frame delay of all UP$<$7 and wastes the bandwidth and increasing RAP1 with constant EAP1 improves system latency for all UP$<$7 as it reduces the traffic congestion.
- Particularly, in low traffic (non-saturated) condition, as the highest user priority nodes have already been prioritised through small CW, employing EAP1 phases does not have a significant effect on the performance of UP7 but degrades the performance of all the other user priorities. Thus, EAP1 phases are not necessary for the non-saturated WBAN network.
- In fact, Short EAP1 and RAP1 phases degrade the overall performance of the network firstly, because slots at these access phases are wasted due to insufficient time for frame transmission. Secondly, at the beginning of the RAP1 phase, to start the frame transmissions, the nodes of UP$<$7 have just unlocked their backoff counter, which had paused in the previous superframe which apparently increases the number

of collided data. As a result, deploying appropriate and relevant EAP1 and RAP1 phases based on traffic load can improve the overall performance of a WBAN network.

- Small CWs boost the collision probability, thus, by the increase in the size of CWs, the performance of the network is improved at the cost of higher energy consumption.

3.4.2 Saturation Condition

Similarly, in the saturated condition, once more, the first scenario is increasing the RAP1 length from 0.2 seconds to 1 second while the EAP1 phase is fixed to 0.05 seconds. In the second scenario, the EAP1 phase has increased from 0.05 seconds to 0.12 seconds while the RAP1 phase is set to 0.3 seconds. It is worth mentioning that, in saturated network conditions, each node has data to send or receive all the time and the buffers are overloaded. Figure 3.3 illustrates the simulation results for the successful transmission probability aspect of the network based on the increment of the RAP1 and the EAP1 lengths.

As per simulation results, the high percentage of the packets of the user priorities other than the highest one is dropped. Increasing the RAP1 or EAP1 does not change the successful transmission probability for all the other user priorities UP<7 due to a lack of channel access by such nodes in the saturated condition. By increasing the length of the EAP1 phase, successful transmission probability of the highest user priority is improved due to larger dedicated phase for UP7. However, the larger RAP1 increases the drop probability of the highest user priority, as the greater RAP1 intervals increase the probability of collision occurrence by all the user priorities. Consequently, in the great majority of times, the medium is accessed by the highest UP while the other user priorities

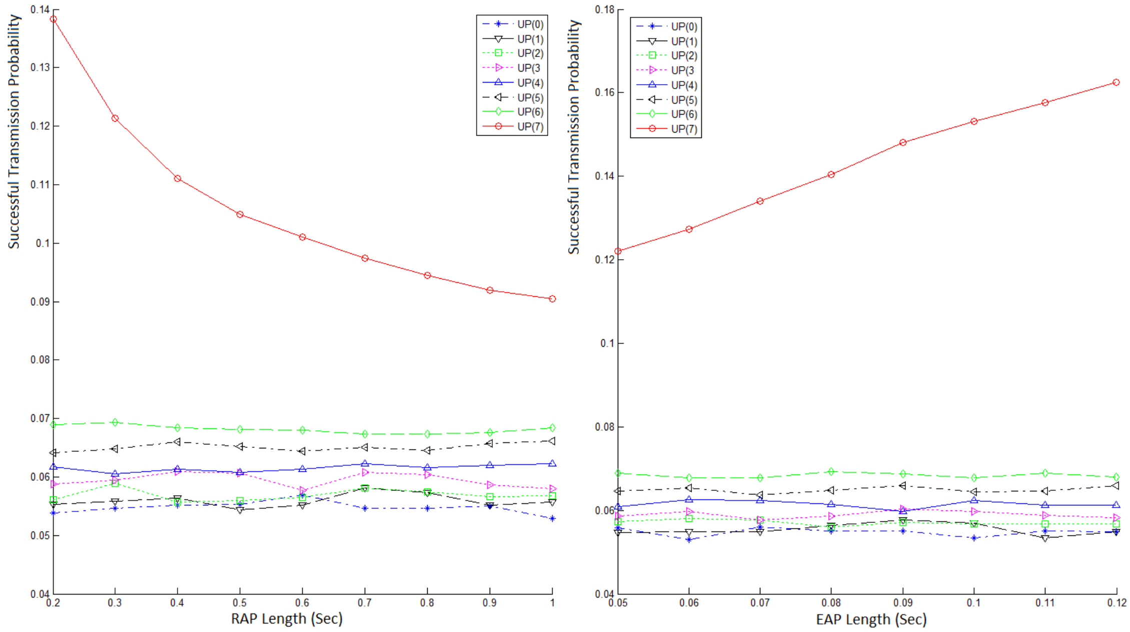

Figure 3.3: Successful Transmission Probability of IEEE 802.15.6 MAC Protocol in Saturation Condition

do have little access to the medium under saturation condition. The simulation results in Figure 3.3 indicates that in the best case scenario for the WBAN with 16 nodes of each user priority, 14 percent of the traffic for highest user priority is transmitted which depicts the inappropriate utilisation of the bandwidth under saturation regime [76][77].

