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Modelling, Analysis and Design of MAC and Routing Protocols for Wireless Body Area Sensor Networks

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Copyright Statement

List of Abbreviations used

AAOD	Adaptive Algorithm to Optimize the Dynamics
ADAPT	Adaptive Access Parameter Tuning
ADCA	Adaptive Duty Cycle Algorithm
AMPE	Adaptive MAC Protocol for Efficient
ATLAS	Traffic Load Aware Sensor MAC
AT-MAC	Adaptively Tuned MAC
ART-GAS	Adaptive and Real-Time GTS Allocation
AODV	Ad Hoc On Demand Distance Vector
A-MPDU	Aggregated-MAC Protocol Data Unit
BAN	Body Area Network
BCS	Backoff Counter Selection
BDD	Battery-Dynamics Driven
BE	Backoff Exponent
BED	Backoff Exponent Differentiation
BER	Bit Error Rate
BI	Beacon Interval
BO	Beacon Order
BP	Blood Pressure
BPC	Backoff time period including CCA
BS	Base Station
B-MAC	Berkeley-MAC
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period

CMAC	Concurrent MAC
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Windows
CWD	Contention Windows Differentiation
C-MAC	Cooperative MAC
CA-MAC	Context-Aware MAC
CoR-MAC	Contention over Reservation MAC
DC	Duty Cycle
DCA	Duty Cycle Adoption
DCLA	Duty Cycle Learning Algorithm
DBPSK	Differential Binary Phase-shift Keying
DLL	Data Link Layer
DNS	Data Need to Send
DQBAN	Distributed Queuing Body Area Network
DRT	Delay, Reliability and Throughput
DSAA	Dynamic Superframe Adjustment Algorithm
DSME	Deterministic and Synchronous Multi-Channel Extension
D8PSK	Differential 8-Phase-shift Keying
EAP	Exclusive Access Phase
ECG	Electrocardiography
ED	Expected Total Delay
EEG	Electroencephalogram
EELDC	Energy Efficient and Low Duty Cycle
EMG	Electromyography
EMAC	Enhanced MAC
ETDMA	Emergency-TDMA

FCS	Frame Check Sequence
FCMA	Fuzzy Control Medium Access
FFD	Full Function Device
FQ-CSMA/CA	Weighted-Fair-Queue CSMA/CA
GDP	Gross Domestic Product
GSM	Global System for Mobile Communications
GTS	Guaranteed Time Services
HBC	Human Body Communication
HEH-BMAC	Human Energy Harvesting MAC Protocol
HUA	Hybrid Unified-slot Access
IETF	Internet Engineering Task Force
IoTs	Internet of Things
ISM	Industrial, Scientific and Medical
LABILE	Link Quality-based Lexical Routing
LLDN	Low-Latency Deterministic Networks
LEDs	Light-Emitting Diodes
LLC	Logical Link Control
LLNs	Low-power and Lossy Networks
LOS	Line of Sight
LQI	Link Quality Indicator
LR-WPANs	Low-Rate Wireless Personal Area Networks
LDTA-MAC	Low-Delay Traffic-Adaptive MAC Protocol
MAC	Medium Access Control
MCAP	Medical Contention Access Periods
MFR	MAC Footer

MICS	Medical Implant Communication Service
MPDU	MAC Protocol Data Unit
MPDS	Maximum Possible Data Size
MSDU	MAC Service Data Unit
MT	Maximum Throughput
MEB-MAC	Medical Emergency Body MAC
MFS-MAC	Modified Frame Structure MAC
NB	Narrowband
NLOS	Non-Line of Sight
NTDMA	Normal-TDMA
PAN	Personal Area Network
PDR	Packet Delivery Ratio
PLCP	Physical Layer Convergence Procedure
PMAC	Priority-guaranteed MAC Protocol
PPDU	Physical Protocol Data Unit
PSDU	Physical Service Data Unit
PTA	Priority-Based Adaptive Timeslot Allocation
PNP-MAC	Pre-emptive and Non-Pre-Emptive MAC
PA-MAC	Priority-based Adaptive MAC
PLA-MAC	Priority-Based Traffic Load Adaptive MAC
QoS	Quality of Service
RAP	Random Access Phase
REL	Routing by Energy and Link Quality
RF	Radio Frequency
RFD	Reduced Function Device

RPL	Routing Protocol for Low-Power and Lossy Networks
RSSI	Received Signal Strength Indicator
RC-MAC	Receiver-Centric MAC
SD	Superframe Duration
SIT	Sample Interval Time
SMAC	Sensor-MAC
SO	Superframe Order
SpO2	Oxygen Saturation Levels
TDMA	Time-division multiple access
TMP	Tele-Medicine Protocol
TSCH	Time Slotted Channel Hopping
T-MAC	Timeout-MAC
UWB	Ultra-Wideband
U-MAC	Urgency-based MAC
WBASNs	Wireless Body Area Sensor Networks
WiseMAC	Wireless Sensor MAC
WLAN	Wireless Local Area Network
WMTS	Wireless Telemetry Medical Services
WPAN	Wireless Personal Area Networks
WSN	Wireless Sensors Networks
ZDOs	Zigbee Device Objects

List of Symbols used

E_{ACK}	Energy Consume for Acknowledgement transmission
E_{frame}	Energy Consume for a Frame transmission
E_{TC}	Total Energy Consumption
E_{WT}	Energy Consume for Waiting Process
$E_{\tau A}$	Energy Consume for Turnaround time
macMinBE	Minimum Backoff Exponent
macMaxBE	maximum backoff exponent
N_{BO}	Number of backoffs in one slot
pExtraIFS	Extrainterframe Spacing
pSIFS	Short Interframe Spacing
P_{Sleep}	Power Consumed for Sleeping
P_{Tx}	Power Consumed Transmission of a frame
Rs	Symbol Rate
T_{Ack}	Transmission time of an acknowledgment
T_{BE}	Random Backoff Time
T_{BOslot}	Time for backoff slot
T_{CW}	Backoff Period For Contention Window
T_{CCA}	Clear Channel Assessment Time
T_{frame}	Tansmission time for a frame with payload length
TREnD	Timely, Reliable, Energy Efficient and Dynamic
T_{SIFS}	Time for Short Interframe Space
T_{symbol}	Transfer time for one symbol
T_{WT}	Total waiting Time
$T_{\tau A}$	Turnaround time that is the time between a data frame

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Author's Declaration

This thesis results in number of publications which is the original work of the author except otherwise indicated for this PhD thesis. These publications include open source journals and conferences. The list of these publications is shown in Chapter 1. I am the first author in all publications and other authors have supervisory role in producing these publications.

Acknowledgements

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Abstract

The main contribution of the thesis is to provide modeling, analysis, and design for Medium Access Control (MAC) and link-quality based routing protocols of Wireless Body Area Sensor Networks (WBASNs) for remote patient monitoring applications by considering saturated and un-saturated traffic scenarios. The design of these protocols has considered the stringent Quality of Service (QoS) requirements of patient monitoring systems. Moreover, the thesis also provides intelligent routing metrics for packet forwarding mechanisms while considering the integration of WBASNs with the Internet of Things (IoTs).

First, we present the numerical modeling of the slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for the IEEE 802.15.4 and IEEE 802.15.6 standards. By using this modelling, we proposed a MAC layer mechanism called Delay, Reliability and Throughput (DRT) profile for the IEEE 802.15.4 and IEEE 802.15.6, which jointly optimize the QoS in terms of limited delay, reliability, efficient channel access and throughput by considering the requirements of patient monitoring system under different frequency bands including 420 MHz, 868 MHz and 2.4 GHz.

Second, we proposed a duty-cycle based energy efficient adaptive MAC layer mechanism called Tele-Medicine Protocol (TMP) by considering the limited delay and reliability for patient monitoring systems. The proposed energy efficient protocol is designed by combining two optimizations methods: MAC layer parameter tuning and duty cycle-based optimization. The duty cycle is adjusted by using three factors: offered network traffic load, DRT profile and superframe duration.

Third, a frame aggregation scheme called Aggregated-MAC Protocol Data Unit (A-MPDU) is proposed for the IEEE 802.15.4. A-MPDU provides high throughput and efficient channel access mechanism for periodic data transmission by considering the specified QoS requirements of the critical patient monitoring systems. To implement the scheme accurately, we developed a traffic pattern analysis to understand the requirements of the sensor nodes in patient monitoring systems. Later, we mapped the requirements on the existing MAC to find the performance gap.

Fourth, empirical reliability assessment is done to validate the wireless channel characteristics of the low-power radios for successful deployment of WBASNs/IoTs based link quality routing protocols. A Test-bed is designed to perform the empirical experiments for the identification of the actual link quality estimation for different hospital environments. For evaluation of the test-bed, we considered parameters including Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI), packet reception and packet error rate. Finally, there is no standard under Internet Engineering Task Force (IETF) which provides the integration of the IEEE 802.15.6 with IPv6 networks so that WBASNs could become part of IoTs. For this, an IETF

draft is proposed which highlights the problem statement and solution for this integration. The discussion is provided in Appendix B.

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Chapter 01: Introduction

1.1. Background and motivation

The major healthcare challenges for the world population include the growth of elderly population due to improved life expectancy, the rise in health care costs and high death rate because of chronic diseases [1]. In Australia, Japan, Switzerland, France, United Kingdom, Germany and the United States, life expectancy has increased up to 82.8 years, 83.7 years, 83.4 years, 82.4 years, 81.2 years, 81 years and 79.3 years respectively. It is estimated that high growth in population will overload the healthcare systems. Moreover, it is expected that the requirement for remote healthcare monitoring services will reach 761 million in 2025 [2]. The current expenditure with respect to Gross Domestic Product (GDP) for different countries is increasing every year. Countries like Australia, Japan, Switzerland, France, United Kingdom, Germany and United States are spending 9.3%, 11.2%, 11.5%, 11%, 9.8%, 11.1% and 16.9% respectively of their total GDP. Recent practices show that cost ratio will reach 20% of the GDP in 2022 [3]. This statistical evidence demands a new shift to the existing health care systems for affordable and approachable healthcare solutions [3].

Every year millions of people die from fatal and chronic diseases including cardiovascular, blood pressure, asthma, and diabetes. Research has revealed that most of these diseases can be avoided if they are identified in the initial stage. Therefore, future monitoring in healthcare systems should focus on proactive wellness by providing early detection and prevention. Patient monitoring systems are capable of early detection of abnormal conditions through monitoring vital signals using various wearable or implanted biomedical sensors. These systems can be deployed by involving a network of biomedical sensor nodes around or inside the body which ultimately improves the quality of life without any disruption in their daily routine life.

Using the latest technological advancements in wearable sensors, a patient can be equipped with biomedical sensors that are capable of continuously monitoring the physiological signals from patient's body like heart activity, muscle movements, blood pressure, body oxygen level and brain stimulation via integrated sensors that is, Electrocardiography (ECG), Electroencephalogram (EEG), Electromyography (EMG), accelerometer, gyroscope, pulse oximeter, blood pressure, temperature, barometer and heart rate monitoring. When these integrated sensor nodes work under a single body coordinator (controller) then the network is known as Body Area Network (BAN). There are some other terms which are also used as an alternative to a BAN, including Wireless Body Area Sensor Networks (WBASNs). In addition to securing lives, widespread use of WBASNs will lower the healthcare cost by replacing the need for expensive in-hospital patient monitoring. In this regard, advance health-care technologies like miniaturized and low power micro and nano nodes started their role for the healthcare sector in form of WBASN [1].

Usually, for communications at MAC and physical layers, WBASNs use the IEEE 802.15.4 Low-Rate Wireless Personal Area Networks (LR-WPANs). ZigBee is a popular industrial standard which works above the IEEE 802.15.4 MAC layer and it is widely available on the market as a ready product. In spite of a challenging economy, the annual sale of ZigBee has grown by 62% since 2007 [4]. Similarly, a research had forecasted that in 2015, 645 million IEEE 802.15.4 based chipsets would be used, this quantity was 10 million in 2009 [5]. The WBASNs provide appropriate flexibility and mobility to patients as well as providing a complete medical status profile of the patient to the doctors. However, along with many merits of WBASNs, there are various technical challenges that need to be addressed. Figure 1-1 presents the architecture of WBASNs. Our focus of this research is around the around the body. We are following Tier 1 of the Figure 1-1 as our system model.

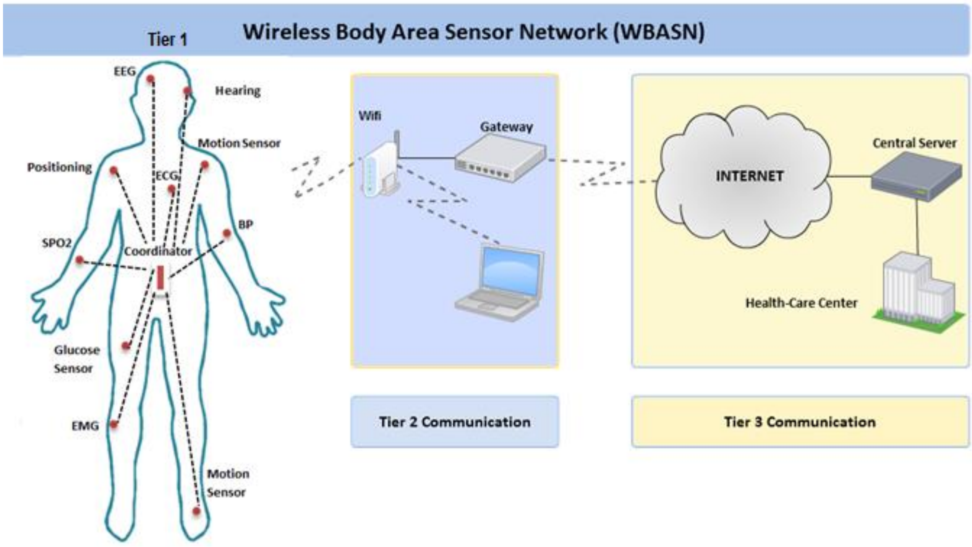

Figure 1-1 Wireless body area sensor networks

The challenges exist at MAC and network layers including limited delay, throughput, better network lifetime, efficient energy utilization, appropriate channel access, efficient routing and forwarding mechanisms and high reliability. The limited delay means its value less than 250 ms. The reliability is defined here as a number of frame retransmissions at MAC layer. These challenges will be addressed in this thesis by optimizing MAC and network layer mechanisms.

The successful execution of IoTs for the applications like health-care is dependent on MAC and network layer performance of WBASNs. Figure 1-2 provides a comparison of two IoTs based protocol stacks that are, IETF based and ZigBee based. The protocol stack (a) is based on the existing and upcoming IETF standards.

This stack, however, is still theoretical and there is yet no available product on the market which follows this stack. The protocol stack (b) is the combination of the existing IETF standards and ZigBee and is widely available on the market. This research refers to protocol stack (b) for the discussions.

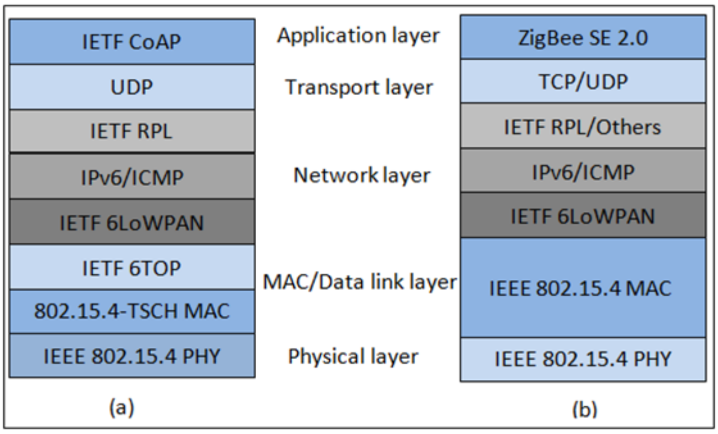

Figure 1-2 IoTs based protocol stacks comparison: IETF vs ZigBee

As the ZigBee-based health-care applications are widely used [4], we preferred to follow the ZigBee-based stack in this research. In the literature, challenges have been discussed independently as well as jointly by using different methodologies and approaches [6-15]. Energy efficiency is attained either optimizing the performance on different layers including network, MAC and physical or using cross-layer optimization approach. The QoS concerns in LR-WPANs are different and more challenging as we are focusing on periodic data traffic for patient monitoring systems, where many small packets are generated in short time interval and these packets require timely and reliable delivery with efficient channel access. Moreover, on the network layer, the WBASNs/IoTs based link quality routing protocols with lower-power radios in hospital environment provide low performance in terms of next hop selection. This result is due to inadequate empirical channel characterization assessment in terms of reliability. There is, therefore, a need to develop a real test-bed of these low-power devices for wireless channel characterization and reliability assessment to improve the routing mechanism.

The main contribution of this thesis is a new enhancement of the MAC and network layers for WBASNs. The thesis addresses the problem of optimizing the QoS parameters: limited delay, appropriate throughput, efficient channel access, reliability, and energy efficiency for the IEEE 802.15.4 and IEEE 802.15.6 standards for remote patient monitoring. This QoS optimization is achieved in three steps. In the thesis, each step is presented in a Chapter, except for Chapter 2 which is a literature review. As a first step, in Chapter 3, we optimized delay, reliability, and throughput for the IEEE 802.15.4 and IEEE 802.15.6 standards using parameter tuning approach. We proposed Delay, Reliability, and Throughput (DRT) profile to obtain the optimized values of the MAC layer transmission parameters using multiple frequency bands for the IEEE 802.15.4 and IEEE 802.15.6 standards. In the second step which is presented as Chapter 4, we optimized the energy utilization and proposed a Tele-Medicine Protocol (TMP) using duty cycle mechanism (sleep and wake-up mode for energy efficiency). TMP uses DRT profile to incorporate the optimization in terms of delay, reliability, and throughput. The third step is presented as Chapter 5 where the optimization of MAC layer QoS parameters is discussed in the context of life-critical applications. Moreover, in Chapter 5, an innovative approach that is frame aggregation is presented to achieve optimized QoS. This contribution is different from the contribution of DRT mentioned in Chapter 3. DRT provides QoS optimization using parameter tuning approach in terms of delay, reliability, and throughput for patient monitoring applications; whereas in Chapter 5 optimization is done using a frame aggregation mechanism that provides energy efficiency while considering delay, reliability, and throughput for life-critical patient monitoring applications. Implementation of DRT does not require any change in the standard IEEE 802.15.4. Following this section, Chapter 6 addresses the network layer, using empirical experiments; intelligent routing metrics are identified for link quality-based routing protocols for WBANSs/IoTs in a hospital environment. A test-bed is deployed in Royal Bournemouth Hospital to analyze Link Quality Indicator (LQI), Received Signal Strength Indicator (RSSI), Packet Error Rate (PER). Moreover, this empirical investigation validates the wireless channel characteristics for four scenarios in a hospital environment. These scenarios include: inside ward, corridor communication, ward to corridor and ward to ward. Moreover, we proposed a cross-layer routing architecture for WBASNs which provides guidelines for upcoming routing architecture. The integration of the IEEE 802.15.4 and IEEE 802.15.6 standards with the IPv6 network is an important concern. Without this integration, these standards could not become the part of IoTs. The IEEE 802.15.4 standard can communicate with IPv6 using IETF standards, but the IEEE 802.15.6 standard is not capable of communicating with IPv6 network due to frame format difference. To address this issue, we presented a solution in form of two Internet drafts in IETF. The draft is presented in Appendix B.

1.2. Applications and challenges

The technical requirements of WBASNs are application specific Therefore for efficient deployment of WBASNs, it is important to know the requirement of the specific application. Figure 1-3 shows various applications of WBASNs. In this thesis, the focus is on medical applications, Table 1-1 includes the distinct categories of WBASNs-based medical applications. These applications demand a distinct set of QoS, including limited delay, appropriate throughput, efficient channel access, high reliability and efficient energy utilization from MAC and network layer to become a useful application for patient monitoring.

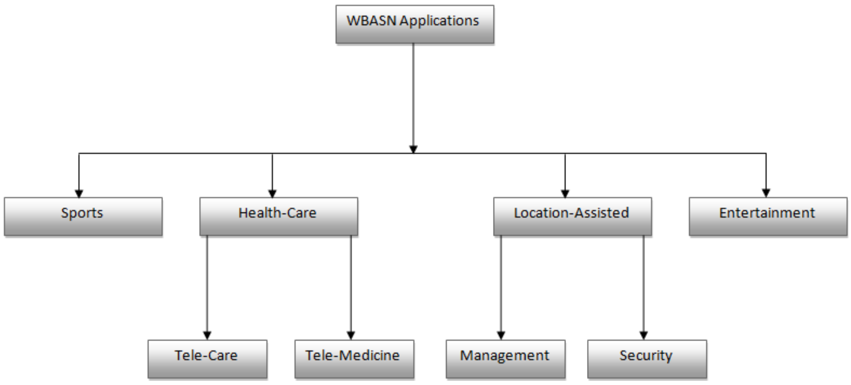

Figure 1-3 Applications of WBASNs for healthcare

Table 1-1 Categorization of Medical Applications

Medical Application Categories	Subcategories
Wearable WBASNs (On-body)	Assessing soldier fatigue
	Aiding sport training
	Sleep staging
	Asthma
	Wearable health monitoring
Implant WBASNs (In-body)	Cardiovascular diseases
	Cancer detection
Remote WBASNs	Ambient assisted living (AAL)
	Patient monitoring
	Tele-medicine systems

Biomedical sensors provide physiological data to physicians for remote patient monitoring. The collected data must reach to the sink (coordinator) node within a predefined threshold of delay otherwise it will not remain meaningful [16-18]. In WBASNs, latency must be less than 250 ms for most of the application; however, it is < 125 ms for some critical medical applications. Similarly, sensor nodes should be capable of reliable data transmission. There are trade-offs; however, because of prioritizing reliability, delay, and energy consumption. To achieve more reliability, for instance, delay and power consumption will increase. Alternatively, if the data is processed with less delay and high reliability, more energy tends to be consumed

[18-21]. Table 1-2 includes the transmission QoS requirements for some biomedical sensor nodes.

Table 1-2 QoS requirements of biomedical sensors [22]

Sensor nodes	Data generation interval	Required Data rate (Kbps)	Delay requirement	Power consumption	Reliability Requirement
ECG	4 ms	34	<125ms	Low	High
EMG	6 ms	19.6	<125ms	Low	High
EEG	4 ms	19.6	<125ms	Low	High
SpO2 (Pulse Oximeter)	10 ms	13.2	<250ms	Low	Medium
BP	10 ms	13.2	<250ms	medium	Medium
Respiration	40 ms	3.2	<250ms	medium	Medium
Skin temperature	60 s	2.27	<250ms	Low	Medium
Glucose sensor	250 s	0.528	<250ms	medium	Medium

Despite the limited battery power of body sensors, some devices are required to work unobtrusively for months or even years. In MAC protocols, energy waste is because of idle listening, collision, and overhearing. WBASN may consist of multiple physiological sensors which require different data rates as mentioned in Table 1-2, therefore, selection of appropriate Radio Frequency (RF) is a crucial part in deploying patient monitoring systems. The heterogeneous nature of biomedical sensors makes the required QoS more complex for the MAC layer as it may need to send data with high priority. Moreover, deployed sensors may require different data rate and latency values as mentioned in Table 1-2.

Therefore, the design of WBASNs protocols must consider enormous factors to ensure efficient implementation for a specific application. Beginning from these application requirements, it is important to design proficient MAC and network layer communication protocols that fulfill the specific WBASN application requirements.

The aim of the proposed research approach is to optimize the QoS by considering stringent application requirements altogether.

1.3. Problem statement

The thesis identifies the existing challenges of WBASNs for the MAC and network layers. Five main problems are addressed in the theses which are discussed below:

Problem_1: The values for the MAC layer transmission parameters for healthcare monitoring applications do not provide the required QoS in terms of delay, reliability, and throughput.

The IEEE 802.15.4 and IEEE 802.15.6 CSMA/CA-based MAC layer transmission profile operates under default parameters values and do not fulfill the QoS requirements altogether at a given time for patient monitoring applications of WBASNs [14, 22]. The IEEE 802.15.4 and IEEE 802.15.6 standards are capable of supporting WBASNs in terms of energy efficiency, reliability, and timely data delivery only if the medium access control parameters are tuned appropriately. These parameters include macMinBE, macMaxCSMABackoffs, and MacMaxFrameRetries [21]. Tuning of these parameters is a challenging task because of unavailability of the MAC layer transmission models. The problem, therefore, is found in trying to identify the suitable combinations of these parameters which could jointly optimize the performance of MAC layer for WBASNs in terms of limited delay (< 250 ms for patient monitoring applications), reliability (for effective and processing and decision making) and throughput. Moreover, detailed performance analyses of different frequency bands including 420 MHz, 868 MHz, and 2.4 GHz is required. The key issues considered to be in this problem are three-fold. The first is how to design and develop a numerical modelling for the IEEE 802.15.4 and IEEE 802.15.6

standards for performance analysis in terms of delay, reliability, and throughput. The second fold involves the experimentation and computation to identify suitable MAC layer parameter combination. The third is how to design the simulation setup to validate numerical modelling. Figure 1-4 shows the centralized WBASN scenario which requires a specified QoS as described above. Moreover, Figure 1-4 shows that all nodes are working under a single coordinator. The scenario requires an efficient MAC protocol which should be capable of managing channel access among the nodes while considering their delay and reliability requirements.

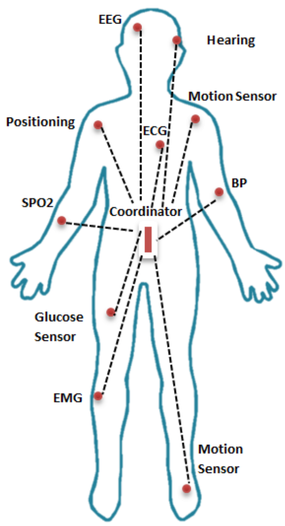

Figure 1-4 On-body centralized (star topology) communication

Problem_02: Optimization of duty cycle-based MAC layer protocol is required for efficient energy utilization.

For WBASNs, current adaptive duty cycle protocols are based on the IEEE 802.15.4 slotted CSMA/CA. These protocols have proven to be expensive in terms of energy utilization [8]. Moreover, for efficient energy consumption, these protocols adjust the duty cycle values based on estimating factors like active periods, buffer occupancy and collision rates. These estimations require resources in terms of delay, throughput, and energy; whereas, medical applications require limited transmission time with less energy consumption and reliable data transmission [27]. The critical issues to be inspected are three-fold. The first is how to design adaptive transmission mechanism/protocol that optimizes the performance of adaptive duty cycle protocol using IEEE 802.15.4. Secondly, another issue lies in how to attain energy efficiency for which there is need to identify superframe durations by considering network traffic load. Yet another issue is in how to design simulation setup for validation and comparative analysis with existing protocols.

Problem_03: Efficient MAC layer mechanism in terms of high throughput, minimum delay and reliability is required for life-critical monitoring applications with saturated traffic patterns for the IEEE 802.15.4.

The life-critical patient monitoring applications generate saturated traffic patterns that are, a high number of small data packets in short time interval which require an efficient channel access mechanism to fulfill the stringent QoS requirements. The situation becomes more complex when multiple sensor nodes try to access the channel under a single coordinator. The existing hybrid channel access mechanism of the IEEE 802.15.4 and IEEE 802.15.6 is proven to be less efficient for healthcare applications. The details lead to four key issues, the first of which is how to develop a traffic pattern analysis mechanism to clearly understand the data transmission requirements from deployed sensor nodes. Following this consideration, mapping of the obtained results from the first fold with the IEEE 802.15.4 hybrid channel access mechanism (Contention Access Period (CAP) and Contention Free Period (CFP)) is required to identify the performance gap. The third issue is to design an efficient scheme which could optimize the performance of the channel access mechanism in terms of QoS. Finally, a numerical modelling and simulation setup needs to be developed to validate the results. Figure 1-5 shows the saturated traffic scenario where multiple nodes are trying to access the CAP slot according to their data rates. It is difficult for CAP slot to manage such periodic channel access attempts.

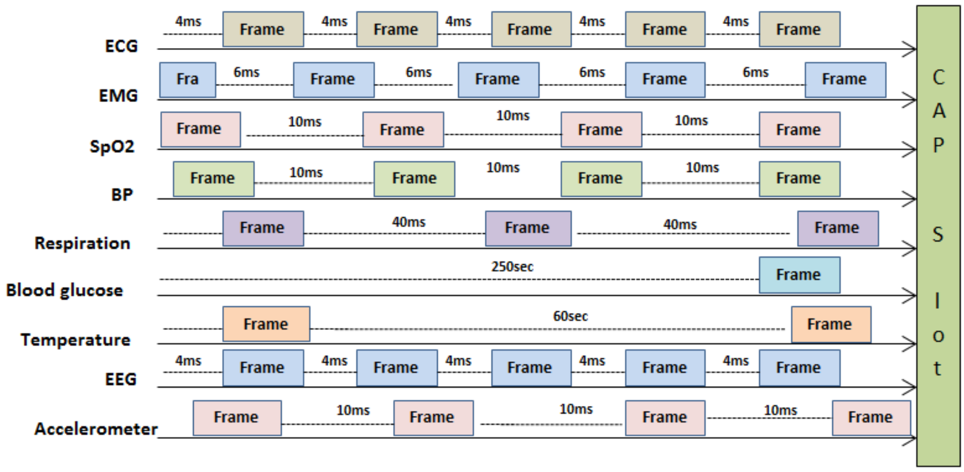

Figure 1-5 Saturated traffic scenario for channel access

Problem_04: Intelligent routing metrics are required to link quality-based routing protocols of WBASNs/IoTs to monitor patients in a hospital environment.

The low-power radio sensors are sensitive to interference, distortion, and noise; therefore, they generally experience link reliability problems. The WBASNs/IoTs based link quality routing protocols in a hospital environment provide low performance in terms of next hop selection because of inadequate empirical channel characterization reliability assessment. There is a need to develop a test-bed for these low-power devices to evaluate wireless channel characterization and reliability. Moreover, there is a need to revisit the routing architecture by considering the requirements of IoTs in the context of low power networks. This goal requires a detailed investigation. These parameters include RSSI, LQI, packet error rate and packet reception rate. Correlations among these parameters also need to be defined to make the routing process stronger. Furthermore, categorization of the hospital environment is essential to investigate the effect of various hospital environments on operating channel. Various scenarios need to be considered in a categorized environment including Line of Sight (LOS), Non-Line of Sight (NLOS) and mobile.

Problem_05: The IEEE 802.15.6 standard is not capable to communicate with IPv6 network due to frame format difference which means the IEEE 802.15.6 standard based devices could not be part of IoTs.

To make the IEEE 802.15.6 standard as part of IoTs, it is necessary to resolve the integration issues between IEEE 802.15.6 and IPv6. The core problem includes the difference between the Maximum Transmission Unit (MTU) size of the IEEE 802.15.6 and IPv6 that is, 256 bytes and 1280 bytes as well as the auto-configuration of WBASNs nodes in the IPv6 network. There is no standard under IETF which provides the integration of the IEEE 802.15.6 with IPv6 networks.

1.4. Aim, objectives, and contributions

The aim of this thesis is to facilitate reliable, timely, energy efficient, fast and accurate communication for remote patient monitoring systems in a hospital to improve quality of life. The aim requires two steps, first is optimization of QoS transmission parameters at MAC layer and second is the identification of intelligent link quality routing metrics to support existing WBASNs/IoTs routing protocols. The careful design of communication schemes at MAC and network layer is necessary so that stringent QoS requirements could be provided.

The stringent requirements include a specific set of QoS transmission parameters. The following research objectives are defined to resolve the highlighted research problems.

Objective_01: To design a MAC layer QoS supportive mechanism using parameter tuning approach.

Design a MAC layer mechanism called QoS profile for the IEEE 802.15.4 and IEEE 802.15.6 standards which optimize the QoS in terms of limited delay, reliability, efficient channel access and appropriate throughput for patient monitoring system using WBASNs. This objective is achieved through the following tasks:

Firstly, it is important to identify the requirements of WBASNs for biomedical applications. These requirements include data rate, delay, mobility and channel conditions. This goal has been achieved through a literature review of existing WBASNs applications. Moreover, the issues regarding prioritizing QoS for biomedical sensor nodes have been discussed through this process. Secondly, the performance of recent MAC protocols for WBASNs has been evaluated by considering the medical and monitoring application requirements. The performance evaluation refers towards the efficiency of channel access mechanisms and protocols used by the standards like the IEEE 802.15.4 and IEEE 802.15.6. Further, various frequency bands are considered for the experiments under the mentioned standards. The performance metrics include end-to-end delay, data rates, energy efficiency and collision rates. Furthermore, to improve the performance of these standards under different frequency bands, a QoS profile will be proposed. To achieve this objective, the steps below were followed:

a) A literature review of existing MAC protocols for Identification of research gap with respect to patient monitoring systems;
b) Selection of the communication topologies that is, star and mesh etc.;
c) Design of a QoS profile using numerical modelling;

d) Implementation of the QoS profile in OMNet++ and CASTALIA 3.2 simulator, Castalia is a simulator for Wireless Sensor Networks (WSN) and Body Area Networks (BAN) for low-power embedded devices. It is based on the OMNeT++ platform;
e) Validation and testing of the proposed QoS profile with respect to patient monitoring systems requirements;
f) Simulate these scenarios using the simulator OMNet++ and CASTALIA 3.2;
g) Evaluate the performance in the scenarios by considering parameters like data rate, delay, channel access fairness, energy usage, channel fading and prioritized QoS;
h) Analysis of the results

The solution provided in objective 1 does not demand any modifications of the IEEE 802.15.4 and IEEE 802.15.6 standards and it is easily implementable.

Objective_02: To design a duty-cycle based energy efficient MAC layer mechanism.

Design a duty-cycle based energy efficient adaptive MAC layer mechanism called Tele-Medicine Protocol (TMP) for the IEEE 802.15.4 slotted CSMA/CA by considering the limited delay and reliability requirements for the patient monitoring system. This objective is achieved via the following tasks:

a) A literature review of existing duty-cycle adaptive MAC protocols for identification of research gap with respect to patient monitoring systems;
b) Selection of optimization methods to be used, we selected two optimization methods i.e., MAC layer transmitting parameter tuning and duty-cycle based optimization;

c) We adjusted duty-cycle based on three factors: superframe duration, DRT profile and offered network traffic load;
d) Development of the numerical models for the end-to-end delay, reliability, energy usage and collision rate for the proposed protocol;
e) Implementation of the mechanism used in the OMNet++ simulator by adopting CASTALIA 3.2;
f) Simulation and evaluation of the proposed mechanism in terms of delay, data rate, channel access, energy;
g) Analysis of the results and its comparison with the existing work

Objective_03: To design a MAC layer frame aggregation scheme to support high throughput and reliability for life-critical patient monitoring environment.

Design of a MAC layer frame aggregation scheme is proposed which composes the Aggregated-MAC Protocol Data Unit (A-MPDU). This process provides high throughput and efficient channel access mechanism for periodic data transmission by considering the specified QoS requirements for critical patient monitoring systems. This objective is completed via the following tasks:

a) A literature review of the existing hybrid channel access MAC protocols in the context of critical patient monitoring systems using WBASNs;
b) Design of a traffic pattern analysis mechanism to extract the periodic transmission of data from sensor nodes in a patient monitoring system. This numerical modelling is needed to extract the information including data generation interval, packet sizes and required data rate. For experiments, nine different biomedical sensors including ECG, EMG, EEG, pulse oximeter,

BP, respiration, blood glucose level, temperature and activity recognition were considered;

c) Mapping analysis of the requirements obtained. This analysis needed to be done with numerical modelling;

d) Design of a frame aggregation mechanism by considering the MAC layer of the IEEE 802.15.4;

e) Numerical analysis of the proposed mechanism to evaluate its performance;

f) Implementation of the mechanism using CASTALIA 3.2 and NS 2.29;

g) Simulation and evaluation of the proposed mechanism in terms of delay, data rate, channel access, and energy;

h) Analysis of the results of the proposed protocol and comparison with existing work

Objective_04: Identification of intelligent routing metrics using empirical experiments in a hospital environment.

Design an empirical reliability assessment mechanism to validate the wireless channel characteristics of the low-power radios for the successful deployment of WBASNs/IoTs based link quality routing protocols in a hospital environment. Figure 1-6 shows the low-power based network scenario in a hospital environment. This objective is completed via the following tasks:

a) A literature review of the existing WBASNs/IoTs routing protocols to identify the most suitable protocol for patient monitoring;

b) Evaluation of the selected protocols using the OMNet++ and CASTALIA 3.2 simulators;

c) Analysis of various existing link quality techniques for routing protocols;

d) Categorization of a hospital environment;

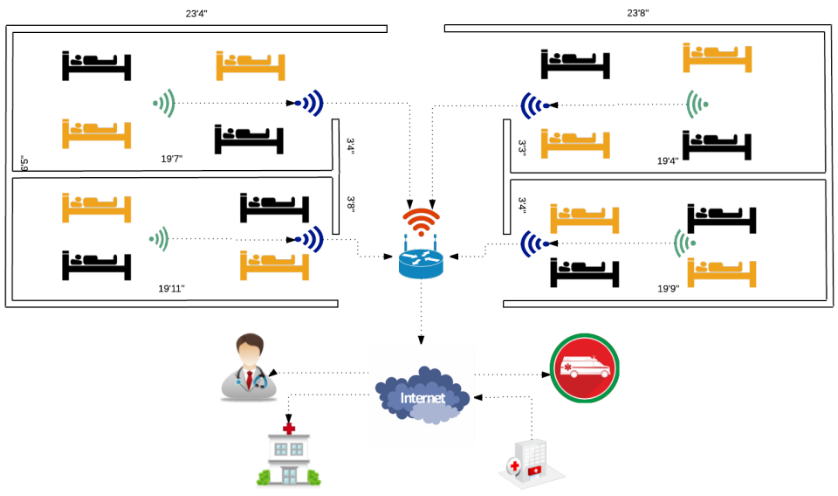

Figure 1-6 Low-power based network scenario in a hospital

e) Test-bed design for experiments which includes hardware selection and its deployment in a hospital environment;

f) Empirical analysis of the different scenarios including Line of Sight (LOS) and Non-Line of Sight (NLOS). Evaluation parameters include RSSI, LQI, packet error rate and packet reception rate;

g) Correlation identification among RSSI, LQI, distance, packet error rate and packet reception rate

Objective_05: To design an adaption layer mechanism that integrates the IEEE 802.15.6 standard and IPv6.

For this goal an adoption layer is required which smooth the integration process by resolving following key issues:

a) Fragmentation and reassembly by considering the MTU size;

b) Stateless address auto-configuration;

c) IPv6 header compression

Table 1-3 shows the contributions of published/submitted research work. Overall three journals and two conferences papers are published. Two journal papers are in the review process. The partial work in this thesis has been published in journals mentioned in Table 1-3

Table 1-3: Thesis contributions

Contributions	List of publications
WBASNs Survey **(**Chapter 2)	Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang,"Wireless Body Area Sensor Networks: A Survey of Application, MAC and Network Layer protocols for Patient Monitoring", (**s**ubmitted in IEEE Communications Surveys & Tutorials 15 September 2017)
DRT profile (Chapter 3)	Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Delay, reliability, and throughput based QoS profile: A MAC layer performance optimization mechanism for biomedical applications in wireless body area sensor networks", Published in Journal of Sensors, 2016, doi: 10.1155/2016/7170943, Impact factor= 1.7 Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Implanted medical devices as future of wireless healthcare monitoring: Investigation and performance evaluation using novel numerical modeling", In proceeding of 22nd International Conference on Automation and Computing, 2016, doi: 10.1109/IConAC.2016.7604973 (Published)
TMP protocol (Chapter 4)	Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "TMP: Tele-Medicine Protocol for Slotted 802.15. 4 With Duty-Cycle Optimization in Wireless Body Area Sensor Networks", Published in IEEE Sensors, vol 17, No 6, 2017, doi: 10.1109/JSEN.2016.2645612, Impact factor =2.5
Frame aggregation mechanism (Chapter 5)	Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "IEEE 802.15. 4 Frame Aggregation Enhancement to Provide High Performance in Life-Critical Patient Monitoring Systems", **Published** in MDPI Sensors, vol 17, No 2, 2017, doi: 10.3390/s17020241, Impact factor= 2.67 Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "A holistic simulation model for remote patient monitoring systems using Wireless Body Area Sensor Networks (WBASNs)", In proceeding of 9th International Conference on Software, Knowledge, Information Management and Applications, 2015, doi: 10.1109/SKIMA.2015.7399990 (Published)

Empirical experiments for identification of intelligent routing metrics (Chapter 6)	Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Channel Characterization and Link Quality Validation of IEEE 802.15.4-based Routing Protocols for WBASNs/IoTs in Hospital Environment", (submitted in IEEE Transactions on Wireless Communications, 25 November 2017)
IETF draft for integration of the IEEE 802.15.6 with IPv6 networks (Appendix B)	Published in IETF https://datatracker.ietf.org/doc/draft-sajjad-6lo-wban/

Figure 1-7 provides an abstract view of the thesis.

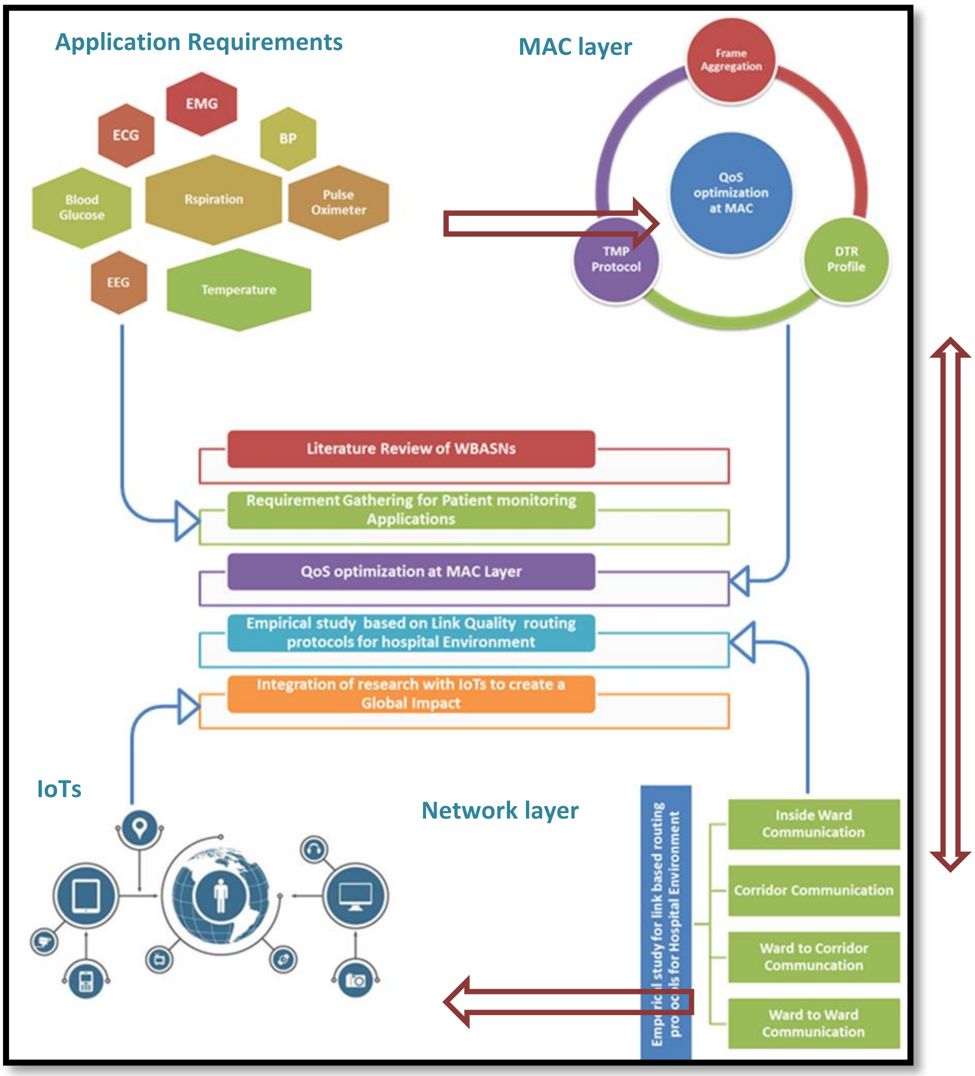

Figure 1-7 Thesis abstract view

Figure 1-8 provides the thesis structure and the relation among the chapters. The thesis consists of seven Chapters. The 1st Chapter presents the introduction, motivations, problems, objectives, and contributions. The 2nd Chapter provides the literature review of the WBASNs for the MAC layer and the network layer. Chapter 3, 4, 5 and 6 consist of our proposed work. The results of Chapter 3 have been partially used in Chapter 4. The partial works in Chapter 3, Chapter 4 and Chapter 5 have been published in three journals and two conferences, mentioned in Table 1-3. The partial work in Chapter 6 and Chapter 2 has been submitted in journals for publications, mentioned in Table 1-3. Chapter 7 provides the conclusion of the thesis with findings and shortcomings. Two Appendixes are given. Appendix A provides the background for WBASNs and Appendix B consist of our IETF draft to support our Objective 5.