Chapter 4

SAUP and SAH Proposed MAC Protocols for WBANs

As WBANs in the saturation condition suffer from the inefficient usage of the transmission medium, new MAC protocol is required to address the shortcomings. Considering medical applications, the probability of having traffic correlation is so high in an emergency situation. It is so important to have reliable network despite of being in a life-critical or normal situation.

In this chapter, two different proposed MAC protocols, SAUP and SAH protocols are presented. The simulation assumptions, simulation results and discussion are provided for each proposed MAC protocol.

4.1 SAUP MAC Protocol and Related Simulation Results

Considering WBANs in the saturated condition, the highest user priority packets collide with each other during EAP1 and with the other user priorities during RAP1. As a result, the collision probability is high and UP7 packets have little access to the medium while the high percentage of the packets for the UP<7 are dropped.

The SAUP MAC protocol is proposed to address these issues in the saturated WBANs. The main objective of this proposed model is to improve the overall performance of all user priorities other than the highest one without decreasing the performance of the highest user priority UP7.

IEEE 802.15.6-based CSMA/CA access scheme with modified superframe structure of IEEE 802.15.6 are used in this proposed protocol as shown in Figure 4.1.

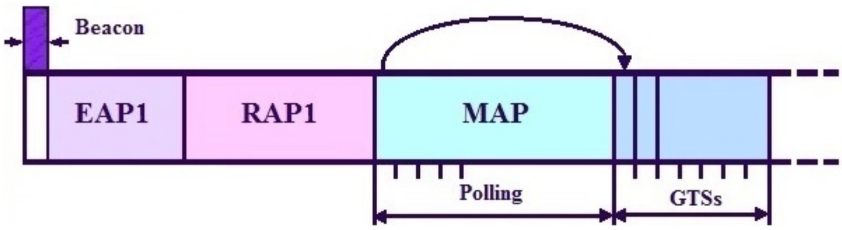

Figure 4.1: Superframe Structure of SAUP Proposed MAC Protocol

In the superframe structure of the proposed protocol, the assumption is made to employ EAP1, RAP1, MAP phases and possibly, a GTS phase. Thus, the lengths of other phases have been set to zero. In SAUP protocol, the polling mechanism is used in MAP phase to grant a GTS to a node during the GTS phase.

The GTS allocation procedure is as follows; the central controller polls a node which cannot obtain a contended allocation and access the medium in predefined numbers of superframes because of the extended collisions. When answering the polled message in the MAP phase, a node indicates if it has data to send and asks for the dedicated time slots. The central coordinator allocates the numbers of required GTSs to it during the GTS phase.

The scenario in the simulation is a WBAN network consisting of a hub and 28 nodes [75] such as EEG, ECG, EMG, blood pressure sensor, glucose monitoring sensor, blood oxygen saturation sensor, body temperature sensor, respiration rate monitoring sensor and physical activity monitoring sensor. The specifications of each node have been illustrated in Table 4.1.

UP	Data Stream	Number of Nodes	Traffic Load (p/s)	Packet Size (Bytes)
7	ECG	1	2	150
	EEG	1	2	150
6	ECG	2	2	150
5	EEG	1	2	150
	Blood Pressure	1	2	150
4	Glucose	1	1	50
	Oxygen Saturation	1	1	50
	Temperature	1	1	20
	Respiration Rate	1	1	20
3	Physical Activity	4	1	50
2	EMG	1	4	500
1	ECG	5	0.8	375
0	EEG	8	0.5	600

Table 4.1: Nodes Specification in Simulation Set-up for SAUP MAC Protocol

The simulation is conducted in 2.45 GHz ISM band with the datarate of 250 Kbps and symbol rate of 600 Ksymbol/s. BER is considered to be $2 \times 10^{-5}$and maximum MAC frame retry is set to 7. Differentiation parameters of CWmin and CWmax based on IEEE 802.15.6 standard are implemented as well.