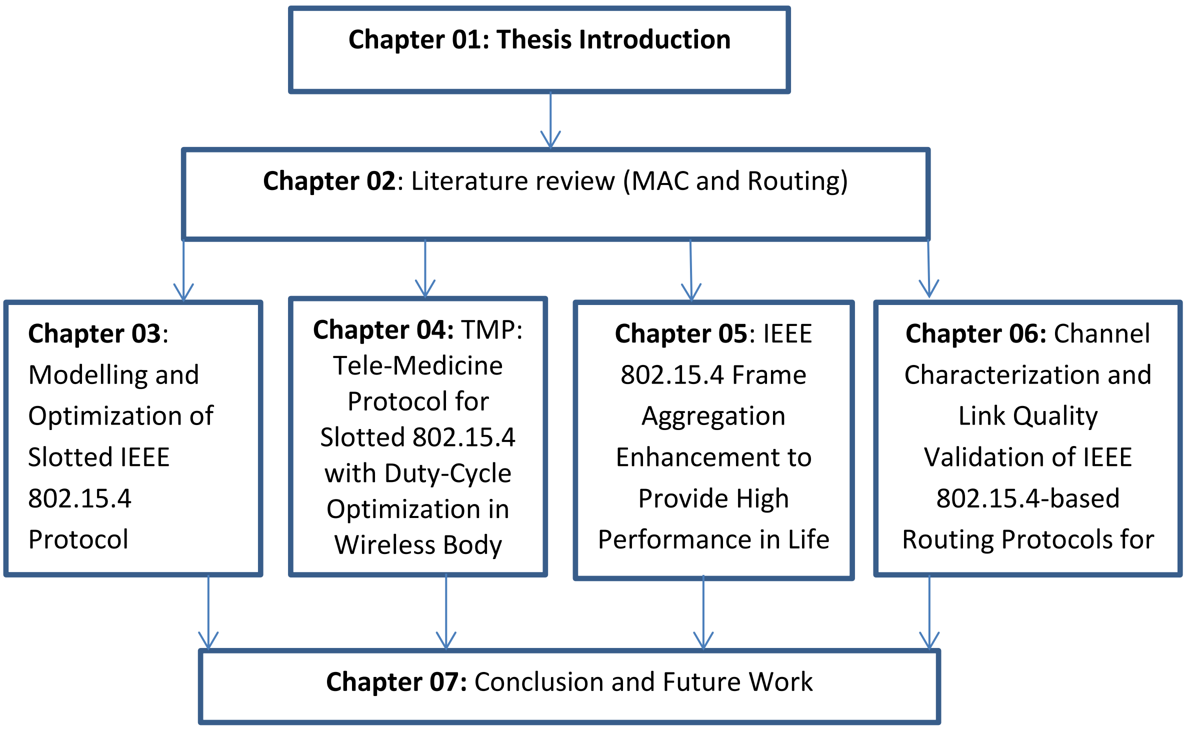

Figure 1-8 Thesis structure

Chapter 2: Literature Review

2.1. WBASNs standards

Implementation of WBASNs is usually done by using WPANs communication protocols including ZigBee (IEEE 802.15.4), IEEE 802.15.6 and Bluetooth. There are various other wireless technologies that can be potentially used for WBASNs and summarized in Table 2-1. The IEEE, International Society of Automation (ISA) and IETF brought new wireless standards which are usually available as a commercial product. In the literature, there are various proposed protocols for WBASNs like ZigBee [4], 6loWPAN [23], 6lo [24], 6tisch [25], WirelessHART [26], ISA SP-100 [27], IEEE 802.15.4 [28] and IEEE 802.15.6 [29].

ZigBee: The ZigBee standard operates under the umbrella of the ZigBee Alliance which consists of more than seventy members from industry. ZigBee is a wireless mesh network standard with characteristics of low-power, low-cost, energy efficient and limited latency. The ZigBee chips are integrated with microcontrollers. It operates under various ISM frequencies bands including 2.4GHz, 784 MHz (China), 868 MHz (Europe) and 915 (the USA and Australia) with data rate from 20 Kbps to 250Kbps.

ZigBee works on network layer by using star, tree and mesh topologies. It works under the same guidelines of the IEEE 802.15.4 that is, a central coordinator as controlling entity. ZigBee is developed over the physical and MAC layer of the IEEE 802.15.4 standard. It adds four additional key components: the network layer, the application layer, manufacturer-defined application objects and Zigbee Device Objects (ZDOs). The “ON World” a famous technology research firm has published a report which states that ZigBee has a big share for the IEEE 802.15.4 based IoTs applications [30]. Table 2-1 gives a comparative analysis of various available technologies.

Table 2-1 Characteristics of available technologies [31]

Technology	**Data rate**	**Frequency**	**Modulation**	**Channel**	**Topology**	**Range**	**Setup time**	**Peak power**	**Market adaptability for WBASNs**
Bluetooth Classic	1-3Mbps	2.4 GHz	GFSK	79	Scatternet	1-10 m	3 sec	~45mA	Low due to high power requirements
Bluetooth Low Energy	1 Mbps	2.4 GHz	GFSK	3	Piconet, Star	1-10 m	< 100 sec	~28mA	Low due to power requirements and less channels
IEEE 802.15.4(LR WPAN) /ZigBee	250 Kbps	2.4 GHz 868 MHz 915 MHz	O-QPSK	16	Star, Mesh	10-100 m	30 sec	~16.5mA	High for its suitability for wearable sensors in terms of QoS
IEEE 802.15.6	10 Kbps -10 Mbps	2.4 GHz, Narrowband, HBC and UWB communication	D8PSK, DBPSK, DQPSK	Multiple channels according to frequency bands	Two hop Star, Mesh	1-5m	<3 sec	~1mA	Still in adoption stage, as it also involves implanted sensors
ANT	1 Mbps	2.4 GHz	GFSK	125	Star, Mesh or tree	10-30 m		~22mA	Low due to high power and limited QoS
Senium	50 Kbps	868 MHz 915 MHz	BFSK	16	Star	1-5 m	< 3 sec	~3mA	Low due to its low data rates
Zaralink ZL70101	50Kbps	402-405 MHz 433-434 MHz	2FSK/4FSK	10	P2P	1-5 m	< 3 sec	~3mA	Low due to its low data rates

The latest standards of WBASNs include IEEE 802.15.6 and IEEE 802.15.4 which aim to provide low-power, reliable and short-range communication within the human body [32-35]. Figure 2-1 presents the sequence of a literature review for MAC layer QoS optimization.

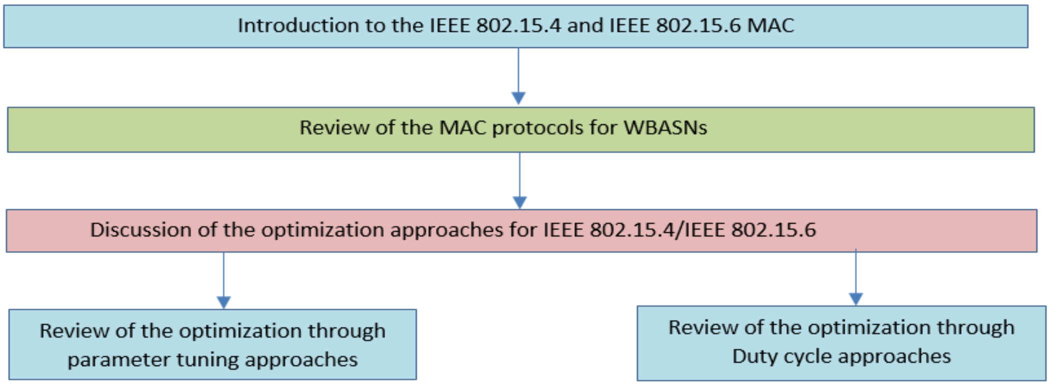

Figure 2-1 Sequence of literature review

2.2. Introduction of the IEEE 802.15.4 and IEEE 802.15.6 MAC

The IEEE 802.15.4 standard defines the Data Link Layer (DLL) and a physical layer for low-rate LR-WPANs. It is developed and maintained by the IEEE 802.15 working group, which provides the basis for WPANs. IEEE 802.15.4 defines two types of devices that are, Full Function Device (FFD) and Reduced Function Device (RFD). FFD supports full functionalities and can act as network coordinator; whereas, RFD supports limited functionality and usually use at network edge device as it consumes low power. The role of the network coordinator is to manage a network as the central controller. The physical layer of the IEEE 802.15.4 uses three frequencies bands: a) 2.4 to 2.4835 GHz with 16 channels; b) 902 to 928 MHz using 10 channels; c) 868 to 868.6 MHz with a single channel. Data Link Layer (DLL) consists of two sub-layers, MAC and Logical Link Control (LLC) layers. LLC is defined in the IEEE 802.2. MAC layer handles various activities including beacon management, Guaranteed Time Services (GTS) management, and channel access mechanism.

Figure 2-2 shows the frame structure which consists of a MAC Protocol Data Unit (MPDU) and a Physical Service Data Unit (PSDU). The PSDU consists of four fields: a) preamble (32-bit length for symbol synchronization); b) packet delimiter (8 bits long) for frame synchronization; c) physical header (8 bits, defines the PSDU length); d) PSDU containing the payload of length 0 to 127 bytes. The MPDU carries three fields: a three-byte MAC header (containing different information fields like frame control field (FCF); duration, sequence control information and address field); frame body of variable length and MAC Footer (MFR).

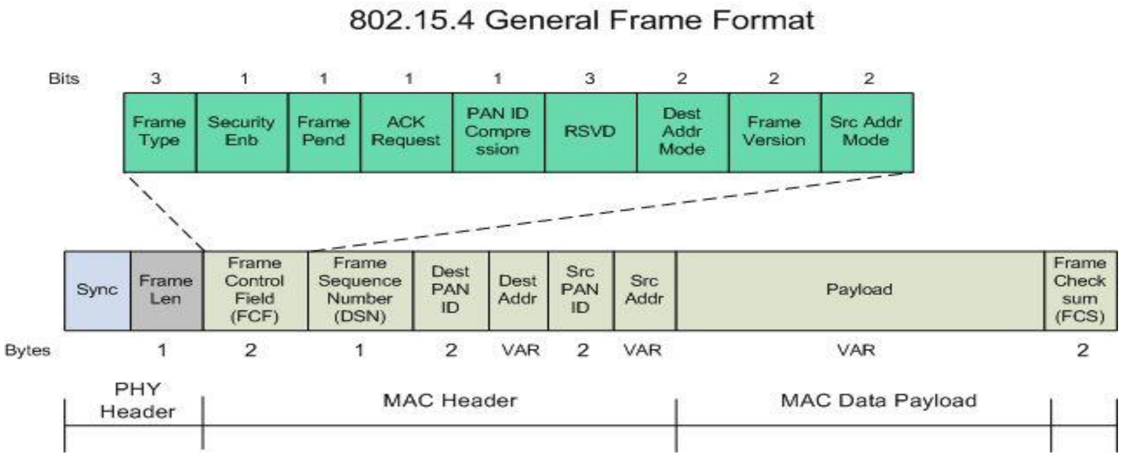

Figure 2-2 Frame format of the IEEE 802.15.4 [36]

Overall, the standard defines four types of frame, namely, beacon frame (mostly the coordinator is used for beacon transmission), a data frame (used for transmission of data), acknowledgement frame and MAC command frame (for all MAC peer entity control transfers). Non-beacon mode (un-slotted) and beacon mode (slotted) are two basic transmission modes of IEEE 802.15.4.

2.2.1. Non- beacon mode and beacon mode for the IEEE 802.15.4

In a non-beacon mode, when a node wants to transmit data, it will sense the channel (unslotted CSMA/CA) and if the channel is free then it will transmit data and receives an acknowledgement (this acknowledgement is optional). The coordinator is set to be in the waiting state in this mode. If the channel is busy, then the device needs to wait for a random amount of time which is defined in the standard. This mode is suitable for those sensors which usually like to sleep for most of the time.

There is no need for any synchronization process from the coordinator; the coordinator is only responsible for the association and disassociation process. This mode provides scalability, long battery life, and self-organization, but it does not guarantee for data delivery. Figure 2-3 shows the data flow diagram for the non-beacon mode. The non-beacon based CSMA/CA is based on three variables, namely Backoff Exponent (BE), backoff delays and Number of Backoffs (NB) attempts. BE is used for backoff delay calculation. The backoff period can be defined as the time required for sending 20 symbols (each symbol represents 4 bits). The number of backoff periods depends on a random value that falls from 0 to $2^{BE} - 1$, where the value of BE is initialized with a variable of the CSMA/CA algorithm macMinBE. NB represents the number of backoffs attempts while accessing the channel. Figure 2-3 shows the data flow diagram for the beaconless mode.

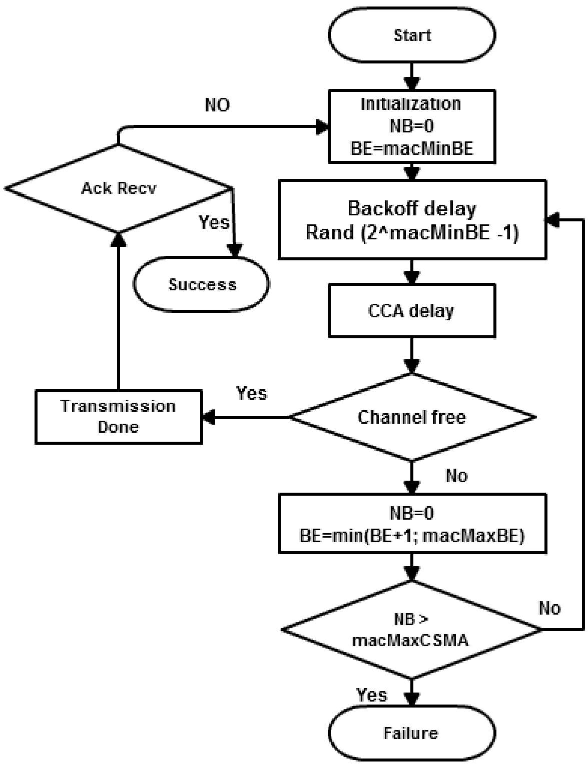

Figure 2-3 Data transmission flow chart of non-beacon/beaconless mode of the IEEE 802.15.4 [36]

In the beacon mode of the IEEE 802.15.4, the coordinator sends a frame called “beacon frame”, which helps to make the superframe structure [28, 34]. The beacon mode is also referred to slotted mode because it uses slotted CSMA/CA, where slot boundaries of devices are aligned with the boundaries of Personal Area Network (PAN) coordinator. In the IEEE 802.15.4, energy efficient channel access mechanisms help to increase the network lifetime. In contention process, nodes delay the carrier sensing by a random backoff delay during which they go to the low power state to save energy. After the random backoff delay, the node wakes-up to listen to the channel for two backoff slots. If it does not get a successful access, then it goes into the sleep mode again to save power. Figure 2-4 shows the superframe structure of the IEEE 802.15.4. The boundary of the superframe is enclosed by beacon frames, where Beacon Interval (BI) is used to describe the time between two consecutive beacons. The MAC layer parameters including Beacon Order (BO) and Superframe Order (SO), defines the BI length and the Superframe Duration (SD) respectively. The superframe is divided into two portions: the active portion and an inactive portion [36].

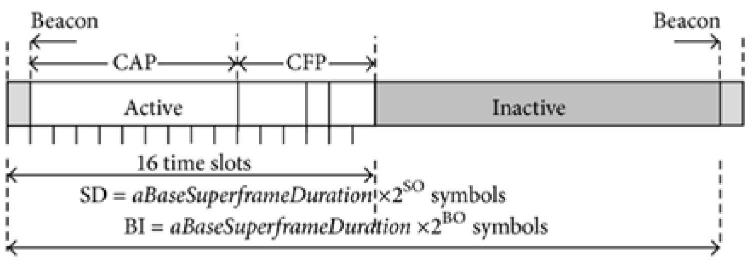

Figure 2-4 Beacon frame format of IEEE 802.15.4 [36]

The active portion of the superframe is divided into three parts: beacon, CAP, and CFP. The beacon is transmitted by the coordinator at the start of an active period of the first slot of each superframe. The CAP starts immediately after the beacon and ends at right before the start of CFP. The PAN coordinator assigns the active superframe slots to the nodes which have requested. These slots are called Guaranteed Time Slots (GTSs). The active portion consists of 16 equally spaced time slots. If the length of CFP is set to zero then CAP will be completed at the end of active period [35]. According to the IEEE 802.15.4, the BI defines the length of the superframe as follows:

$$\text{BI} = \text{aBaseSuperframe Duration}*2\text{BO symbols} \quad \text{for } 0 \leq \text{BO} \leq 14 \qquad (2\text{-}1)$$

The active period follows the following formula:

$$\text{SD} = \text{aBaseSuperframe Duration}*2\text{SO symbols for } 0 \leq \text{SO} \leq \text{BO} \leq 14. \qquad (2\text{-}2)$$

In slotted CSMA/CA, the MAC layer ensures that after initial random backoff, the remaining CSMA/CA operations (Clear Channel Assessment (CCA), data transmission and acknowledgement) can be completed before the end of CAP. Hence, in the case where the number of backoff periods is higher than the remaining slots in the CAP, the MAC sub layer pause the backoff countdown at the end of CAP period and resumes the backoff counter at the start of next CAP of the superframe. If the number of backoff slots is less than or equal to the remaining slots in CAP, then the MAC sub layer goes for next step which is CCA [57]. In the beacon mode, nodes contend for the channel using the slotted CSMA/CA algorithm shown in Figure 2-5. Each node maintains three parameters for transmission: NB, Contention Windows (CW) and BE. NB is set to zero for a new transmission attempt. The parameter CW is the CW length. BE represents the number of backoff slots a device should wait before channel access attempt, where each slot represents 20 symbols. It has two types, namely, minimum backoff exponent (macMinBE), maximum backoff exponent (macMaxBE). The value of BE is initialized with macMinBE. The slotted algorithm for CSMA/CA initializes the values of NB, CW, and BE, then locate the boundary for the next slot period [33]. The MAC sub layer delays for the random number of backoff units time assigned range between 0 and $2^{\wedge BE-1}$. After completion of initial random backoff delay, CCA is performed. In case of an idle channel, CW is decremented and after one decrement another CCA attempt is made at the end of next backoff period slot boundary. The packet transmission is only allowed when CW reaches zero. If the channel is busy in both of the CCA attempts, then the values of NB and BE are incremented by one, ensuring that the value of BE is not more than macMaxBE. If the NB value is less than or equal to macMaxCSMABackoffs then the process will go for random delay procedure again, otherwise, transmission failure occurs [36]. Figure 2-5 describes the flow chart for the beacon mode.

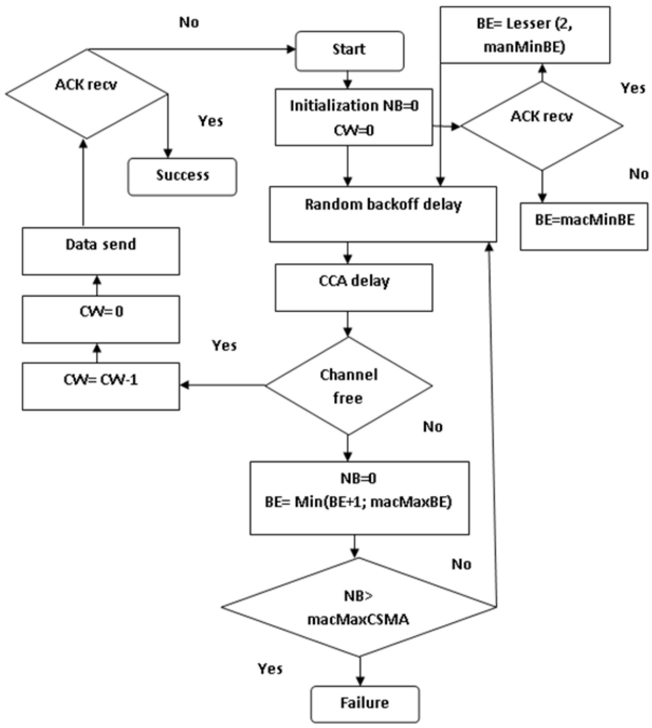

Figure 2-5 Data transmission flow chart for beacon mode of IEEE 802.15.4 [36]

2.2.2. IEEE 802.15.6

Task group for the IEEE 802.15.6 was established in November 2007and the IEEE 802.15.6 standard was approved as WBAN standard in 2012. This standard operates in and around the human body with a focus on operating at lower frequencies and short range [1, 37, 38]. The focus of this standard is to design a communication standard for the MAC and physical layers to support different applications. Namely, these are medical and no-medical. Medical applications collect vital signal information for diagnoses and treatment of various diseases with the help of different sensors (such as an accelerometer, temperature, BP, and EMG). It defines a MAC layer that can operate with three different PHY layers: Human Body Communication (HBC), UWB and Narrowband NB. IEEE 802.15.6 provides a specification for MAC layer to access channels. The coordinator divides a channel into superframe time structures. Superframes are bounded by equal length beacons frames. Usually, beacons are sent at beacon periods except for inactive superframes or limited by regulation. The standard supports three channel access modes.

2.2.2.1. Beacon Mode with Beacon Period Superframe Boundaries

Beacons are sent at beacon periods by the coordinator and the superframe structure is managed by the coordinator by using beacon frames. Figure 2-6 shows the frame structure of the IEEE 802.15.6. NB deals with data transmission/reception, CCA and deactivation/activation of the radio transceiver. The Physical Protocol Data Unit (PPDU) frame of NB consists of a PSDU and a Physical Layer Convergence Procedure (PLCP). PLCP preamble supports the receiver for the synchronization process. PLCP header sends decoding information for the receiver and it is transmitted after PLCP preamble. PSDU is the last module of PPDU and consists of MAC header, Frame Check Sequence (FCS) and MAC frame body. PSDU is transmitted after PLCP. Different modulations schemes can be used with NB, namely, Differential Binary Phase-shift Keying (DBPSK), Differential Quadrature Phase-shift Keying (DQPSK) and Differential 8-Phase-shift Keying (D8PSK) [1]. NB uses seven frequency bands and operates under different data rates and modulation schemes. Medical Implant Communication Service (MICS) is the first licensed band of NB and is used for implant communication with a range of 402-405 MHz in most countries. Lower frequencies create less attenuation and shadowing effect. Wireless Telemetry Medical Services (WTMS) is another license band and is used for telemetry services. Although, Industrial, Scientific, and Medical (ISM) band is free worldwide, however, it generates a high probability of interference for the IEEE 802.15.4 and IEEE 802.15.6. Figure 2-6 describes the frame structure of IEEE802.15.6 [1].

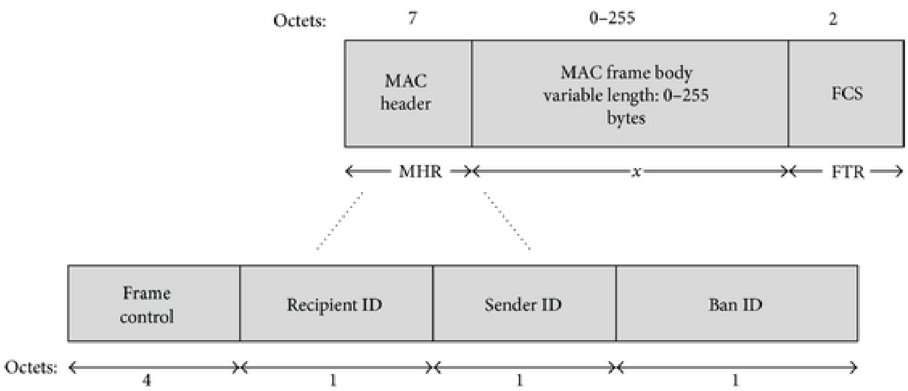

Figure 2-6 Frame structure of IEEE 802.15.6 [1]

The superframe structure consists of several phases: Exclusive Access Phase 1 (EAP 1), Random Access Phase 1 (RAP1), type I/II phase, EAP 2, RAP 2 and CAP. CSMA/CA or slotted Aloha is used by EAPs, RAPs, and CAPs. For emergency services and high priority data, EAP 1 and EAP 2 are used; whereas, CAP, RAP 1 and RAP 2 are used for normal data traffic. Type I and II are used for bi-link allocation intervals, up-link, and down-link allocation intervals. For resource allocation, the type I and II polling mechanisms are used [1]. Figure 2-7 shows the distinct phases of channel access options for the IEEE 802.15.6.