4.1.1 Simulation Results and Discussion of Proposed SAUP MAC Protocol

The comparison between IEEE 802.15.6 MAC protocol and proposed SAUP MAC protocol on the drop probability aspect is illustrated in Figure 4.2.

As the system is in the saturation mode and each node has data to send every time and high collisions are more likely to happen. The simulation results indicate that our proposed method can improve the poor saturated network performance.

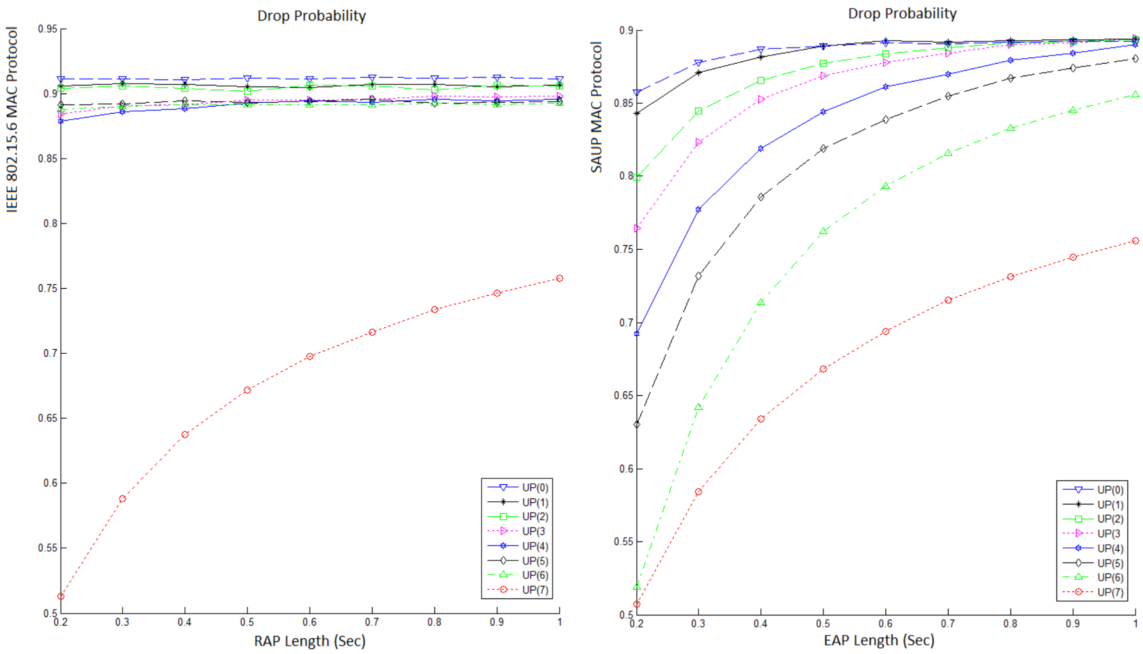

Figure 4.2: The Comparison between IEEE 802.15.6 MAC Protocol and SAUP MAC Protocol

In Figure 4.2, the effect of increasing the duration of RAP1 interval on the drop probability aspect for all the user priorities are illustrated for implementing IEEE 802.15.6 and SAUP MAC protocols.

The results indicate that utilising IEEE 802.15.6 MAC protocol, the drop probabilities of the user priorities other than the highest one (UP<7) are around 90 percent of the packets. However, proposed SAUP MAC protocol dramatically improves the drop probability for the UP<7 without reducing the performance of the highest one (UP7). The reason for the improvements is utilising the dedicated GTSs for UP<7 by the SAUP polling procedure.

By increasing the RAP1 period, the drop probability for all user priorities is decreased, as indicated in the Figure 4.2. This is because the system is saturated and greater RAP1 raises the possibility of the collision occurrence.

4.2 SAH MAC Protocol and Related Simulation Results

By implementing the SAUP proposed protocol, the performance of the user priorities other than the highest one is improved. Considering the highest user priority, the performance is slightly improved or in the worst case scenario remains without change. However, the performance of UP7 is much more important as it may carry life-critical emergency information. Accordingly, the SAH proposed protocol aims to enhance the performance of highest user priority in the saturated network.

In the SAH proposed protocol, changes are made on top of the SAUP superframe structure. As in the saturated condition, all the nodes have data to send all the time. Consequently, there is no need for the highest user priority traffic to contend for an allocation in the EAP1 period. Utilising GTSs through a TDMA scheme in the EAP1 access phase is a much better approach than contentions as the saturated packets are collided with each other. Thus, in the SAH MAC protocol, whenever the packets of UP7 become greater than a predefined threshold in the network, the central controller dedicates the GTSs in the EAP1 interval using TDMA protocol instead of utilising CSMA/CA protocol. In this case, the UP7 packets can access the medium without contention in a more efficient and collision-free approach. However, during RAP1, the highest user priority with the smallest CW still contends for an allocation along with all the other user priorities. As per IEEE 802.15.6 CSMA scheme, the greater CW applies for the lower user priorities. In the SAH protocol, the other user priorities UP$<$7 are also polled by a central coordinator and access GTSs after the predefined numbers of superframes.

The same scenario as in the SAUP is used. The drop probability and total power consumption factors of the network performance are compared between the proposed

SAUP and SAH and the IEEE 802.15.6 MAC protocols. The simulation results are illustrated in Figure 6. In all three MAC protocols, the highest priority performs better than UP6 and it is better that UP5 and so on. However, for better clarity only UP0, UP4 and UP7 are considered in Figure 4.3.

The packet drop probability is so high as the network is saturated and the buffer is full of data packets waiting in the queue. Consequently, increasing or decreasing the traffic load does not have any effect on the network performance. The results show that the drop probability performance of UP0 and UP4 are decreased utilising SAUP protocol with a slight improvement for UP7. Dedicating GTSs by the central controller to the UP$<$7 and decreasing the collision probability during the RAP1 period are the main reasons for the improvement. However, employing SAH MAC protocol, the drop probability of the highest user priority is dramatically improved, while there are moderate improvements for all the other ones. This is because, having GTSs during the EAP1 interval omits the packets collision. Therefore, there are lower chances for UP7 packets to contend during the RAP1.

Similarly, the simulation results for the energy consumption indicate that the SAUP protocol is a much more energy efficient approach compared to IEEE 802.15.6 protocol. This is mostly because of the reduction in collision probability and the need for retransmissions. However, the SAH MAC protocol reduces the power consumption for UP7 while it remains unchanged for the UP$<$7 because of the dedicated GTSs in EAP1 instead of competing for the allocation of UP7 traffic. As per Figure 4.3, the energy consumption for UP7 is higher than UP4 and UP0. This is due to a larger number of packets being transmitted and consequently there is an increase in the power consumption.