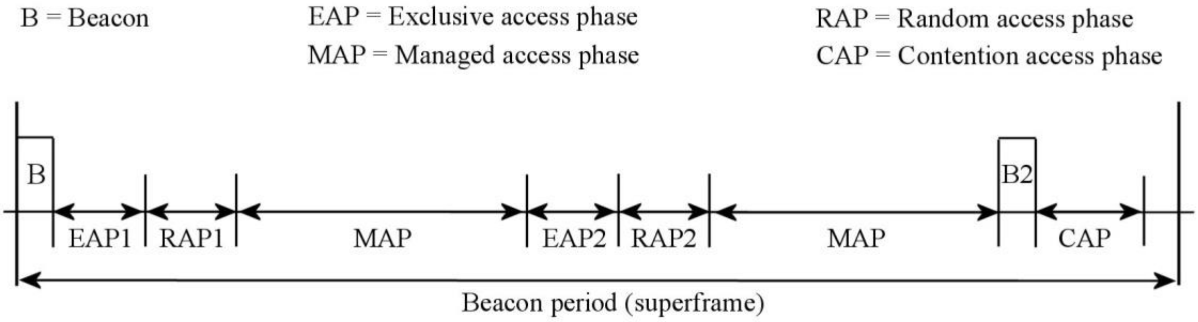

Figure 2-7 Phases of the IEEE 802.15.6 superframe [1]

Figure 2-8 shows a flowchart of CSMA/CA mechanism. A node's backoff counter value is set to a random integer number between 1 and CW, where CW (default value is CWmin) belongs to CWmin and CWmax which is dependent on user priority. When the algorithm starts, the node begins a counter decrement by one for each idle CSMA/CA slot. A node considers a CSMA/CA slot idle. When the backoff counter reaches zero, the node transmits the data frame. In case the channel is busy because of some other frame transmission, the node locks its backoff counter until the channel in question becomes idle. The value of CW becomes double in the case of an even number of failures until it reaches CWmax [36].

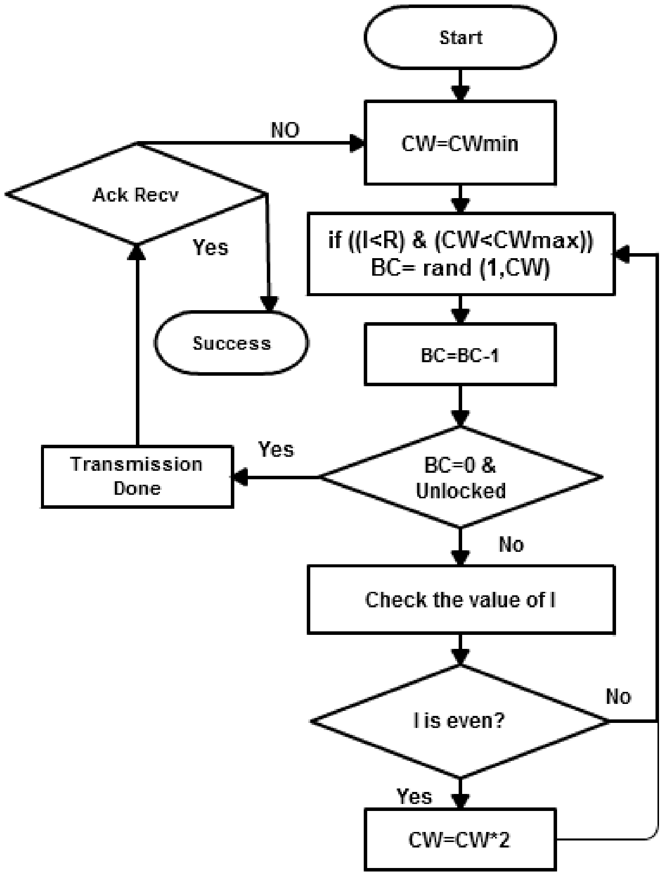

Figure 2-8 Data transmission flow chart for CSMA/CA in the IEEE 802.15.6 [36]

2.2.2.2. Beacon mode with superframe boundaries

In this channel access mode, beacons are not transmitted, and the channel is assigned by using a polling mechanism to access the transmission channel.

2.2.2.3. Beacon mode without superframe boundaries

For this mode, the coordinator provides an unscheduled poll allocation and each node establish its own schedule. Different access mechanisms are used in superframe phases: schedule access (connection-oriented and contention-free access), improvised and unscheduled access (connectionless and contention-free access) and random access [1].

2.3. MAC protocols in WBASNs

The interest in WBASNs for remote patient monitoring has increased considerably. This trend is reflected by recent, which has proven that the medium access method used in WBASNs plays a vital role to fulfil the specific QoS requirements for the biomedical devices [18]. These QoS requirements are data rates, reliability, and energy consumption. During the last few years, many MAC protocols for WBASNs have been proposed for medical applications. The WBASNs MAC protocols are classified into three broader categories based on the channel access mechanisms used, specifically: contention, scheduled and hybrid access mechanisms.

2.3.1. Distributed queuing body area network

The Distributed Queuing Body Area Network (DQBAN) [39] MAC is a hybrid protocol which provides the required QoS (delay and reliability) by using adaptive mechanisms. Two queues are introduced for successful channel access: collision resolution queue and data transmission queue. DQBAN uses a cross-layer fuzzy-rule based scheduling algorithm which allows a node to reserve a time slot for the next session to get a guaranteed channel access. The proposed technique is evaluated in a star topology by considering a hospital environment. The DQBAN uses Slotted-ALOHA for normal traffic, reservation protocol for heavy traffic and polling mechanism for collision-free traffic. Although the DQBAN provides less delay and high reliability, it is not energy efficient and it requires changes in the hardware existing standards like the IEEE 802.15.4 and IEEE 802.15.6.

2.3.2. Dynamic delayed MAC

The Dynamic delayed Medium Access Control (MAC) [40] algorithm addresses the problem of traffic diversity in WBASNs and works above the IEEE 802.15.4 MAC.

A fuzzy logic is implemented in the algorithm to make it adaptive and it receives two inputs that are, required data rate and successful channel access history. As a result, the backoff time for each node is adjusted according to its QoS requirements. It claims to provide fair channel access among nodes by improving the delay reliability. The algorithm only considers data rate to improve the IEEE 802.15.4 MAC. Testing is done with the limited number of nodes, whereas in WBASNs reliability, energy efficiency and scalability are also important in the context of medical applications.

2.3.3. Urgency-based MAC

The Urgency-based MAC (U-MAC) [41] is proposed by considering the IEEE 802.15.4 standard to meet the requirements of medical applications for WBASNs. U-MAC categorizes the sensor nodes in critical and non-critical nodes. It provides the priority channel access to the critical nodes by using mathematical modelling. The key for this protocol is to reduce the retransmission traffic of non-critical nodes. The Slotted ALOHA is used as channel access mechanism to reduce the energy consumption. The nodes in WBASNs are highly diverse in terms of data transmission requirements; whereas, the U-MAC protocol is complex and involves overheads in terms of data categorization and identification of retransmission packets. This complexity may hinder the required QoS of biomedical sensor nodes in terms of delay, reliability and energy consumption.

2.3.4. Hybrid unified-slot access

The Hybrid Unified-slot Access (HUA) [42] protocol is designed with the purpose of energy efficiency. For channel access, slotted ALOHA is used in CAP. HUA-MAC introduces the use of the mini-slot method to increase the efficiency of the CAP.

HUA claims to be an adaptive protocol because of its efficient contention mechanism and less collision probability which results in in-sufficient time being allocated to contending nodes. HUA works well in a small star topology where applications have small packet sizes; however, it shows QoS limitations in the scalable and diverse application scenarios of WBASNs [41].

2.3.5. Single-radio multi-channel TDMA MAC protocol

The medical applications of WBASNs require guaranteed data delivery within restricted time. The standard considers a single radio channel for communication which can create a large amount of latency. To address this issue various TDMA based multi-channel protocols have been proposed [43]. The sensor hardware that is available, however, only consists of a single transceiver. The Single-Radio Multi-Channel TDMA MAC protocol is proposed to address the mentioned problems. The authors implemented the proposed protocol on ZigbeX-I and ZigbeX-II modules which are based on the IEEE 802.15.4. Overall, it reduces the transmission and queuing delay. That said, the management of multichannel is still challenging due to co-channel interference and restricted band allocation. Another issue that arose was the channel requires more energy to manage the multichannel operations.

2.3.6. Energy efficient and low duty cycle

An Energy Efficient And Low Duty Cycle (EELDC) protocol [44] using TDMA is proposed for remote monitoring of physiological signals in WBASNs. This protocol focuses on energy efficient and reliable communication. TDMA mechanism is enhanced to provide very low idle listening. The experiments are conducted in a star topology. For energy efficiency, the duty cycle mechanisms are discussed. This protocol is more suitable in scenarios where high data rate traffic is generated.

Whereas, WBASNs medical applications are highly diverse in terms of data generation and require an optimized QoS by considering delay, reliability, and throughput.

2.3.7. Context-aware MAC

In WBASNs, biomedical sensor nodes are diverse in term of data generation and QoS requirements. Due to the body movements, the sensor nodes may suffer from fading which creates packet loss and eventually produces unacceptable latency values. To address this issue, a Context-Aware MAC (CA-MAC) protocol [45] is proposed which is aware of traffic loads and channel conditions. A hybrid approach is used for channel access that is, contention based and TDMA based mechanisms. These mechanisms work according to the application requirements. To address the fading conditions, CA-MAC proposes the use of a dynamic control mechanism which has the capability to amend the frame structure. For periodic and emergency data transmission, polling and scheduling-based techniques are incorporated. CA-MAC provides better reliability to cater and avoid fading. A serious concern that remains about this sensor, however, is the dynamic change in a frame structure which is not easy to implement with the IEEE 802.15.4 and IEEE802.15.6 standards.

2.3.8. Battery-dynamics driven TDMA MAC

The Battery-Dynamics Driven TDMA MAC (BDD-TDMA MAC) [46] is proposed to handle the energy issues of battery-operated biomedical sensors devices. The design of BDD-TDMA MAC considers the electro-chemical features of batteries, queuing and wireless channel conditions as fading. Improvements in latency and reliability of data transmission are the characteristics of this protocol. TDMA based scheduling is used for guaranteed data transmissions. The proposed protocol is analyzed and evaluated using a Markov chain model. The evaluation shows the increase in lifespan of batteries. The experiments have been conducted to verify the performance of ECG node, but the discussion and evaluation of a biomedical sensor node network on a body are missing.

2.3.9. Pre-emptive and non-pre-emptive MAC

WBASNs applications have diverse QoS requirements which demand different data transmission patterns like periodic, event-based and emergency. The challenge gets more complex when these applications need to run simultaneously. Pre-emptive and Non-Pre-Emptive MAC (PNP-MAC) [47] are proposed to handle this issue. This is achieved through the fast allocation of time slots and flexible superframe adjustments for pre-emptive and non-pre-emptive transmissions. The PNP-MAC provides limited latency to physiological patient monitoring systems. The other QoS parameters, however, such as reliability and energy consumption are ignored. Moreover, the traffic load of low priority sensors is also ignored which may cause delay and consume more energy in case of retransmission [36].

2.3.10. Enhanced MAC

The Battery-powered biomedical sensor nodes need an improved MAC protocol which could work under low-power conditions to increase lifetime. In this context, an Enhanced MAC (EMAC) protocol is proposed which uses relay nodes with dynamic power control mechanism to save power. These relay nodes act as intermediate nodes to save the energy of the monitoring nodes. The dynamic power control mechanism helps the nodes to save energy by transmitting data under a predefined threshold value of Received Signal Strength Indicator (RSSI). EMAC works well with slotted CSMA/CA of the IEEE 802.15.4 and provides energy efficiency. However, the channel characterization and integration issues of these relay nodes are not discussed. These issues play a significant role in the efficient utilization of the EMAC protocol.

2.3.11. Cooperative MAC

WBASNs play a crucial role in healthcare monitoring applications in a hospital environment. Patient equipped with biomedical sensors may move in a hospital which raises the question of mobility support for the nodes. The Cooperative MAC (C-MAC) [48] is proposed which provides access mechanisms for mobile clusters. In application, nodes are divided into different clusters which are not working on the same frequencies. The C-MAC requires a strong synchronization mechanism to work effectively.

2.3.12. Medical emergency body MAC

WBASNs applications for healthcare have been gaining attention due to their appropriate physiological monitoring services. These applications are categorized as critical applications and non-critical applications. Both have different communication requirements e.g., critical applications need high priority services for data dissemination [49]. These emergency data transmissions require high reliability with limited delay. IEEE 802.15.6 beacon mode with contention and contention-less mechanisms can adjust the superframes durations. Short superframes are used for emergency traffic as they provide less delay. Yet on this setting, that advantage is countered by higher energy consumption. The large superframe durations provide energy efficient communication, however the latency increases. To address this issue a Medical Emergency Body MAC (MEB-MAC) is proposed which create a balance between these trade-offs by inserting listening slots in CFPs. These listening slots are inserted according to the delay requirement of the application. This protocol works well in small networks. A downside, however, is that the protocol is not scalable to a large WBASN.

2.3.13. Modified frame structure MAC

Implanted biomedical sensor nodes require energy efficient mechanisms for data transmission. To improve the energy consumption a Modified Frame Structure MAC (MFS-MAC) [50] is proposed which modifies the existing frame structure of the IEEE 802.15.6. It works like a master-slave structure. This type of structure gives full authority to the master node to control all the communication activities including channel assignment. This mechanism proved to be more energy efficient. Yet, there is still a need to define the authorities of the master node.

2.3.14. Priority-based adaptive MAC

The existing standards, which are the IEEE 802.15.4 and IEEE 802.15.6, do not provide a differentiated QoS to the diverse data traffic. In this regard, Priority-based Adaptive MAC (PA-MAC) [51] is proposed which provides adaptive QoS to diverse traffic types by considering ISM bands. The data traffic is divided into four categories including emergency, on-demand, normal and non-medical data traffic. The categories are assigned priorities from P1to P4 respectively. Time slots are assigned dynamically by considering the traffic priorities. PA-MAC redefines the duties of two available channels: beacon channel and data channel. PA-MAC introduces priority based CSMA/CA which is used to provide priorities to CAP and CFP. PA-MAC is built over the IEEE 802.15.4 and IEEE 802.15.6.

2.3.15. Low-delay traffic-adaptive MAC protocol

In WBASNs guaranteed services is one of the important aspects of medical applications. The current IEEE 802.15.4 standard provides Guaranteed Time Services (GTS); however, for medical applications, it may need to transmit the data at any stage. To address this concern, a Low-Delay Traffic-Adaptive MAC Protocol (LDTA-MAC) [52] is proposed which assigns GTS dynamically by considering the network traffic load. Moreover, it also considers reasonable time duration of the superframe to make this protocol energy efficient. After getting successful GTS request and response, the related traffic is sent in the current superframe duration so that latency remains limited. For a successful execution of such a protocol, it requires a good synchronization mechanism between the node and superframe. Furthermore, a clear priority assignment scheme is missing from this service.

2.3.16. A traffic load aware sensor MAC

A Traffic Load-Aware Sensor MAC (ATLAS) [53] is proposed for priority-based services for patient monitoring applications for emergency data traffic. For this protocol, a new scheme Priority-based Adaptive Timeslot Allocation (PTA) is designed to assign time slots to the prioritized data traffic. PTA is based on the IEEE 802.15.4 and operates in Contention Access Period (CAP). It provides guaranteed channel access to prioritized traffic. Initially, classification of prioritized data is done. Adaptively assigning the slots are the key element of ATLAS. The main downside to this MAC is a detailed discussion about backoff procedure for the waiting nodes is missing. Additionally, adding an additional mechanism to the IEEE 802.15.4 may cause more energy consumption for sensor nodes.

2.3.17. Traffic priority and load adaptive MAC protocol

WBASNs consist of biomedical sensor nodes having heterogeneous characteristics which create challenges to fulfil the QoS requirements of each node as part of a network. To adjust the traffic load adaptively, a Priority-Based Traffic Load Adaptive MAC (PLA-MAC) [54] is proposed. PLA-MAC provides priority channel access in energy efficient manner by classifying the priorities of sending packets. Moreover, the superframe duration varies according to the traffic conditions. The protocol works well to provide reliability and delay. To adopt this mechanism more energy resource is required since energy efficiency computation is not discussed in simulations that are run with this protocol.

2.3.18. Priority-guaranteed MAC protocol

A hybrid and secure Priority-guaranteed MAC Protocol (PMAC) [55] is proposed for WBASN. It is based on the IEEE 802.15.4 and uses two channel access mechanisms: CAP (for a small amount of critical data) and CFP (for normal large data sizes). PMAC assigns priorities to the sensor nodes by adjusting their backoff window size in CAP. Moreover, PMAC uses the security key to avoid any intrusion from outside. PMAC works well in terms of security for a small network. One limitation of the protocol is the applied security mechanism requires more time for sharing key and decryption which can hinder the effectiveness of this protocol for WBASNs.

2.3.19. Hybrid polling MAC protocol

A human energy harvesting based protocol called Human Energy Harvesting MAC Protocol (HEH-BMAC) [56] is proposed for energy efficient communication. For the medium access, HEH-BMAC operates on a hybrid polling mechanism which uses a combination of polling mechanism and a probabilistic contention access mechanism. These mechanisms have the capability to adopt variations in energy states (sleep/awake). The energy variations usually occur because of the different state timings of harvesting sources. Access is given based on the defined priority. Additionally, the adaptive capability of this protocol permits the topology to add or remove the nodes from the network. The energy harvesting mechanism is helpful for efficient energy consumption. Its suitability for critical medical applications is not discussed, which limits the frame to which the protocol can be applied.

2.3.20. Adaptively tuned MAC

To guarantee the QoS in WBASNs, MAC layer transmission parameters can play a crucial role. The Adaptively Tuned MAC (AT-MAC) [57] is proposed to provide the adaptive tuning to achieve a higher reliability. The protocol defines the priorities of the biomedical sensor nodes according to their transmission requirements. For analysis of these MAC layer parameters of slotted CSMA/CA, a Markov chain-based model is used. The parameters reliability and energy are obtained from this model. The proposed mechanism focuses on reliability for medical applications and trade-off discussion among reliability, delay, and energy usage is missing.

2.3.21. Concurrent MAC

Usually in-patient monitoring, multiple biomedical attached sensors collect real-time data and send it to a coordinator node. Such data traffic patterns increase the probability of collision among the transmitting nods. To handle this issue, Concurrent MAC (CMAC) [58] is proposed. CMAC operates in two-phase; CSMA/CA is used in the first phase for the IEEE 802.15.6 standard with an ordering-based mechanism which is used to avoid a collision. In the second phase, sensor nodes could be switched to standby mode to prevent idle listening. The theme is validated by comparing the theoretical and simulated results.

2.3.22. Receiver-centric MAC

An event-driven monitoring system operates with light data traffic. It may happen that when an event is triggered, a small number of large packets are generated. To handle this traffic bursts in event-driven sensor networks, Receiver-Centric MAC (RC-MAC) [59] is proposed. RC-MAC operates adaptively by integrating the receiver-centric scheduling and duty cycle mechanism. It provides high throughput by using underlying multichannel to support the IEEE 802.15.4 without wasting extra energy. It is done in two phases: receiver-centric access and channel assignment in a distributed manner. Receiver-centric access refers towards the activity of the receiver to keep checking on the channel to avoid collisions. This protocol is suitable for event-based applications. WBASNs medical applications, however, require limited delay with appropriate reliability and energy consumption.

2.3.23. Contention over reservation MAC

The provision of guaranteed timeslots through reservation mechanism for emergency data traffic is useful; however, this reservation may cause channel unfair assignment problem. To address this issue, the Contention over Reservation MAC (CoR-MAC) [60] protocol is proposed. CoR-MAC operates with a dual reservation mechanism: one for reservation of emergency traffic and the other is the utilization of vacant time slot from already-reserved slots. In this way, the overall delay is reduced. For the implementation of such mechanism, a strong synchronization is required between the reservation mechanisms.

2.4. Approaches to optimize beacon-enabled IEEE 802.15.4 MAC protocols

The existing literature regarding the optimization of the IEEE 802.15.4 MAC is categorized in the following sub-sections.

2.4.1. Parameter tuning-based approaches

These approaches recommend that minimum modification should be made to the standard so that appropriate benefits can be achieved. This approach suggested that transmission parameters should be tuned properly. The advantages of this approach include avoiding the introduction of new mechanisms and their relevant overhead in form of energy consumption. The drawback of this approach is that such optimization may only be application specific [63]. Such approaches are discussed in the literature [61-67].

Performance of slotted CSMA/CA mainly depends on four parameters: macMinBE, macMaxBE, CW and Maximum Number of Backoffs (macMaxCSMAbackoffs). IEEE 802.15.4 defines a fixed backoff range where the default value of macMinBE = 3 and macMaxBE = 5. Variations in these values will affect network performance. Decreasing the values for macMinBE and macMaxBE will reduce the waiting time of a node. When a node tries the channel access with less waiting time, throughput will increase. If there are different nodes that are trying to access the channel, the collision probability will increase if the values of macMinBE and macMaxBE are increased, there is more chance of the delay with less network throughput. It is notable, then, that higher values of macMinBE and macMaxBE decrease the collision probabilities and reduce the retransmission as well. Table 2-2 presents the default MAC layer parameters.

Table 2-2 Default MAC transmission parameters setting [1, 3, 31]

Parameters	Default values
MacMinBE	3
MacMaxBE	5
MacMaxCSMABackoff	4
MacMaxFrameRetries	2

2.4.1.1. Backoff exponent

IEEE 802.15.4 defines a fixed backoff range, which constitutes default value of macMinBE = 3 and macMaxBE = 5. These values clearly describe the limit of backoff interval between 2^3 to 2^5. If these values are incremented or decremented, then the network performance is also affected. If we decrease the values for macMinBE and macMaxBE, it will reduce the waiting time of a node in case CCA detects the busy channel. Ultimately, when a node tries the channel access with less waiting time, there is a chance that the node's throughput will increase. These decrements can decrease the network performance. Likewise, the collision probability will increase. The variables macMaxBE, macMinBE, and macMaxCSMABackoffs are bounded by the constraint: macMaxCSMABackoffs ≥ macMaxBE – macMinBE.

2.4.1.2. Contention window

Contention window is another important parameter for slotted CSMA/CA, which creates waiting time after successful CCA. The standard recommends that this wait should be equal to two-time CCA attempts. The purpose of this wait is to reduce the collision probability by protecting acknowledgement frames of the receiver. Usually, the receiver sends the acknowledgement after T_{Ack} which is from 12 to 31 symbols (20 symbols = one backoff period). Hence, time for one CCA can cause collision for a new transmission. The higher values of CW reduce the chances of the collision but can cause delays.

2.4.1.3. Number of backoffs

NB (MacMaxCSMABackoff) represents the number of CSMA/CA backoff attempts and considered as one of the important channel access parameters. The default value is 4 which means, after 4 times, if the device under CSMA/CA does not get the channel access then data packet will be dropped. This parameter helps to increase the packet delivery ratio [36].

2.4.1.4. Retransmissions

A higher number of retransmissions increases the reliability of data transmission. Retransmission occurs when a sending device does not receive an acknowledgement from the receiver. There are several reasons for not receiving the acknowledgement including packet loss due to a collision on receiving side, acknowledgement lost and late reception of acknowledgement. A high number of retransmissions assures the reliability, but at the same time, they cause a delay in the network. Table 2-3 provides an analysis of parameter tuning approach which is discussed in the Section 2.4.1.

Table 2-3 Existing optimization mechanisms of the MAC layer CSMA/CA WBASN

Paper	Considered MAC Parameters	Contribution
Adaptive and real-time protocols [68]	Backoff Exponent (BE)	Analysis of macMinBE and macMaxBE values: by increasing these values the delay increases, and the throughput decreases, however, collision probability decreases and vice versa
Analysis of CAP [69]	BE	For large networks, the throughput is independent of the BE initial value, however, for small networks, it generates high impact
A comprehensive analysis of the MAC unreliability problem [70]	Contention Windows (CW)	Propose CW values for time-critical applications, higher values of CW reduce collision chances, however, for time-critical applications where ACK is disabled the CW set to lower values for fast communications
MAC unreliability problem in IEEE 802.15.4 WSN [71]	Retransmissions	In ideal channel conditions, when the number of retransmissions is increased from 1 to 2, a significant improvement is observed in packet delivery; however, there is no significant improvement in

		packet delivery if the number of retransmission is a further increase from 2 to 7
Performance evaluation with different backoff ranges [72]	BE	Provide priority-based QoS by assigning different BE values to different applications
Priority-based delay mitigation for event monitoring [73]	MAC frame modification , CCA	Collision avoidance-based priority mechanism by using one-time CCA
Priority-based service differentiation scheme [74]	CW	Contention Windows Differentiation (CWD) mechanism is proposed
MAC protocol implementation [75]	Superframe Order (SO)	Conduct a study by applying different values of superframe Order (SO), results show that high values of SO provide high throughput, whereas low SO values result in less delay
Performance evaluation with backoff [76]	BE	Propose an Adaptive Backoff Exponent (ABE) mechanism which reduces the devices probability to reduce collisions

The higher number of retransmissions represents the better reliability of the data transmission. IEEE 802.15.4 and IEEE 802.15.6 standards are capable of providing optimized performance by adjusting the different MAC parameter values (BE, CW, SO and retransmissions). Most of the optimization mechanisms applied in Table 2-3 usually consider one of the QoS aspects of the MAC layer; whereas, a WBASN demands a set of QoS parameters. In this context, research develops a Delay, Reliability, and Throughput (DRT) profile by considering different frequency bands and data rates of the IEEE 802.15.4 and IEEE 802.15.6. This profile helps to increase the performance of these standards.

The discussion above concludes that the IEEE 802.15.4 standard can support time-critical applications by tuning the MAC parameters. There are few performance trade-offs between reliability and latency, similarly between delay and energy consumption.

2.4.2. Cross layer-based approaches

These approaches use information from the other layers to tune the MAC layer parameters. Although, such methods fulfil the requirement of the applications, as they are depending on the information of the other layers, so there are high chances that delay will occur, which is not tolerable for medical applications.

Adaptive Access Parameter Tuning (ADAPT) [77] is proposed as a cross-layer protocol to attain energy efficiency and reliability. The idea of ADAPT is to understand the applications reliability requirements and then perform parameter tuning. ADAPT operates under an adaption module that can interact with other layers of ZigBee stack. This adaption module collects the information from different layers to optimize performance. When ADAPT receives requirements from the application layer, it maps this data to the MAC layer so that suitable tuning can be performed to the parameters including macMinBE, macMaxCSMABackoffs, and MacMaxFrameRetries. It considers single-hop and multi-hop scenarios. An optimization problem is developed with the objective function of minimizing energy. The proposed model works with few constraints, such as the delay value should not be greater than the threshold [77]. An adaptive-variable scheme is used to allocate the bandwidth which considers the requirement of the application and the physical layers. The ADAPT optimizes the performance in terms of energy and bandwidth.

The Timely, Reliable, Energy Efficient and Dynamic (TREnD) [78] is a cross-layer protocol and focuses on industrial applications. TREnD enables an interaction with routing algorithms, the MAC layer, and power modules to achieve the required reliability and latency. TREnD operates in inter-cluster and intra-cluster architecture by accommodating local and dynamic routing. A hybrid MAC protocol (which considers both contention-based and time-based channel access mechanisms) with TDMA/CSMA is used with local routing. The nodes wake up on their predefined slot time in the TDMA based approach to saving energy. The TDMA mechanism is applied in such a way that different clusters are synchronized with it. The receiving nodes send multicast beacons to stay in the topology.

2.4.3. Duty cycle-based approaches

Duty cycle mechanism is considered as an efficient solution for idle listening and over-hearing problems. Usually, it works well in random access networks, where periodic cycling is done between sleep time and wakeup time state. Duty cycle mechanisms provide low power listening without any external hardware. These mechanisms are more appealing to dynamic network conditions, especially in cases where data traffic and the location of a node changes with time.

The beacon mode provides a complete synchronization mechanism which leads towards efficient utilization of energy resources. The slotted mode of the IEEE 802.15.4 experiences several challenges including lack of dynamic adaptive capabilities, unfair channel access in saturation conditions and longer backoff periods in case of channel access failure. These challenges create a low performance for WBASNs; whereas, these applications of WBASNs demand limited delay, specified throughput, reliability and efficient energy utilization at a given time.

There are several studies which optimize the performance of slotted mode in terms of end-to-end delay and energy consumption by adjusting the duty cycle. These approaches deal with channel access management during active and inactive periods of the superframe, with the purpose of making efficient power utilization. This approach increases the network lifetime by managing the duty cycle period.

The Adaptive MAC Protocol for Efficient (AMPE) [74], adjusts the duty cycle on the basis of the occupancy rate of the Superframe Order (SO). The algorithm computes the superframe occupancy rate in terms of SO and compares it with upper and lower thresholds. If the computed rate is higher than the upper threshold then the coordinator increases the length of SO for the next superframe and vice versa. The algorithm assumes that the busy channel duration responds to offer load. Moreover, it uses PLME-CCA, which is a mechanism in the IEEE 802.15.4 standard to get the information of the busy channel. Inspire of these efficiencies, sensor nodes need to invoke the primitive, which uses more energy resources.

The Dynamic Superframe Adjustment Algorithm (DSAA) [79] adjusts the duty cycle on the basis of two factors: superframe occupancy rate of SO in the superframe and collision rate. At the end of each active portion of the superframe, the coordinator computes the occupancy and collision rate. The occupancy rate is compared with superframe occupancy threshold. Collision rate is compared with the collision threshold. The coordinator adjusts the length of SO for the next superframe. DSAA requires more resources in terms of energy.

The Duty Cycle Adoption (DCA) [80] uses the information of buffer occupancy and queuing delay and adjusts the length of the active portion of the superframe. By using the algorithm, a node sends the buffer status and queuing information through a reserved MAC control field of the frame structure. The information is extracted by the coordinator to adjust the active period of a superframe. DCA computes the queue occupation, which is integrated to all frames during the active period. It can, however, underestimate the number of transmission requests.

In [81], an Adaptive Algorithm to Optimize the Dynamics (AAOD) is proposed which considers the number of received packets in each superframe to adjust the active periods. The received packets in a superframe are compared with the received packets in the previous superframe. If the number of received packets in the current superframe is higher than the threshold, then the active period length for the next superframe is increased and vice versa.

Suh et al. [82], proposed an algorithm that is used to optimize the performance of real-time data transmission by adjusting the active periods. The nodes that could not send their packets in the active period will send a request to the coordinator to extend the length of the active period.

Usually, duty cycle adaptations are considered where it is easy to predict traffic loads. For such applications, it is easy to change the values of SO and BO in advance. Yet the issue that emerges from this advantage is that such mechanisms are not suitable for instantaneous traffic bursts because they consume time on estimating and adjusting the duty cycle. To solve this issue, several solutions are proposed which consider the dynamical extension of active periods. In [83], the authors proposed a solution that extends the active period on the basis of a busy tone. If the device fails to send its entire data frame, then the busy tone is sent at the end of Contention Access Period (CAP). The authors considered the extension based on traffic types, especially the CAP extension is considered for real-time data traffic. As these extensions integrate new structures immediately at the end of the CAP, so they require modification in the structure of the IEEE 802.15.4.

In [84], the authors discussed the problem to adjust the active and inactive periods with the intention to save energy under light network loads. They presented a reinforcement learning method which can adapt change of data flow and make a good trade-off between the delay and energy efficiency.

The authors [85] proposed a Duty Cycle Learning Algorithm (DCLA) that is capable of adopting a duty cycle at runtime with the purpose of minimizing power consumption while considering data delivery and delay considerations. DCLA collects information during active periods and estimates traffic for the next active period.

In [32], Adaptive Duty Cycle Algorithm (ADCA) is proposed for the IEEE 802.15.4 beacon-enabled mode, which mainly optimizes the energy utilization by adjusting the duty cycle on the basis of network traffic. ADCA provides better energy consumption. The main flaw in this algorithm however is, it does not provide the limited delay. The reason is the inappropriate selection of the SO duration which does not accommodate collisions and retransmission aspects.

2.4.4. Priority-based approaches

These approaches improve the IEEE 802.15.4 MAC by considering a priority for channel access mechanisms. These studies introduce mechanisms to recognize the priority of the nodes. The Weighted-Fair-Queue CSMA/CA (FQ-CSMA/CA) [86] algorithm is proposed to differentiate between the emergency signals and normal signals. The preference is given based on urgency. The algorithm aims at reducing the latency for emergency signals without disturbing the normal signals. Overall signals are divided into five categories according to their urgency including sensor data traffic, ACK traffic, command control traffic, system setting, and alarm signal traffic. Examples for priority-based approaches include [66, 67, 68].

A Markov-based analytical model is designed [87] for CAP which deals with nodes having two priority classes: high and low. These priorities consider contention windows values to adjust the prioritized traffic.

Differentiated services are delivered to prioritized traffic classes which are made for critical data transmission. The work in [88] adjusted the MAC layer transmission parameters including macMinBE, macMaxBE, and contention window. This adjustment is applied based on priority. Mostly, normal data is assigned the lowest priority; whereas, alarms reports, command frames and GTS data are assigned high priority. Lower backoff time-periods values are given high priority traffic and vice versa; moreover, for high priority traffic, a priority queue is introduced.

An explicit priority scheme is designed [89] for the IEEE 802.15.4 standard by categorizing transmission nodes into critical and non-critical nodes. Critical nodes have urgent data to send; whereas, the non-critical nodes have normal traffic data. A secondary beacon is used by the nodes to inform the coordinator about the urgency. Coordinator only allows those nodes in CAP which request to send urgent data. Additionally, after receiving the secondary beacon the coordinator generates the primary beacon and inform the other nodes about activities in the upcoming CAP.

Two mechanisms are proposed including Contention Windows Differentiation (CWD) and Backoff Exponent Differentiation (BED). These mechanisms provide differentiation services to the IEEE 802.15.4 based nodes [74]. Nodes are categorized based on s priorities that are, emergency and high bandwidth. These priorities are assigned based on data traffic. Overall the contention window and binary exponent values are used to provide these prioritize services. Further, CWD and BED are used to make another scheme known as Backoff Counter Selection (BCS). BCS is used to select the next backoff period when it finds the medium busy. A Markov-based model is developed to validate the performance of CWD and BED.

2.4.5. Superframe modification approaches

These approaches improve the slotted CSMA/CA protocol of the IEEE 802.15.4 standard by proposing modifications in superframe structure. An emergency beacon service is used to manage the normal, emergency and periodic data transmission services in CAP through contention access mechanism [90]. The coordinator is responsible for transmission of emergency beacon to handle the emergency data in

CAP period. The energy consumption analysis shows that existing superframe structure is not enough to manage emergency traffic. The Priority-based Traffic Load Adaptive MAC (PLA-MAC) protocol [54] proposed four data classes including ordinary, delay, reliability and critical data. Few dedicated slots are introduced in a superframe to handle emergency data traffic. In Low-Delay Traffic-Adaptive Medium Access Control (LDTA-MAC) [52] extends the contention periods in CFP. Despite these factors, this protocol stops the new transmission after all channels are occupied. The Adaptive and Real-Time GTS Allocation (ART-GAS) [91] handles the differentiated services by introducing the GTS slots in superframe duration. It is noticed that performance of nods having normal data traffic suffers because of GTS slots. Differentiated service classes are proposed including Emergency-TDMA (ETDMA) [91], Medical Contention Access Periods (MCAP) and Normal-TDMA (NTDMA). This scheme works well; however, managing slot assignment for different nodes is a complex task and requires more energy resources. The Fuzzy Control Medium Access (FCMA) [92] is used to decide about slot assignment in CAP and CFP based on predefined fuzzy rules which are made on priorities. It works in three phases including data acquisition, fuzzy logic, and implementation of the algorithm. The Priority-Based Adaptive Timeslot Allocation (PTA) [53] divides the CAP channel into chunks. Different slots are assigned to the nodes according to priorities, but it must also be considered that the mechanism is expensive in the context of limited latency and energy consumption.

2.5. Discussion

This section provides a brief review of literature and comparison of literature with the work done in the thesis. Particularly, we are focused towards the communication schemes that provide a joint optimization of QoS parameters including latency, reliability, energy, and throughput for physiological data monitoring applications.

2.5.1. Review of the presented literature

In the above, various existing WBASNs based MAC protocols are discussed. These protocols work for healthcare applications in a various environment including home, hospitals and elderly care centers.

MAC protocols play a critical part in providing QoS for WBASNs by extending network lifetimes, avoiding packet collisions, less overhearing and idle listening. Generally, efficient WBASNs based MAC protocols have distinctive characteristics including energy efficiency, low latency, and fairness in terms of channel access. Based on channel access mechanisms, the MAC protocols are categorized into three types: scheduled based, contention based and hybrid-based access mechanisms. For WBASNs, mostly hybrid-based mechanisms are used due to their flexibility to adjust light and heavy data traffic. The hybrid MAC protocols combine the benefits of both access mechanisms: contention-based MAC and schedule-based MAC. IEEE 802.15.4 and IEEE 802.15.6 MAC standards have been evolved from the idea of adaptive MAC protocols which combine slotted ALOHA and TDMA [93]. Therefore, several MAC protocols derived from the IEEE 802.15.4 and IEEE 802.15.6 superframe structure.

Above mentioned protocols are based on various approaches, including:

- Fuzzy logic-based mechanisms;
- Introducing priority queues for different traffic types in WBASNs;
- Adaptive QoS mechanisms which usually considers the application layer requirement;

- Multi-channel mechanisms;
- Strict reservation-based mechanisms;
- Dynamically superframe duration assignment;
- Introducing relay nodes;
- Combination of different channel access mechanisms;
- Inserting new time slots in superframes duration;
- Master-slave architecture;
- Improving backoff mechanisms;
- Receiver centric mechanisms;
- Adjusting traffic loads dynamically;
- Combining reservation based and duty cycle-based mechanisms

These approaches provide QoS by focusing on a single QoS parameter or combination of QoS parameters simultaneously. These parameters include latency, throughput, reliability, prioritized QoS, energy efficiency, scalability and collision avoidance.

Table 2-4 summarizes the characteristics of the proposed protocols, their underlying standards, and access mechanisms. Moreover, we have shown the contribution to QoS as delay (D), reliability (R), energy efficiency (E), throughput (T), collision (C)**,** priority **(**P)**,** Mobility **(**M) and scalability (S). It is important to analyze the QoS when a patient is moving (mobility state) as most movements make difficulties for these low-power IEEE 802.15.4 based devices. Scalability is an important concern for the QoS for multi-hop scenarios.

Table 2-4 Analysis of WBASN protocols

Protocol	**Year**	**Standard**	**Access scheme**	**Shortcomings**	**QoS**
DQBAN	2009	IEEE 802.15.4	Hybrid	Requires the management of different queues as well as the fuzzy-logic system implementation in every	R, C

				sensor node	
D2MAC	2013	IEEE 802.15.4	Slotted CSMA/CA	Consideration of single QoS parameters from application i.e., the data rate to make the protocol adaptive	D
U-MAC	2010	IEEE 802.15.4	Slotted ALOHA	Complex and involve overheads in terms of data categorization and identification of retransmission packets	D
HUA-MAC	2010	IEEE 802.15.4	Slotted ALOHA	Shows QoS limitations in the scalable and diverse application scenarios	D, R
Single-radio multi-channel TDMA MAC protocol	2014	IEEE 802.15.4	TDMA	The management of multichannel is still challenging due co-channel interference and restricted band allocation	D
EELDC	2009	IEEE 802.15.4	TDMA	Fixed scheduling is used for data transmission which does not fulfill the application diversity in WBASNs	E, R
CA-MAC	2011	IEEE 802.15.4	Hybrid	Dynamic change in a frame structure which is not easy to implement with the IEEE 802.15.4 and IEEE802.15.6 standards	R
BDD	2009	IEEE 802.15.4	TDMA	The performance is only validated for one biomedical sensor i.e., ECG, hence QoS performance in the scalable environment is a concern	E
PNP-MAC	2010	IEEE 802.15.4	Hybrid	The traffic load of low priority biomedical sensors is ignored which may cause delay and consume more energy in case of retransmission	D, E
EMAC	2013	IEEE 802.15.4	Hybrid	The channel characterization and integration issues of these relay nodes are not discussed which is an important aspect to validate the performance	E
C-MAC	2013	IEEE 802.15.6	TDMA - FDMA	The solution is complex due to the usage of multiple access mechanisms simultaneously i.e., TDMA and FDMA, a strong synchronization is needed	C, M
MEB-MAC	2012	IEEE 802.15.6	Hybrid	Scalability is a concern as insertion of many new slots will create QoS degradation for the other nodes of the network	D
MFS-MAC	2014	IEEE 802.15.6	Hybrid	There is need to define authorities of the master node; moreover, this solution is not scalable	E
PA-MAC	2016	IEEE 802.15.4 IEEE 802.15.6	Hybrid	It requires hardware modification which is a challenging task for existing standards	P,E,C
LDTA-MAC	2011	IEEE 802.15.4	Hybrid	Successful execution of such protocol requires a good synchronization mechanism between node and superframe; moreover, a clear priority assignment scheme is missing	D
ATLAS	2013	IEEE 802.15.4	Hybrid	The detailed discussion about backoff procedure for the waiting nodes in this modified scheme is missing; moreover, adding additional mechanism on the IEEE 802.15.4 may cause more energy consumption for sensor nodes	P
PLA-MAC	2013	IEEE 802.15.4	Hybrid	To adopt this mechanism more energy source is required, whereas energy	P, R

				efficiency computation is not discussed in simulations	
PMAC	2014	IEEE 802.15.4	Hybrid	The applied security mechanism requires more time for sharing key and decryption which can hinder the effectiveness of this protocol in terms of stringent QoS for WBASNs	P, S
HEH-BMAC	2015	IEEE 802.15.4	Hybrid	Its suitability for critical medical applications is not discussed, whereas such applications require limited latency and high reliability	P, E
AT-MAC	2016	IEEE 802.15.4	Hybrid	The proposed mechanism focuses on reliability for WBASNs medical applications, whereas tradeoff discussion among reliability, delay, and energy usage is missing	R
C-MAC	2017	IEEE 802.15.6	Hybrid	A strong a-synchronization mechanism is required to avoid the collision by incorporating duty cycle mechanism	D, E
RC-MAC	2015	IEEE 802.15.4	Hybrid	Receiver centric access mechanism demand resources in terms of power; moreover, the synchronization among receiving nodes to avoid collision exploits duty cycle mechanism	T
CoR-MAC	2016	IEEE 802.15.4, IEEE 802.15.6	Hybrid	For the implementation of such mechanism, a strong synchronization is required between reservation mechanisms	D

We have also discussed the different optimization mechanisms to improve the IEEE 802.15.4 slotted CSMA/CA mechanism. Table 2-5 summarizes the advantages and disadvantages of optimization approaches.

Table 2-5 Advantages and disadvantages of optimization approaches

MAC optimization Approaches	**Advantages**	**Disadvantages**
Parameter Tuning	▪ No explicit modification is required to IEEE 802.15.4 ▪ One-time parameters tuning is required ▪ Applicable to another standard that is, IEEE 802.15.6.	▪ Application specific solutions ▪ Restricted to a theoretical range of parameters
Cross-Layer	▪ Optimal performance by using the information from other layers ▪ Adaptive to the situation	▪ Overhead for control messages ▪ High latency with respect to medical applications
Duty cycle-based	▪ Adaptable with minimum	▪ Add overhead to the

	modification to IEEE 802.15.4 ▪ Numerous opportunities to save power with original standard	coordinator for analysis and processing
Prioritized based	▪ Provide the required QoS to the transmitting nodes	▪ Introduce operating and processing overheads
Superframe modification	▪ Provide scalability, multiple topologies support, make the IEEE 802.15.4 more adaptive	▪ Major changes in operations of the standard ▪ Adaptability demands resource usage for sensors

2.6. Similarities and differences between related work and thesis

The crucial concern for communication schemes in WBASNs for health monitoring is to achieve high energy efficiency under the strict QoS constraints including limited latency, high reliability, appropriate throughput and fair channel access. The following discussion is specifically focused on WBASNs for healthcare applications.

Similarity_1

The parameter tuning approach is considered as one of the best approaches because it does not require any modification in the existing IEEE 802.15.4 standard. In the related work, we have discussed many studies based on parameter tuning approaches. Overall, the discussion is around tuning one or two MAC layer transmission parameters of the IEEE 802.15.4 to achieve optimized QoS in terms of delay, reliability, throughput, and energy. Our approach is like the existing work in the sense that we are tuning parameters to achieve optimized QoS.

Difference_1

In the numerical modelling, we have considered multiple frequency bands; whereas, in the existing literature the focus is only on 2.4 GHz. We have covered the details regarding this in Chapter 3.

Similarity_2

The adaptive IEEE 802.15.4 duty cycle-based approaches are famous to improve transmission QoS and they require minimum changes for the implementation. These approaches deal with channel access management during active and inactive periods of the superframe, with the purpose of making efficient power utilization. The advantage of this approach is an increase in network lifetime by managing the duty cycle period.

Difference_2

The existing research work regarding adaptive duty cycle-based approaches lacks providing a combined set of QoS parameters which is an essential requirement for monitoring applications. Further, these adaptive duty cycle mechanisms mostly adjust the duty cycle values on various estimations, especially buffer occupancy, collision rates and active periods. These estimations consume resources in terms of energy and memory, whereas medical applications require limited latency and less energy consumption. In this research, optimization is done by combining two approaches: a duty cycle-based approach and MAC transmission parameter tuning approach. In the literature of adaptive duty-cycle optimization, adaption is based on estimations such as buffer occupancy, collision rate and past active duty-cycle periods. For our research, duty-cycle is adjusted on three factors: offered network traffic load, DRT and superframe duration. We have covered the details regarding this approach in our second contribution, mentioned in Chapter 4.

Similarity_3

Protocols are proposed to provide various aspects of QoS like latency, energy, reliability, efficient channel access, high throughput and prioritized QoS. Various methods are used including fuzzy logic-based mechanisms, priority queues, adaptive

QoS mechanisms, multi-channel mechanisms, strict reservation-based mechanisms, dynamically superframe duration assignment, a combination of different channel access mechanisms, inserting new time slots in superframes duration, master-slave architecture, backoff mechanisms, receiver-centric mechanisms and adjusting traffic loads dynamically. Most of them optimized one aspect of QoS and some of them use multiple aspects of QoS. Our third contribution is based on the similar approach of achieving a set of QoS by enhancing the existing IEEE 802.15.4 MAC mechanism.

Difference _03

The existing protocols for the IEEE 802.15.4 MAC are based on complex mechanisms and require a significant change in the standard. In this research, our focus is to find a smart approach that can jointly optimize the QoS for the medical applications with less modification in the existing IEEE 802.15.4 standard. In this context, a new mechanism is proposed which introduces the concept of frame aggregation for the IEEE 802.15.4 standard. It provides high throughput with less delay and high reliability. Moreover, collision probability reduces with less energy consumption. We have covered the details regarding this contribution in Chapter 5.

The partial work in this Chapter has been submitted to the IEEE Communications Surveys & Tutorials (Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Wireless Body Area Sensor Networks: A Survey of Application, MAC and Network Layer protocols for Patient Monitoring") for consideration of possible publication.