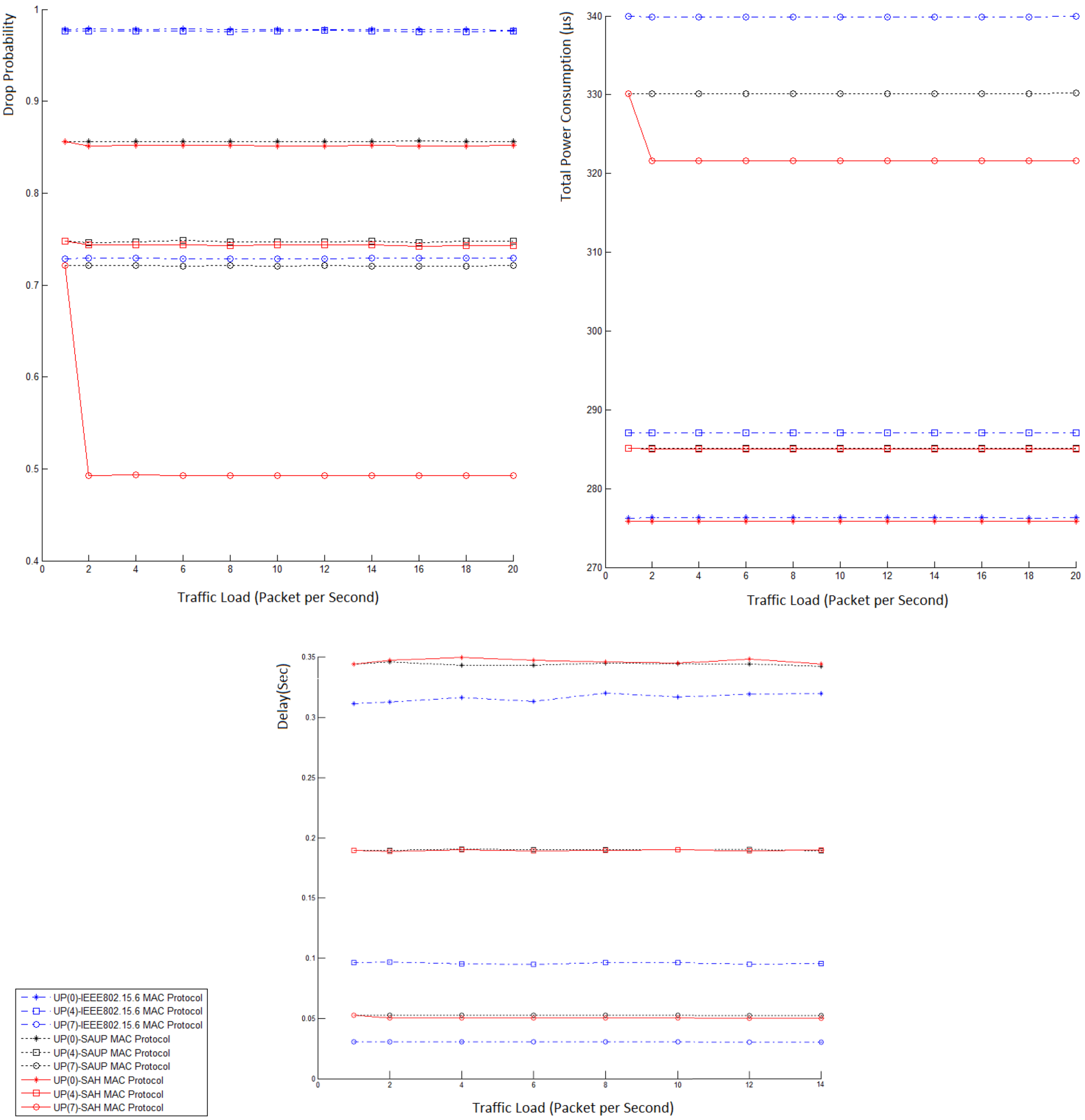

Figure 4.3: The Comparison between IEEE 802.15.6 MAC Protocol and Proposed SAUP & SAH MAC Protocols

However, better performance for the packet drop probability and power consumption produces slightly higher frame delay. This is mostly because more packets are delivered compared to utilising IEEE802.15.6 MAC protocol. Importing GTSs with TDMA access method is slightly increased the frame delay in SAH MAC protocol compared to SAUP MAC protocol which is ignorable as the better performance for UP7 is most important factor in designing a MAC protocol for WBANs.

Chapter 5

Conclusion and Future Works

5.1 Conclusion

Recent technological advancements in wireless communication and developments of micro and nano-technology biosensor have made WBANs to be utilised in or around the human body in order to monitoring the body function and its surrounding area. QoS requirements of WBANs are energy efficiency, reliability, scalability, low latency and packet loss as well as priority and emergency handling. Hence, to meet the requirements of WBANs, a very careful approach should be considered in designing MAC protocols related to these networks. In this regard, some challenges in employing existing wireless MAC protocols in WBANs were investigated and some solutions have been presented.

Two IEEE standards are applicable in WBANs; IEEE 802.15.4 and IEEE 802.15.6. MAC protocols. An overview on the specifications of these standards has been presented. Also, their behaviour has been simulated in the MATLAB framework. Simulation results have illustrated some issues for each protocol in both saturated and non-saturated network.

Considering the poor performance of IEEE 802.15.6 in saturated networking condition, two IEEE 802.15.6-based MAC protocols, SAUP and SAH have been proposed to address these shortcomings for all the user priorities.

The overall network performances along with power consumption results indicate significant improvements in the network performance and energy efficiency for the user priorities other than the highest one in the proposed SAUP protocol comparing to IEEE 802.15.6 MAC protocol in saturated WBANs.

We further have modified the IEEE 802.15.6 protocol to better manage the higher user priority packets. Our results show remarkable improvements in the network performance and power consumption aspects of the highest user priority in the SAH method compared with IEEE 802.15.6 MAC protocol in the saturation condition.

Finally, the performance of three MAC protocols on the key aspects; drop probability, power consumption and delay for SAUP, SAH and IEEE 802.15.6 protocols have been compared and shown in the same graph to give the better understanding of such protocols and the improvements in our proposed methods compared to IEEE 802.15.6 MAC protocol.

5.2 Future work Plans

WBANs are facing many challenges in the recent years as they require to be low in energy consumption and capable of supporting a wide range of applications. Moreover, advancements in technology have led to the integration of small-sized biosensors in WBANs that leads to a higher density of nodes which makes the communication even more challenging.

Our proposed protocol have been focused on improving the performance of all the user priorities during the saturation regime by maintaining TDMA protocol where needed. The future work can focus on designing dynamic and traffic adaptive MAC protocols where the TDMA protocol is not a solution in the presence of high numbers of nodes in the network.

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