Chapter 3: Modeling and Optimization of the IEEE 802.15.4 Protocol using DRT Profile

3.1. Introduction

Remote healthcare monitoring systems demand a specific set of QoS parameters from the MAC layer protocols and standards like the IEEE 802.15.6 and IEEE 802.15.4. These QoS parameters mainly include time-bounded services (limited latency), reliable data transmission, fair channel access, and specified data rates. Most of the existing MAC protocols of WBASNs pay attention to a single QoS parameter at a time (discussion is provided in Chapter 2: Literature Review, Section 2.3). In contrast, WBASNs demand the consideration of a set of QoS parameters to function efficiently. To address the demand of WBANs, this chapter investigates, evaluates and maps the current state of the art with respect to QoS provision for the IEEE 802.15.4 and IEEE 802.15.6 standards. To optimize the performance of MAC layer mechanisms for patient monitoring applications, we propose a QoS profile named Delay, Reliability, and Throughput (DRT) using Parameter-tuning approach. The discussion regarding Parameter-tuning approaches is provided in Chapter 2: Literature Review (Section 2.4.1). Further Section 2.4.1 also provides the details of the MAC layer transmission parameters used to develop DRT profile. DRT is the first step to achieve the MAC layer QoS. In Chapter 4, we will use the proposed DRT profile for energy efficiency.

The word profile refers here to a set of QoS parameters. A series of experiments are conducted to produce statistical results under different frequency bands with respect to delay, reliability and PDR. The calculated results are verified through extensive simulations in the CASTALIA 3.2 framework using OMNET++ network simulator.

Moreover, performance analysis is done between significant DRT based profile values and the default profile (existing QoS profile) in the CASTALIA 3.2 simulator by considering variations of the number of nodes and packet sizes. In the end, the DRT values are suggested which can be used for various medical applications, particularly ECG, EEG, EMG, accelerometer, gyroscope, pulse oximeter, blood pressure, temperature, barometer, and heart rate monitoring. DRT does not require any modification in the IEEE 802.15.4 and IEEE 802.15.6 standards and can be easily implemented on network nodes. Finally, results show that the low power standards including the IEEE 802.15.4 and IEEE 802.15.6 are capable of providing effective communication for WBASNs by tuning the MAC layer parameters properly [36].

3.2. Delay, reliability and throughput profile

In this section, the DRT profile is computed after a series of statistical computations (calculations by using ED equation 3-1 where different values of frames retry, backoffs and frame retransmission are applied to find ED within 250 ms) with the aim of performance optimization at the MAC layer for WBASN medical applications. DRT profile works by tuning the medium access control parameters including macMinBE, macMaxCSMABackoffs, and MacMaxFrameRetries. To evaluate DRT, in terms of delay, reliability, and throughput, a numerical model for the delay is proposed based on the IEEE 802.15.4 and IEEE 802.15.6 standards. The model is evaluated for saturated and unsaturated data traffic. These DRT values provide reliability for data transmission within acceptable latency. The DRT is based on the CSMA/CA channel access mechanism and considers the IEEE 802.15.4 and IEEE 802.15.6 standards. Another major contribution of this research is the detailed performance analysis of different low and high-frequency bands which are standardized for WBASNs: 420 MHz, 868 MHz, and 2.4 GHz.

As we are trying to optimized the MAC layer performance of the IEEE 802.15.4 and IEEE 802.15.6 for healthcare applications, so channel access models of the IEEE 802.15.4 and IEEE 802.15.6 are used to calculate the delay and reliability (frame retries attempt) [29, 35]. Furthermore, the discussion about the flowchart models is provided in Chapter 2 (Section 2.2). Here, we only considered the most significant values of the DRT profile which provide maximum reliability of data transmission within an acceptable latency. The word profile is used because it refers to a combination set of QoS parameters. DRT focuses on CSMA/CA mechanisms of the IEEE 802.15.4 and IEEE 802.15.6 standards.

The numerical formulas help to drive a flexible and reliable set of combinational values which provide reliability within acceptable latency. In the IEEE 802.15.4 standard, the DRT profile is used for beaconless and beacon-enabled modes. Reliability is defined here as several frame retransmissions attempts when the sending node does not receive the MAC layer acknowledgement. The parameter MacMaxFrameRetries is used for the reliability computation. Packet Delivery Ratio (PDR) is defined as the ratio of the number of successfully delivered packets to a total number of transmitting data packets to a node.

The following terminologies are used in the calculation of delay for the channel access mechanism of the IEEE 802.15.4:

$\mathrm{ED} = \text{Expected Total Delay}$

$\mathrm{BPC} = \text{Backoff time period including CCA}$

$\mathrm{T_{frame}} = \text{Tansmission time for a frame}$

$T_{\tau A}$ = Turnaround time that is the time between the data frame

T_{Ack} = Transmission time of an acknowledgment

T_{SIFS} = Time for Short Interframe Space

N_{BO} = Number of backoffs in one slot

T_{BOslot} = Time for backoff slot

T_{CW} = backoff period for contention window

ED_{213} = End to end delay

So, in the ED_{213} $BE = 2$, $macCSMABackoff = 1$ and $macMaxFrameRetries = 3$

Using the above notations, we can modify the equations in [94], these equations are used to estimate the acceptable values of delay, reliability, and throughput. These equations are extracted from flow transmission flow charts of the IEEE 802.15.4 and IEEE 802.15.6 standards (Chapter 2: Literature Review, Section 2.2). By applying a various set of values of notations, we achieve a suitable combination of these values which provide acceptable delay, reliability and throughput values and we named it DRT profile. Equation 3-1 calculates the end-to-end delay for the IEEE 802.15.4 based channel access mechanism. Equation 3-1 represents an end-to-end delay for CSMA/CA process in the beaconless/un-slotted mode. macFrameRetries represents the number of retransmission attempts when the MAC layer does not receive acknowledgement. Its default value is 4 and the maximum value is 7. BPC represents the backoff time which will be assigned to a node before going to channel access attempt. CCA is the clear channel assessment time. We add this value with the backoff time in equation 3-2, so every time when a node senses the channel, it must wait for two-time periods that are, backoff and CCA.

$$ED = macFrameRetries * (BPC + T_{frame} + T_{\tau A} + T_{Ack} + T_{SIFS}) \quad 3\text{-}1$$

$$BPC = macCSMABackoff * (N_{BO} * T_{BOslot} + CCA) \quad 3\text{-}2$$

BPC in 3-2 is computed by multiplying the backoff attempts with the sum of backoff periods and CCA as mentioned in IEEE 802.15.4 standard [29, 35]. N_{BO} represents a discrete value. In the IEEE 802.15.4 standard, the value of N_{BO} can be zero, if the value of macMinBE is set to zero. In our calculations, macMinBE starts at 1, so N_{BO} value cannot be zero.

$$N_{BO} = (2^{macMinBE} - 1) \quad 3\text{-}3$$

$$T_{BOslot} = 20 * T_{symbol} = \frac{20*1}{Bitrate} \quad 3\text{-}4$$

$$CCA = 8 * T_{symbol} = 0.000390 \text{ sec} = 0.390 \text{ ms} \quad 3\text{-}5$$

$$T_{frame} = \frac{(PhyHeader(\text{in bits}) + MACHeader\ (\text{in bits}))}{\text{Data rate}} \quad 3\text{-}6$$

The values of the parameters used in these equations are taken from the IEEE 802.15.4 and IEEE 802.15.6 standards [29, 35].

For example, if we send a maximum payload size then T_{frame} is:

$$T_{frame} = 133 * \frac{8}{20 * 1024} = 51.95 \text{ ms}$$

$$T_{\tau A} = 12 * T_{symbol} \quad 3\text{-}7$$

$$T_{Ack} = \frac{31*8}{20*1024} = 12.1 \text{ ms} \quad 3\text{-}8$$

$$T_{SIFS} = 12 * T_{symbol} \quad 3\text{-}9$$

The default value of macFrameRetries is 4 [35] and the maximum value is 7. In equation 3-3 N_{BO}represents the number of backoffs (a specific time) in one slot.

T_{BOslot} represents the time for a backoff slot in equation 3-4. The CCA is computed in equation 3-5. The value of T_{frame} is computed by using equation 3-6. For analysis, we considered the bit rate of 20 kbps and 250 kbps (868.0-868.6 MHz and 2.4G Hz frequency band are considered with BPSK modulation and a symbol represents 1 and 4 bit). $T_{\tau A}$, T_{Ack} and T_{SIFS} are computed using 3-7, 3-8 and 3-9. DRT is depending on ED values which are computed in equation 3-1. ED values are computed using three main variables which are BE, macCSMABackoff andmacFrameRetries. The BE and macCSMABackoff are mainly used for delay computation; whereas, macFrameRetries is used for reliability. A higher value of the macFrameRetries represents more reliability. Different combinations of these three variables are used in the computation of ED. In Table 3-1 and Table 3-2 we showed few of them which give the delay value less than 250 ms.

Table 3- 1 End-to-end delay in the beacon-less mode for 868 MHz

Few DRT-combination of Reliability and Delay sensitive applications for 868 MHz and 20 kbps for the non-beacon mode	
Parameter combination	**ED delay (ms)**
ED_{253}	222.072
ED_{352}	168.7
ED_{333}	237.8
ED_{442}	235
ED_{413}	217
ED_{522}	237

Table 3-2 End-to-end delay in the beacon-less mode for 2.4 GHz

DRT-combination of Reliability and Delay sensitive applications for 2.4GHz and 250 kbps for the non-beacon mode) IEEE 802.15.4	
Parameter combination	**ED delay (ms)**
ED_{212}	13
ED_{375}	108
ED_{473}	117
ED_{475}	195
ED_{545}	223
ED_{573}	222
ED_{625}	225
ED_{643}	250
ED_{662}	248

From a series of experiments, several significant values for the DRT profile are selected for WBASNs in medical applications. Table 3-1 and Table 3-2 show the combination (the combinations that provide maximum reliability within 250 ms) of the DRT profile computed after statistical experiments with different frequency bands.

Similarly, equation 3-10 represents the delay for the IEEE 802.15.4 beacon enable mode. The difference between the IEEE 802.15.4 beacon mode (slotted CSMA/CA) and the non-beacon mode (unslotted CSMA/CA) is the addition of T_{CW} which represents the time for CW. Table 3-3 represents significant (which contain only those reliable values which show latency within 250 ms) statistical experiment results of the beacon mode [36].

$$ED = macFrameRetries * (BPC + T_{frame} + T_{\tau A} + T_{Ack} + T_{SIFS} + T_{CW}) \quad 3\text{-}10$$

Where the value of $T_{CW} = 7.8125$ ms

Table 3-3 DRT profile values for the IEEE 802.15.4 beacon-enabled mode

Suitable Combination for Reliability and Delay Sensitive (with retransmission) for 2.4GHz and 250 kbps for the Beacon Mode	
Parameter combination	**ED delay (ms)**
ED_{212}	29
ED_{272}	42

ED_{473}	141
ED_{475}	235
ED_{535}	213
ED_{572}	164
ED_{573}	246
ED_{652}	224
ED_{633}	218

Equation 3-11 represents the end to end delay for the IEEE 802.15.6 standard with different priority values. In equation 3-12, to compute the value of T_{CW}, we considered the average values of $CW_{min,}$ and CW_{max}.

$$ED = macMaxFrameRetries * (T_{CW} + T_{frame} + T_{\tau A} + T_{Ack}) \qquad 3\text{-}11$$

According to IEEE 802.15.6 [35], the value of T_{CW} is computed in 3-12, where the additional waiting time of 20 μs is added with T_{CCA} to increase the waiting time

$$T_{CW} = Avg(CW_{min,} CW_{max}) * (T_{CCA} + 20\ \mu s) \qquad 3\text{-}12$$

We considered data rate = 75.9 kbps and 250 Kbps with symbol rate = 187.5 kbps and 600 kbps respectively.

$$T_{CCA} = \frac{63}{Rs} = \frac{63}{187*1024} \qquad 3\text{-}13$$

In equation 3-13, we considered two different values for T_{CCA} that is, 0.329 ms for 420-450 MHz frequency band and 0.102 ms for 2.4 GHz frequency band. $T_{\tau A}$ represents the turnaround time, which is the elapsed time from the end of the received frame to start of the transmitted frame. This should be between Short Interframe Spacing (pSIFS) and pSIFS+ Extrainterframe Spacing (pExtraIFS). $T_{\tau A}$ and T_{Ack} are computed using 3-14 and 3-15.

$$T_{\tau A} = pSIFS + pExtraIFS = 85\ \mu s = .085\ ms \quad 3\text{-}14$$

$$T_{Ack} = \frac{(9*8)+31}{\text{Data rate}} = 103/75.9*1024 = 1.32\ ms \quad 3\text{-}15$$

Table 3-4 shows several combinations of the DRT profile which is computed using ED values with the frequency band of 420-450 MHz, the data rate of 75.9 kbps and packet size of254 bytes. Moreover, Table 3-4 provides different values of ED which are less than 250 ms. This section demonstrates that performance of MAC layer QoS for the IEEE 802.15.4 and IEEE 802.15.6 can be optimized for patient monitoring applications using parameter tuning approach. This approach not only helps to estimate the required delay but also considers the reliability.

Table 3-4 Significant DRT profile values for the IEEE 802.15.6

User Priority	**CW_{min}**	**CW_{max}**	**T_{CW} (ms)**	**ED (ms)**	**ED values with different retransmission values**					
					2	**3**	**4**	**5**	**6**	**7**
0	16	64	10.92	21	42	63	84	105	126	147
1	16	32	6.552	16.6	33.2	49.8	66.4	83	99.6	116.2
2	8	32	5.46	15.5	31	46.5	66	77.5	93	108.5
3	8	16	3.27	13.8	27.6	41.4	55.2	69	83	96.6
4	4	16	2.73	12.74	25.4	38.1	51	64	77	88.9
5	4	8	1.638	11.67	23.34	35.01	46.68	58.35	70.2	81.6
6	2	8	1.365	11.37	22.7	34	45.3	56.5	67.8	80.2
7	1	4	0.81	10.81	21.6	32.5	45	49	64	75.6

3.3. Validation and simulation for DRT profile

Open source Castalia 3.2 is used as the simulator in this research; moreover, the throughput test application is used which is integrated with the OMNET++ simulator. Radio model of the Castalia demonstrates a realistic physical process that is, CC2420 chip standard. This model is defined in C++ and NED files. The physical behavior of the model provides various characteristics including low power radio, multiple states, different frequency bands and Signal to Interference and Noise Ratio (SINR) [36].

We have considered a star topology with a centralized controller which is the coordinator node in the IEEE 802.15.4 standard. Each node is fully synchronized with the coordinator for transmission. All nodes send data directly to the coordinator. To incorporate the real environment (with interference and signal power loss), in our simulated results we used Log Shadowing channel mode with path loss exponent value 2.4. We are assuming that there is no background traffic. The different data rates of the sensor nodes are mentioned in Table 3-5.

In the simulated scenario, all transmitting nodes send a packet to a central hub (node 0). Figure 3-1 shows a simulation scenario where we have a central coordinator and various nodes. All the nodes are directly connected to the coordinator.

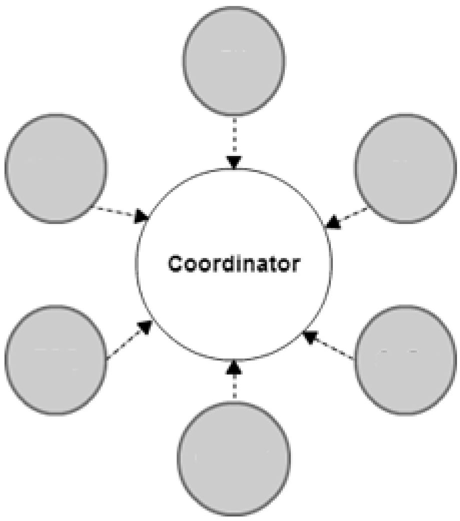

Figure 3-1 Simulation scenario

Table 3-5 shows the simulation parameters. This section contains three steps below:

- Validation of the proposed DRT profile by comparing statistical results of Maximum Throughput (MT) with the MT values defined by the IEEE 802.15.4 and IEEE 802.15.6 standards;

- Comparison in terms of Packet Delivery Ratio (PDR), of the proposed DRT profile values with the default IEEE 802.15.4 profile mentioned in Table 2 using ED values;
- Delay (ED) computation with different packet sizes to check the performance and usability of DRT (which is dependent on ED) for different medical applications

Table 3-5 Simulation setup

Parameters	Value
Number of nodes	6-20
MAC	IEEE 802.15.4, IEEE 802.15.6
Channel mode	Log Shadowing Wireless Model
Path loss exponent	2.4
Simulation time	5-20 minutes
Seed value	11
Frequencies band	420 MHz, 868 MHz, 2.4 GHz
Data rates	20 kbps, 75.9 kbps, 242.9 kbps, 250 kbps
Evaluation parameters	Delay, PDR, Throughput
Considered variations	Packet sizes, Number of nodes

3.3.1. Validation of the proposed DRT profile

The presented numerical and statistical model is validated by comparing the MT values obtained from numerical and theoretical values (those values under different frequency bands and data rates of the IEEE 802.15.4 and IEEE 802.15.6. The MT is defined as a ratio of payload size X (bytes) to the total transmission delay as mentioned in equation 3-16 [54]. MT refers towards many MAC Layer Service Data Units (MSDUs) in a unit time. Each MSDU involves overhead at MAC and PHY layers including headers, control frames, inter-frame spacing, and backoff.

$$\mathrm{MT} = \frac{8 * \mathrm{x}}{\mathrm{ED(x)}} \qquad 3\text{-}16$$

Figures 3-2, 3-3 and 3-4 show the comparative MT analysis between Numerical Analysis (N.A) and Theoretical Analysis (T.A). Figure 3-2 describes MT comparison of the IEEE 802.15.4 beaconless mode under to frequency bands i.e. 868 MHz (European licensed band) and 2.4 GHz (ISM band).

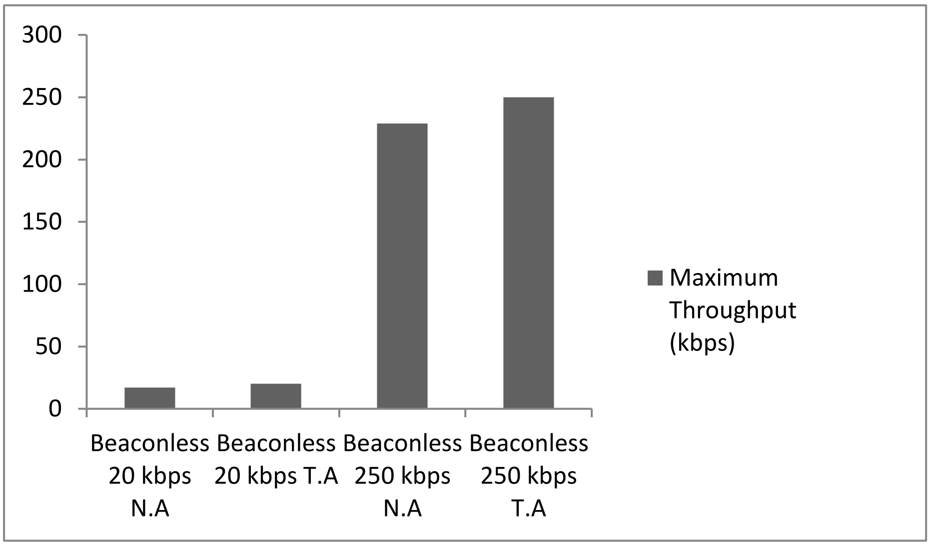

Figure 3-2 MT numerical and theoretical comparison of the IEEE 802.15.4 beaconless (Un-slotted) mode with 868 MHz and 2.4 GHz

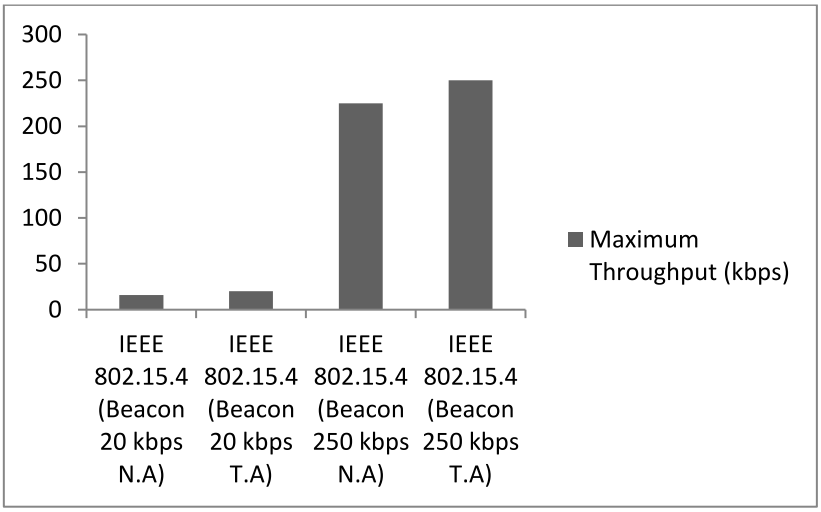

Figure 3-3 MT numerical and theoretical comparison of the IEEE 802.15.4 beacon-enabled mode

Theoretical values of throughput refer here as the maximum throughput claimed by the standard. These values are dependent on frequency bands. The numerical values are those values which are generated after numerical computation. Theoretically, in ideal conditions, 868 MHz provides a data rate of 20 kbps, whereas 2.4 GHz provides up to 250 kbps depending on the symbol rate of the underlying modulation scheme. The N.A values are close to T.A values, since they are, respectively, 17 kbps for 868 MHz and 235 kbps for 2.4 GHz. Figure 3-3 demonstrates the result in the same conditions as described in Figure 3-2. In Figure 3-4, we considered two frequency bands 420 MHz (for implanted body sensors) with 75.9 kbps and 2.4GHz with 242.9 kbps. N.A values, in this case, are close to actual theoretical values, these two being 60 kbps and 225 kbps. The results of the first step validate the proposed numerical model theoretically by mapping theoretical values with computed values. In the second step, extensive simulation is conducted by considering various QoS aspects of WBASNs.

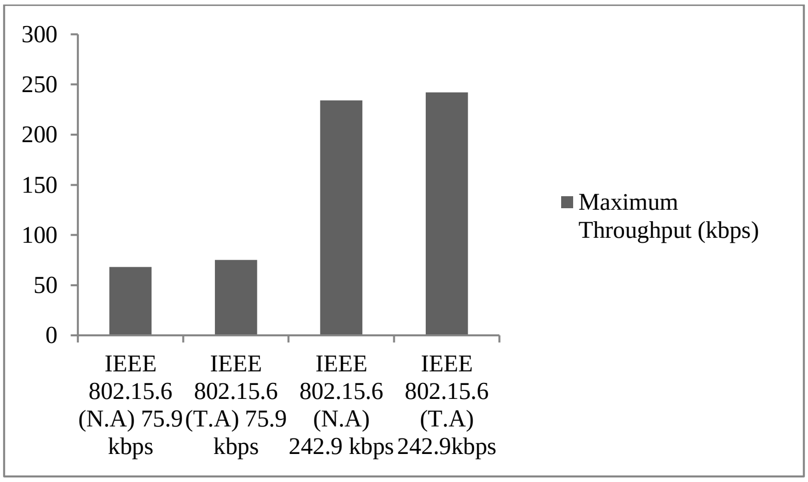

Figure 3-4 MT numerical and theoretical comparison of the IEEE 802.15.6

3.3.2. Comparison in terms of PDR of the Proposed DRT profile

Figures, 3-5 and 3-6 show the PDR values comparison between the default standard profile and the DRT profiles. The significant improvement is observed for the DRT profile. Default profile provides 65 % PDR; whereas, the DRT profile values provide up to 90%. The reason for the improvement is the selection of maximum reliability within a limited time. Figure 3-6 shows the comparison result of priority 3 and priority 7 class defined by the IEEE 802.15.6 standard [29] with their default and DRT profile. It is observed that priority classes with the DRT profile provide better PDR values, that is, for priority 3 with the default MAC parameter settings the PDR is 67%; whereas, for the DRT profile the PDR is 84%. Similarly, for the default profile with priority 7 the PDR is 77% and with the DRT profile, the PDR is 90 %. The difference between the PDR values is due to improved reliability values under the DRT profile [36].

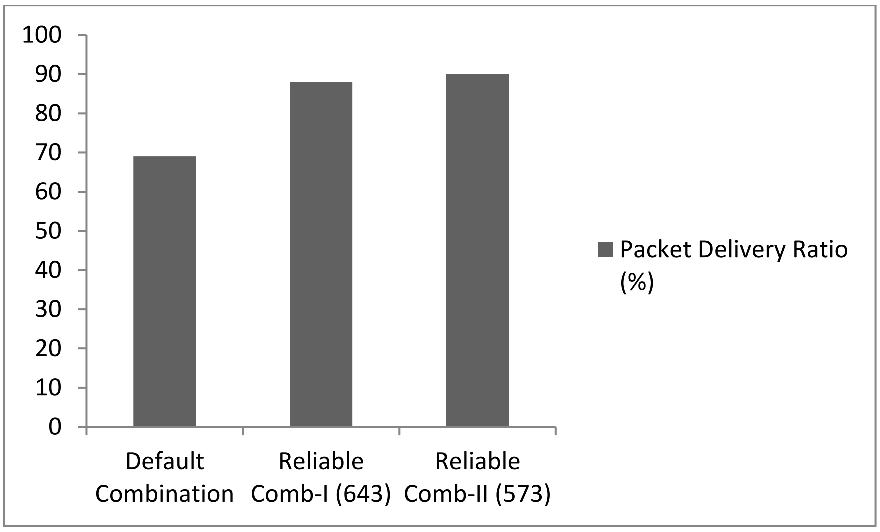

Figure 3-5 PDR comparison between the default profile and the DRT profile for IEEE 802.15.4

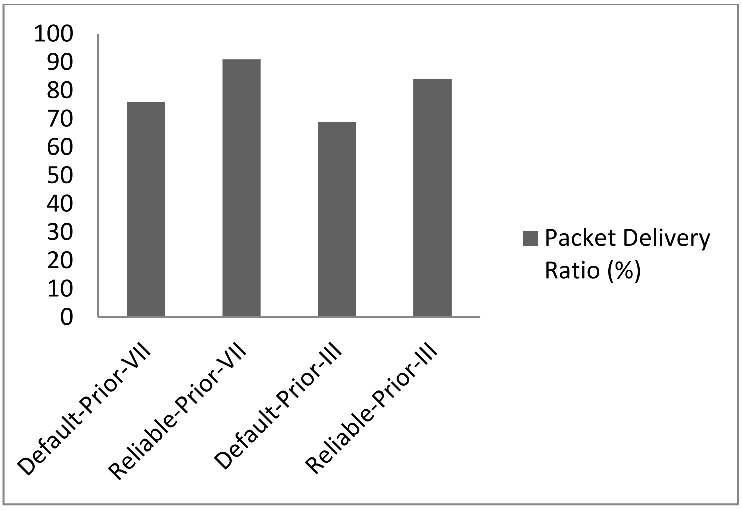

Figure 3-6 PDR comparison between the default profile and the DRT profile of the IEEE 802.15.6

3.3.3. Delay computation of the DRT profile with different packet sizes

After proving that the DRT profile performed better in terms of packet reception, we evaluate and validate the DRT profile values for latency (we compare statistical results with simulation results) by considering the different packet size of various WBASNs applications with a different number of nodes in a star topology. The purpose of packet size variation is to align our research with various biomedical sensor network requirements, for example, an ECG node requires 8 kbps, a blood pressure device requires 960 bps, and a temperature node requires 320 bps. These data rate changes are due to packet sizes of data. These simulations focus on analyzing the performance of different evaluating parameters like PD) and latency for WBASNs applications under different packet sizes (as each sensor has its own packet size requirement) [36].

Latency is defined as arrived message time minus the message sending time, whereas PDR is defined as the ratio of the number of successfully delivered packets to a node to a total number of transmitting data packets to a node. Most of the

WBASNSs applications require time-bounded services in the form of specific latency which is 250 ms. In simulations, we choose several significant (the combinations which provide delay values within 250 ms) DRT profile values which provide maximum reliability within 250 ms [36]. The following assumptions were made while conducting simulations under this step:

- The node always continuously tries to send a packet;
- Normal channel conditions;
- There are multiple senders and one receiver

Figures 3-7 and 3-8 show the delay comparison between N.A and Simulated Analysis (S.A) of the different DRT profiles values for the IEEE 802.15.4 (beacon-enabled with 20 kbps (868 MHz) and 250 kbps (2.4GHz)). The delay is computed for different packet sizes up to the maximum packet size, that is, 127 bytes in the IEEE 802.15.4. Here, it is important to mention that these delay values are those which considered reliability (in terms of retransmission) in proposed DRT profile. Moreover, for throughput, we have shown experiments in Section 3.3.1 and 3.3.2. Overall, delay increases with the increase of the packet size, but it remains around 250 ms for the DRT profile. It is observed that delay values of the S.A curve are higher than the N.A values. This is obvious as the number of nodes increases; the collision probability also increases and results in higher delay values. Different frequency bands and data rates for the same DRT profile gave different values for the delay. Usually, a higher frequency of 2.4 GHz with 250 kbps provides lesser delay values as compared with a low-frequency band. This difference is because higher data rates offer more bandwidth to the data traffic, which produces less delay.

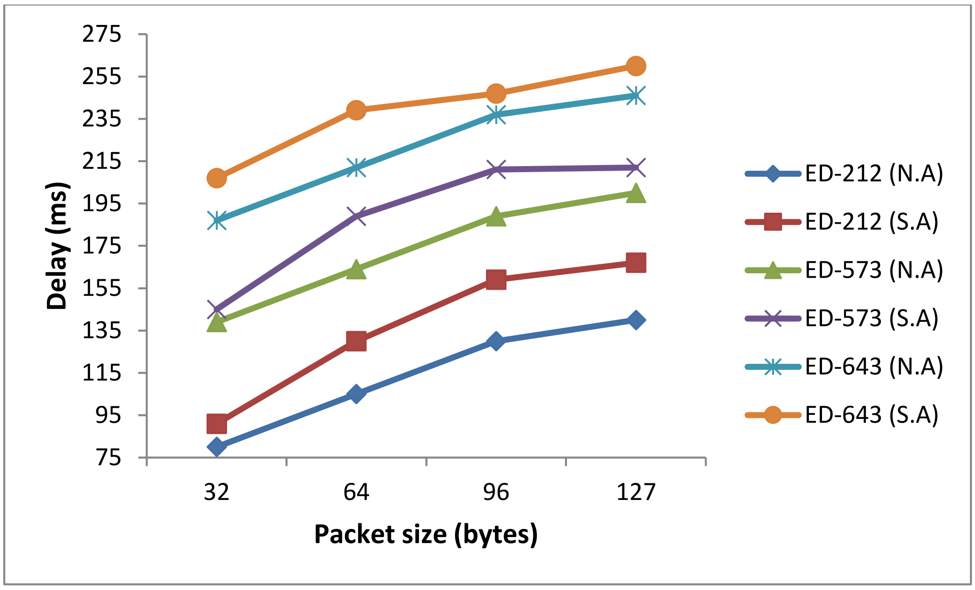

Figure 3-7 Delay comparison of the IEEE 802.15.4 (beacon-enabled 20 kbps)

Figures 3-9 and 3-10 demonstrate the delay comparison between N.A and S.A for the different DRT profiles of the IEEE 802.15.4 (beaconless with 20 kbps and 250 kbps). It is noticed that delay increases with the increase of packet size, but it remained around 250 ms for the DRT profile. The DRT profile values are different for beaconless and beacon-enabled modes. It is observed that the beaconless mode provided less delay than the beacon-enabled mode. It is also observed that delay values of the Simulated Analysis (S.A) are higher than the N.A values. The reason for this outcome is, as the number of nodes increases, the channel access attempts will also increase and only one node gets the channel. Remaining nodes have to wait until the next channel access, which increases the end-to-end delay [36].

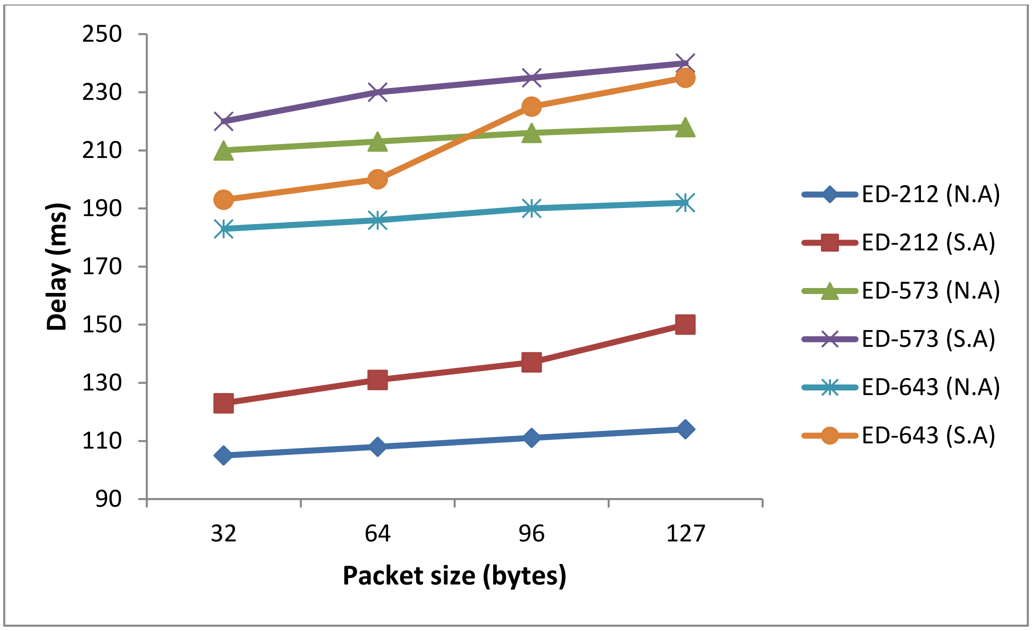

Figure 3-8 Delay comparison of different combinations of the IEEE 802.15.4 (beacon-enabled, 250 kbps)

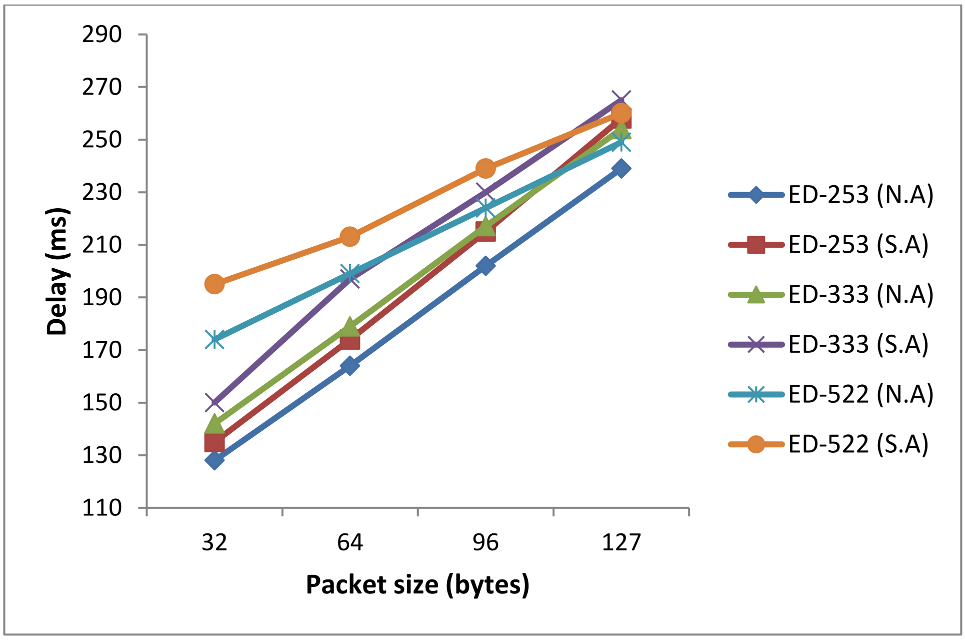

Figure 3-9 Delay comparison of different MAC layer combinations (beacon-less 20 kbps)

Figures 3-11 and 3-12 show the delay comparison between N.A and S.A for the different DRT profiles under different user priorities of the IEEE 802.15.6. The delay is computed for different packet sizes. Overall, the delay increased with the increase of packet size, but it remained around 250 ms for the DRT profile.

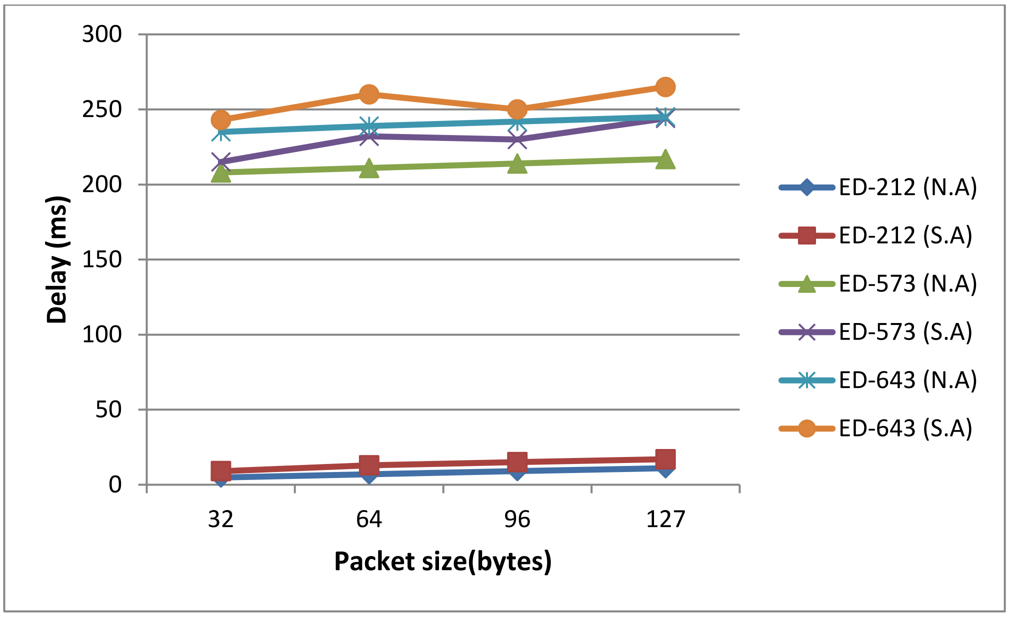

Figure 3-10 Delay Comparison of Different Combinations of IEEE 802.15.4 (Beacon-Less, 250 kbps)

It is observed that delay values of the S.A are higher than the N.A values. The reason is the difference in delay between priority 3 and priority 7. Moreover, as the number of nodes increased, the collision probability also increased.

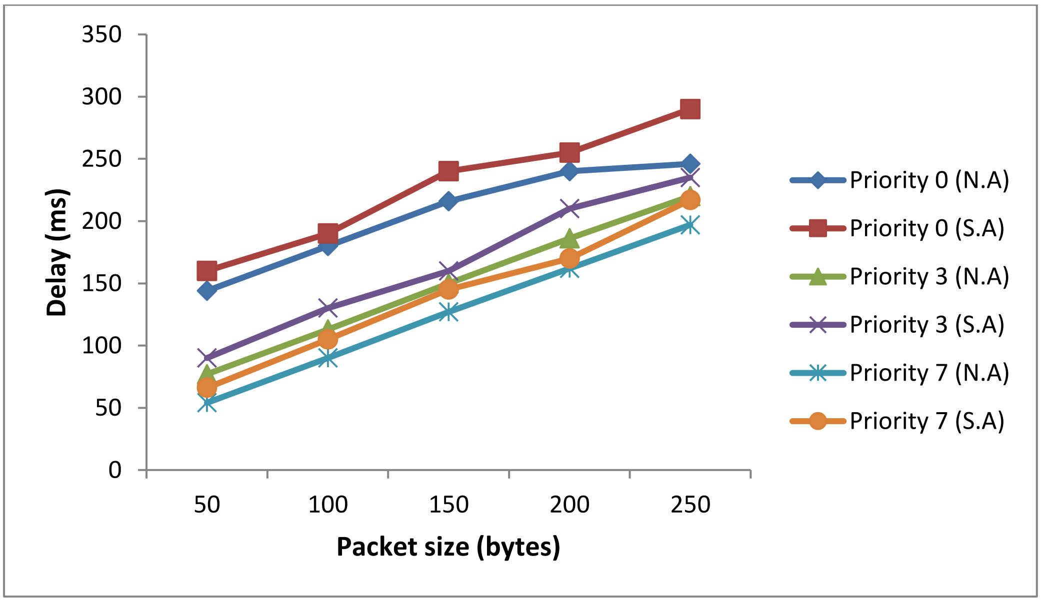

Figure 3-11 Delay comparison of different priority classes of the IEEE 802.15.6 (75.9 kbps)

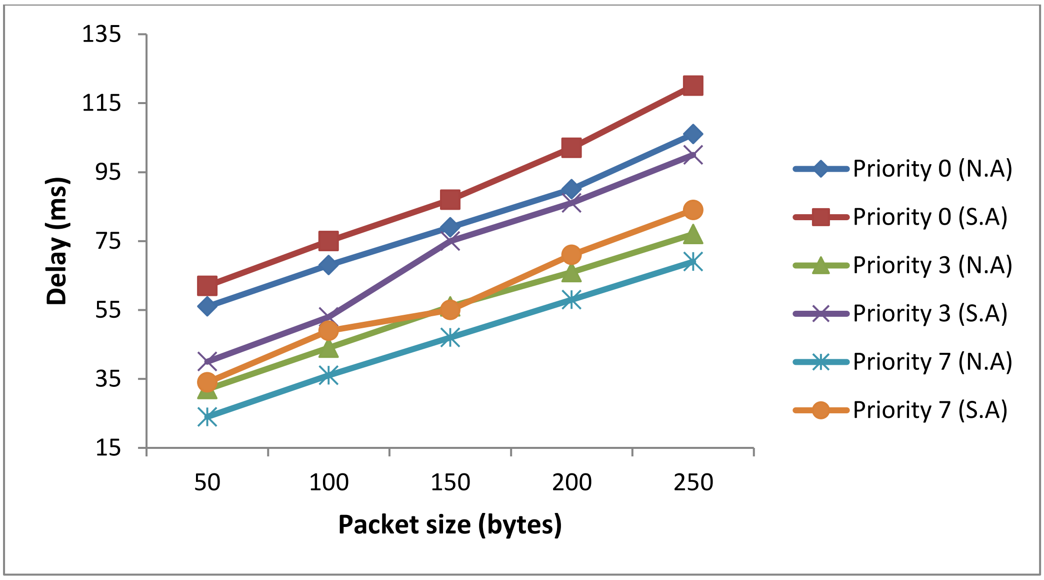

Figure 3-12 Delay comparison of different priority classes of the IEEE 802.15.6 (242.9 kbps)

Results from Figures 3-7 to 3-12 demonstrate that using parameter tuning approach, IEEE 802.15.4 and IEEE 802.15.6 standards can provide required MAC layer QoS for patient monitoring applications. The results of numerical modelling are validated through simulations for different frequency bands. It is observed that each frequency band requires a separate set of DRT profile (ED values with a different combination of BE, macCSMABackoff, and macFrameRetries) to support healthcare applications, in terms of delay value less than 250 ms, while considering the reliability.

3.4. Conclusion

WBASN provides new opportunities for the deployment of medical applications including patient monitoring and activity recognition. The DRT profile is proposed based on end-to-end delay model which considers reliability and latency. The DRT profile considers three MAC layer parameters: BE, macMaxCSMABackoffs, and MacMaxFrameRetries (used for reliability). The values of BE and macMaxCSMABackoffs represent delay; whereas, MacMaxFrameRetries values are used for reliability. By using parameter tuning approach, different combinations of these variables are applied in numerical computations with multiple frequency bands including 420 MHz, 868 MHz, and 2.4 GHz. For IEEE 802.15.4 with 868 MHz, a set of ED values are provided in Table 3-1 which gives the delay under 250 ms and this value is suitable for healthcare applications. The numerical model has been validated in OMNET++ with the Castalia 3.2 simulator. The numerical values of the IEEE 802.15.4 with 868 MHz are validated in the simulator in terms of delay by varying the packet sizes. It is observed that the delay for these ED values increases with the packet size; however, it remains under 250 ms with the maximum packet size which is 127 bytes. Similarly, by using parameter tuning approach, ED values are identified for 420 MHz (for IEEE 802.15.6) and 2.4 GHz (for IEEE 802.15.4). These ED values provide delay values less than 250 ms for most of the cases. Additionally, simulations have been used for evaluating the end to end delay, PDR and MT by varying the packet size, a number of nodes, frequency bands, and data rates.

We have concluded that the IEEE 802.15.4 and IEEE 802.15.6 standards with higher data rates and high-frequency bands could provide a less delay value at the MAC layer as compared with low-frequency bands. The purpose of applying different packet sizes is to provide suitability of CSMA/CA mechanisms for medical applications. An acceptable performance gap has been observed between numerical and simulated results which is due to collisions and channel occupancy of different nodes. We believe that the conclusions and experimental results obtained in this research can be helpful for protocol designers and researchers to establish optimized MAC protocols and standards for a variety of medical applications [36]. The partial work presented in this Chapter has been published in one journal and one conference paper, which are indicated below:

1. Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Delay, reliability, and throughput based QoS profile: A MAC layer performance optimization mechanism for biomedical applications in wireless body area sensor networks", Journal of Sensors, 2016, doi: 10.1155/2016/7170943, Impact Factor = 1.7

2. Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Implanted medical devices as future of wireless healthcare monitoring: Investigation and performance evaluation using novel numerical modeling", Proceeding of the 22nd International Conference on Automation and Computing, 2016, doi: 10.1109/IConAC.2016.7604973

Chapter 4: Tele-Medicine Protocol (TMP) for Slotted 802.15.4 with Duty-Cycle Optimization for Wireless Body Area Sensor Network

4.1. Introduction

This Chapter is the second step to achieve MAC layer QoS and our focus is on energy efficiency by using the DRT profile (Chapter 3). The DRT profile provides less delay (within 250 ms), reliability and throughput. The discussion about MAC layer QoS is mentioned in Chapter 1 (Section 1.1).

Many adaptive duty cycles-based MAC protocols based on IEEE 802.15.4 standard (for low-power devices) have been proposed to address these requirements. The discussion about duty cycle-based protocols is provided in Chapter 2: Literature Review (Section 2.4.3). Although these protocols provide energy consumption and throughput, they still suffer limitations in the context of the QoS for scenarios in a health monitoring environment. It is also worth noting that, for efficient energy consumption, these protocols adjust the duty cycle values on the estimation of several factors like active periods, buffer occupancy and collision rates. These estimations require resources in terms of delay, throughput, and energy, whereas medical applications require limited time-bounded services with less energy consumption for reliable data transmission.

These biomedical sensor nodes demand an energy-efficient communication framework which provides time bounded transmission, reliable data delivery and specified data rate [95, 96].

To address the above requirements, mostly, WBASNs make use of the IEEE 802.15.4 standard. The standard provides two working modes: beacon mode with slotted CSMA/CA and beaconless mode with simple CSMA/CA mechanism. The MAC protocols of WBASNs incorporate sleep and wake-up mechanisms (duty cycles) with listening periods of the transmitter and receiver to save energy. Mainly, these sleep and wake-up mechanisms are divided into synchronous and asynchronous categories. In the synchronous approach, wakeup schedules are shared with the neighbouring nodes to save the energy by simultaneously waking up and listens to the channel. In this context, this research proposes a Tele-Medicine Protocol (TMP) protocol based on the IEEE 802.15.4 beacon mode. To achieve the required QoS, TMP mainly combines two optimization approaches including the MAC parameter tuning (Proposed DRT profile: mentioned in Chapter 3 (Section 3.2)) and duty cycle-based approach. Further, the duty cycle is adjusted by the offered network load, delay-reliability factor, and superframe duration. The consideration of these factors makes TMP capable of providing a flexible and balanced set of QoS values [97].

4.2. Design and analysis for the TMP

We aim to design an energy efficient MAC protocol TMP for remote patient monitoring systems which provides low latency, specific data rate, and reliability. The system model is same as described in Chapter 3, since in this part of the thesis; we focused on delay, reliability, and throughput. In this Chapter, however, we will optimize the energy consumption by considering the DRT. We have considered the star topology with a centralized controller which is the coordinator node in the IEEE 802.15.4 and IEEE 802.15.6. Each node is fully synchronized with the coordinator for transmission. All the nodes send data directly to the coordinator node for processing. To incorporate the real environment (with interference and signal power loss), in our simulated results we are using Log Shadowing channel model. We are assuming no background traffic. We use a combination of computation methods to achieve the requirements. Our approach has three steps. In step 1, network traffic and its transmission time are estimated by considering a monitoring network with six to ten biomedical sensor nodes. The purpose of this computation is to estimate the total required time for the transmission of data at 100 kbps. The reason for data at100 kbps is that we are considering it as a maximum data rate required by a biomedical node for transmission. The detailed discussion of requirements of these nodes is mentioned in Chapter 1 (Section 1.2). In step 2, channel access and collision probabilities are computed. This step involves using the proposed DRT profile, to make the TMP reliable with low latency which is suitable for biomedical applications. For energy consumption analysis, we consider low power based CC 2420 (radio chip) [97] as a radio model in the simulations. The reason we use CC2420 is that it is the radio chip based on the IEEE 802.15.4 and widely available in existing sensing devices. The energy consumption for a node also depends on the selection of the duty cycle value. In Step 3, the optimized duty cycle value is computed by considering the superframe duration value of the system [97], a detailed discussion of which is provided below. Figure 4-1 shows a state flow chart of TMP.

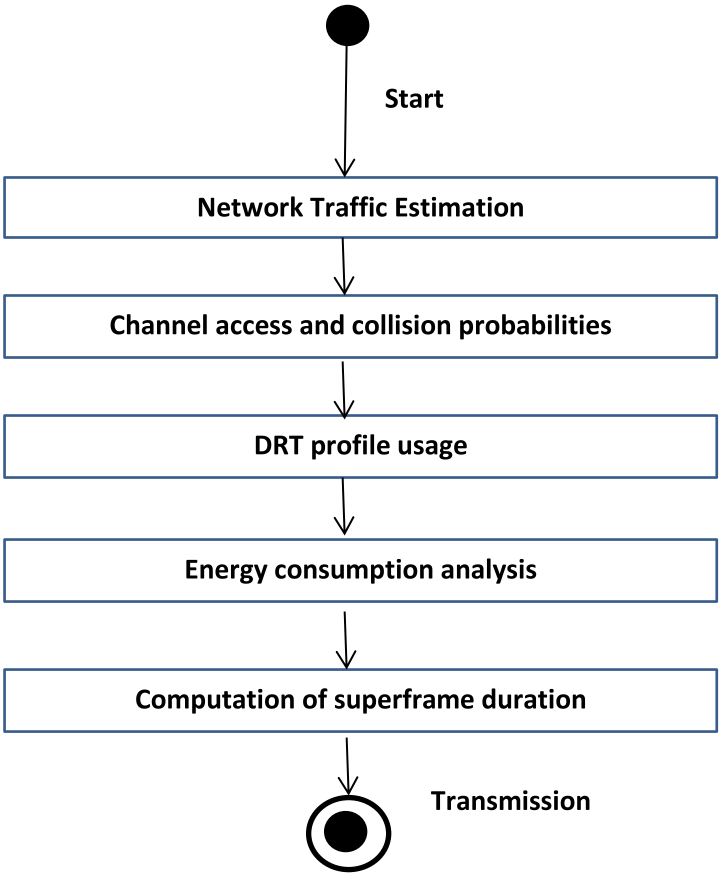

Figure 4-1 State transition diagram for TMP

4.2.1. Network traffic estimation

This research considers that Full Function Devices (FFDs) act as a coordinator in a star topology. It is assumed that the value of Contention Free Period (CFP) is zero which means Clear Channel Assessment (CAP) represents the complete active period. The discussion regarding FFDs, CFP and CAP is provided in Chapter 2: Literature Review (Section 2.2). It is also assumed that FFDs are only the receivers. The selection of the appropriate active Superframe Duration (SD) is an important aspect for the performance of the slotted CSMA/CA. If the length of SD is higher than the required interval, then the network nodes spend more time in the active state which will consume more energy. Similarly, if the length of the active period is less than the required interval then packets suffer more delay. The throughput decreases because of many collisions which may result in the retransmission of lost packets and wastage of more energy. In this research, we optimize the existing slotted CSMA/CA of the IEEE 802.15.4 (Chapter 2: Literature Review (Section 2.2)) for a patient monitoring system. In remote patient monitoring applications, a patient is equipped with a limited number of biomedical sensor nodes such as ECG, EEG, EMG, accelerometer, gyroscope, pulse oximeter, BP, temperature, peripheral capillary oxygen saturation SpO2, barometer, and heart rate monitoring. Table 4-1 describes the data rate and acceptable delay for the biomedical applications. These nodes continuously monitor the patient physiological conditions and send the data to a coordinator, which means they want to access the channel continuously as they always have data to send [97].

Table 4-1 Biomedical application requirements [1, 2]

Medical applications	**Data rate**	**Delay**
Accelerometer	35 kbps	<250ms
Temperature	120 bps	<250ms
ECG	50 kbps	<250ms
SpO2	1.2 kbps	<250ms
BP	960 bps	<250ms
Glucose monitor	1.6 kbps	<250ms

In our proposed system, we assumed that there are 6 to 10 biomedical nodes which generate data up to 100 kbps. If the payload size is 100 bytes (assuming that 6 bytes of PHY header and 9 bytes of MAC header are included in 100 bytes), then the time required to send a single frame can be calculated according to [36] as mentioned in equations 4-1, 4-2 and 4-3.

$$T_{\text{frame}} = \frac{(\text{PhyHeader(in bits)} + \text{MACHeader (in bits)} + data)}{\text{Data rate}} \qquad \text{4-1}$$

Equation 4-1 computes time to send a frame

$$T_{\text{One frame}} = \frac{(100*8)}{250*1024} = 3.12 \text{ ms} \qquad 4\text{-}2$$

Equation 4-2 computes time to send a frame with 100 bytes

$$T_{\text{otal bytes offered load}} = \frac{(100*1024)}{8} = 12800 \text{ bytes} \qquad 4\text{-}3$$

Equation 4-3 computes total bytes for 100 kbps

The $T_{\text{otal time required}}$ to send 12800 bytes is computed by,

$$T_{\text{otal time required}} = \frac{(12800*8)}{250*1024} = 400\ ms$$

4-4

Overall, using equations 4-1 to 4-4, the required time is computed to transfer 100 Kbps of data with the purpose to identify the superframe duration.

4.2.2. Channel access and collision probabilities

The packet loss occurs due to two main reasons: the channel access failure and packets collision. The channel access failure occurs when nodes try to access the channel and the channel is found busy [98]. In the following successful channel access and collision, probabilities are computed for the beacon mode of the IEEE 802.15.4 standard.

The probability for a node to successfully access the idle channel P_{SC} with the maximum backoff periods is given by equation 4-5 [97]

$$P_{SC} = \sum_{k=1}^{k=b} P_{IdleCh} (1 - P_{IdleCh})^{(k-1)}$$

4-5

Where k represents channel access attempts from 1 to macMaxFrameRetries, P_{IdleCh} represent the success probability that a node accesses the channel at the end of backoff period. Equation 4-5 is assuming the saturated system model, where a node always has a packet to send. The purpose of equations 4-5 to 4-7 is to estimate collision and channel access probabilities. As G.Bianchi Markov chain model is only for the IEEE 802.11, therefore, it is not fully applicable in the IEEE 802.15.4. The authors, however, have extended the IEEE 802.11 based G.Bianchi Markov chain model for the IEEE 802.15.4 to describe channel access probabilities. These simple probabilities computation in 4-5 to 4-7 is inspired by the G.Bianchi Markov chain model.

For n network devices, the P_{IdleCh} is

$$P_{IdleCh} = (1 - q)^{(n-1)} \quad 4\text{-}6$$

where q is the transmitting probability of a node.

The packet collision occurs when during CCA two or more than two nodes try to access the channel at the same time, the overall total collision probability (P_{TPC}) is

$$P_{TPC} = \sum_{l=1}^{l=r} P_C (1 - P_C)^{(n-1)} \quad 4\text{-}7$$

where P_C is the collision probability.

4.2.3. Delay and reliability factor (DRT profile)

The purpose of this research is to develop an energy efficient protocol by considering limited delay and DRT profile at the same time. Therefore, in this section, we use the MAC layer parameter optimization approach and tune the MAC layer parameter according to delay and reliability needs of remote patient monitoring systems. The method in [36] used to compute and suggest a DRT profile for patient monitoring applications. Table 4-2 presents the DRT profile using equation 4-8 which is explained in Chapter 3 as well.

$$ED = macFrameRetries * (T_{WT} + T_{frame} + T_{Ack} + T_{SIFS} + T_{\tau A}) \quad 4\text{-}8$$

4-8 represents the total delay in the slotted CSMA/CA process which includes the total waiting time (T_{WT}), where T_{WT} represents the backoff time which is assigned to a node before going to channel access attempt. In ED, delay includes the transmission and propagation delay. For propagation delay, we have used the values mentioned in the IEEE 802.15.4 and IEEE 802.15.6 standards [28, 35]. Equation 4-8 also includes frame transmission time (T_{frame}), acknowledgement receiving time (T_{Ack}), short interframe space time (T_{SIFS}) and turnaround time ($T_{\tau A}$). These equations are extracted from flow transmission of the IEEE 802.15.4 and IEEE 802.15.6 standards mentioned in Chapter 2: Literature Review (Section 2.2).

T_{WT} in equation, 4-9 represents the total waiting time before transmission which is computed with the help of the random backoff exponent time (T_{BE}), the clear channel assessment time (T_{CCA}) and the contention windows time (T_{CW}) [29, 35].

$$T_{WT} = \text{macCSMABackoff} * (T_{BE} + T_{CCA}) + T_{CW} \qquad 4\text{-}9$$

The contention windows time (T_{CW}) in slotted CSMA/CA is

$$T_{CW} = 2 * T_{BOslot} \qquad 4\text{-}10$$

T_{BOslot} denotes the time for a single backoff slot. For analysis, we consider the bit rate of 250 kbps (2.4G Hz frequency band is considered with BPSK modulation and a symbol represents 4 bit).

The bit rate used in equation 4-4 is dependent on the frequency band. The time for single backoff slot is

$$T_{BOslot} = 20(\text{symbols}) * T_{symbol} = \frac{20*4}{\text{Bitrate}} = \frac{80}{250\ \text{Kbps}} \qquad 4\text{-}11$$

According to beacon mode of the IEEE 802.15.4 the Clear Channel Assessment Time (T_{CCA}) is

$$T_{CCA} = 8(\text{symbols}) * T_{symbol} \qquad 4\text{-}12$$

The random Backoff Time (T_{BE}) is the waiting time for channel access which is computed by

$$T_{BE} = (2^{BE} - 1) * T_{symbol} \qquad 4\text{-}13$$

The example below shows the steps in computing T_{BE}

Time to transmit a single frame is computed by

$$T_{frame} = \frac{(\text{PhyHeader(in bits)} + \text{MACHeader (in bits)})}{\text{Data rate}} \qquad 4\text{-}14$$

where T_{Ack} is the transmission time for an acknowledgement and is given as

$$T_{Ack} = \frac{\text{Packet size}}{\text{Data rate}} \qquad 4\text{-}15$$

Short interframe space (SIFS) is defined as the time in micro seconds required for a wireless interface to process a received frame and to give a response. Derived using the IEEE 802.15.4 and IEEE 802.15.6 standards [29, 35]. It is valid in beacon mode and T_{SIFS} is computed by

$$T_{SIFS} = 12 * T_{symbol} \qquad 4\text{-}16$$

$T_{\tau A}$ is the turnaround time which is the time between data frame transmission till and its acknowledgement. It is valid with non-beacon mode and it is calculated as

$$T_{\tau A} = 12 * T_{symbol} \qquad 4\text{-}17$$

Numerical equations from 4-8 to 4-17 are used to calculate the set of combinations of BE, macCSMABackoff and macMaxFrameRetries values which provide reliability of data transmission within an acceptable latency and data rates. The parameter “macFrameRetries” describes the number of retransmission attempts, its default value is 4 and the maximum value is 7.

Table 4-2 shows the combinations which are already computed in Chapter 3 (Section 3.2) and each combination can be defined as follows:

$$ED_{212} = \text{End to end delay, where BE} = 2, \text{macCSMABackoff} = 1, \text{and macMaxFrameRetries} = 2$$

Table 4-2 Computed combination of delay and reliability for slotted CSMA/CA

Parameter combination	ED (ms)
ED_{212}	13
ED_{375}	108
ED_{473}	117
ED_{475}	195
ED_{545}	223
ED_{573}	222
ED_{625}	225
ED_{643}	250
ED_{662}	248

4.2.4. Energy analysis for slotted CSMA/CA

The energy consumption for a sensor node can be computed as specified time duration for a corresponding state and its consumed power levels. In the slotted CSMA/CA, nodes go to the sleeping state during waiting intervals: backoff, Clear Channel Assessment (CCA) and Contention Windows (CW). We present an energy consumption analysis for a node to estimate the device lifetime with slotted CSMA/CA. Total Energy Consumption (E_{TC}) for a node is the sum of energy consumptions for various steps involved in the slotted CSMA/CA as shown in equation 4-18 [97]. Total energy consumption for CSMA/CA operation of beacon mode is

$$E_{TC} = E_{WT} + E_{frame} + E_{ACK} + E_{\tau A} \qquad \text{4-18}$$

Equation 4-18 includes energy consumed in waiting process (E_{WT}) for the channel access, frame transmission (E_{frame}), receiving acknowledgement (E_{ACK}) and turnaround time ($E_{\tau A}$). Based on these values, we computed the value of energy consumption in OMNet++. In our experiments, CC2420 is used as the radio model. Table 4-3 represents the characteristics of CC2420. It is a single-chip with operating frequency of 2.4 GHz IEEE 802.15.4, RF transceiver designed to support low-power and low-voltage wireless applications.

The energy consumed in a waiting process (E_{WT}) for channel access is computed by equation 4-19 with the combination of the waiting time (T_{WT}) and the power consumed for sleeping (P_{Sleep}). The values of P_{Sleep} is mentioned in Table 4-3 which is 1.4 mW [97].

$$E_{WT} = P_{Sleep} * T_{WT} \quad \text{4-19}$$

The energy consumed in sending a frame is computed by using two parameters: the transmission power (P_{Tx}) requires sending a frame and the time consumed (T_{frame}) to send a frame and the value of P_{Tx} is mentioned in Table 4-3 which is 57.42 mW

$$E_{frame} = P_{Tx} * T_{frame} \quad \text{4-20}$$

After processing the received frame, an acknowledgement is sent, and the energy consumed in sending an acknowledgement (E_{ACK}) can be computed using the two parameters particularly, transmission power (P_{Tx}) at the measurement of, 57.42 mW to send an acknowledgement frame and the time required (T_{Ack}) as:

$$E_{ACK} = P_{Tx} * T_{Ack} \quad \text{4-21}$$

Table 4- 3 Transceiver characteristics

Transceiver characteristics	**Values**
Tx-Rx, Rx-Tx (transition time)	0.01 ms
Rx-Sleep, Tx-Sleep (transition time)	0.05 ms
Sleep-Rx, Sleep-Tx (transition time)	0.194 ms
Transmit power level	-5 dBm
Tx (power consumed)	57.42 mW
Rx (power consumed)	62 mW
Tx-Rx, Rx-Tx (power consumed)	62 mW
Sleep-Rx, Sleep-Tx (power consumed)	62 mW
Rx-Sleep, Tx-Sleep (power consumed)	1.4 mW
Sleep power level	1.4 mW

Three states are involved in the operation of CSMA/CA: transmission, receiving and sleep state. Each state consumes a certain power level as defined in Table 4-3. Overall, Table 4-3 shows the power consumed during transmission (Tx), the power consumed during the reception (Rx) and power level during sleep mode. Moreover, Table 4-3 also includes the power required to shift from one state to another like from Tx to Rx, it will consume 62 mW. During the operation of CSMA/CA, the wireless interface keeps switching during these states according to the requirement. Those switching also consume power and require a specified time, as defined in Table 4-3. Overall, the switching time is defined as transition energy ($E_{Transition}$) as shown in equations 4-22 and 4-23. The sum of transition energies consumed in switching from sleep to transmission ($E_{Sleep-Tx}$), transmission to receiving state (E_{Tx-Rx}) and receiving state to sleep state ($E_{Rx-Sleep}$) [97] is calculated as

$$E_{Transition} = E_{Sleep-Tx} + E_{Tx-Rx} + E_{Rx-Sleep} \qquad 4\text{-}22$$

$$E_{Transition} = (P_{Sleep-Tx} * T_{Sleep-Tx}) + (P_{Tx-Rx} * T_{Tx-Rx}) + (P_{Rx-Sleep} * T_{Rx-Sleep}) \qquad 4\text{-}23$$

4.2.5. Superframe duration and the optimum duty cycle value

The method discussed in section 4.2.1 can be used to compute the time required to send 100 Kbps as it is a requirement of our system. In section 4.2.3, we also identified the CSMA/CA parameters inform of the combination. Therefore, using the methods in sections 4.2.1 and 4.2.3, the superframe duration can be calculated. The values BI and SD depend on the constant value of aBaseSuperframeDuration, Beacon Order (BO) and Superframe Order (SO). IEEE 802.15.4 standard computes the value of aBaseSuperframeDuration as mentioned in equations 4-24 and 4-25.

$$SD = aBaseSuperframeDuration * 2^{SO} \text{ symbols} \qquad 4\text{-}24$$

$$aBaseSuperframeDuration = aBaseSlotDuration * aNumSuperframeSlots * symbolTime \quad 4\text{-}25$$

The symbol time can be computed as mentioned in the equation in 4-26. For 2.4 GHz, IEEE 802.15.4 uses 4 bits per symbol:

$$symbolTime = 1 / (phyDataRate * 1000 / phyBitsPerSymbol) \quad 4\text{-}26$$

We computed the required time from equation 4-4 which shows we need 400 ms (for 12800 bytes) to manage 100 kbps of data. For our experiments, we are considered DRT from Table 4-2 that is, ED_{662} which suggests the delay of 248 ms. Therefore, the SD time should be near 700 ms, which is applied in the simulator for testing purpose.

$$SD = 15.36 * 2^6 = 983.04 \text{ ms}$$

Duty cycle mechanism is considered as a proficient solution for the idle listening and over-hearing problem, where periodic cycling is done between the sleep time and wakeup time state. After defining the required SD length that supports the limited delay and reliability, the challenge is to decrease the energy consumption and increase the network lifetime by testing different values of the duty cycle to get optimized value [97]. The Duty Cycle is

$$DC = \frac{2^{SO}}{2^{BO}} \quad 4\text{-}27$$

DC is optimized by considering the above computations related to network traffic load, delay and reliability factor and specified SD value. Now this DC value optimizes the network life time not only basis of energy but also considering delay and reliability. Table 4-4 shows the different values of the duty cycle with respect to energy consumption, where the values are obtained from a series of experiments in OMNet++ and Castalia 3.2. After testing different DC values, we use the DC value of 17 % as it provides less energy consumption with limited delay (within 250 ms). DC values of 5% and 10% provide less energy consumption. In spite of these advantages, such long sleeping intervals could miss some important communication. Hence, DC value of 17% is more appropriate for healthcare applications.

Table 4-4 Duty cycle vs energy consumption

Duty cycle (%)	Energy consumed (Joules/Sec)
5	1.7
10	2
17	2.3
20	2.5
25	2.9
50	3.8
100	6.8

4.3. Simulation and results for proposed TMP

The star topology is used in the simulations, where a node communicates with the coordinator using slotted CSMA/CA. The coordinator is placed in the center and nodes are distributed randomly around the coordinator. The coordinator sends beacon messages at the beginning of a superframe. In active period, nodes content for the channel by using slotted CSMA/CA. The coordinator sends an acknowledgement on reception of a packet. It is assumed that the value of CFP is zero, which means CAP represents the complete active period (The discussion regarding CAP and CFP is provided in Chapter 2: Literature review (Section 2.2).

To make the simulation results more realistic, the conducted simulation also considers the consumed energy value. In this context, the radio model CC2420 is used and Table 4-3. The simulation scenario is designed on the theme of patient monitoring applications where a patient is equipped with a limited number of biomedical sensor nodes like ECG, EEG, EMG, accelerometer, gyroscope, pulse oximeter, BP, temperature, Peripheral capillary oxygen saturation SpO2, barometer, and heart rate monitoring. We set the packet generation rate of each sensor node according to its data rate requirement for the devices. These nodes continuously sent their data to the coordinator, which means they wanted to access channel continuously as they always have data in their queues. In our proposed system, we assume that there are 6 to 10 biomedical nodes and each of it is capable of generating data up to 100 kbps [97].

Performance of the proposed protocol is compared with existing protocols AAOD [81], AMPE [74], ADCA [32], DSAA [79], DCA [61] and the default IEEE 802.15.4. Evaluating parameters include average delay, PDR, energy consumption, and collision rate. Moreover, the effect of different factors like several nodes and the network load is considered. Table 4-5 provides the simulation parameters. We consider 10 nodes in a star topology by using a frequency band of 2.4 GHz. As in Castalia 3.2, there are 11 random variables, so to get the more accurate results; we used the seed value 11.

These protocols are based on the IEEE 802.15.4 whose implementation is available as open source simulators like OMNet ++ and NS-2 [97]. Moreover, the authors in [61, 62, 99, 100] provided discussions on the extended algorithms to implement in OMNet++ and CASTALIA 3.2.

Table 4-5 Simulation parameters

Parameters	**Values**
Number of nodes	Varies from 6 - 10
MAC	IEEE 802.15.4
Channel mode	Log Shadowing Wireless Model
Seed value	11
Frequency band	2.4 GHz
Data rate	250 kbps
Evaluation parameters	Delay, PDR, Energy consumption
Packet size	Varies from 32 bytes to 100 bytes
Simulation time	100-2000 seconds

4.3.1. End-to-end delay analysis

Figure 4-2 shows the average end-to-end delay comparison of TMP with existing protocols. We considered 250 ms as the acceptable benchmark delay for medical applications. The challenge is to reduce the delay by considering the reliability factor. It is observed that TMP provides the average end-to-end delay within 250 ms. The main reason for the low delay is the consideration of a suitable set of MAC layer parameters mentioned in Table 4-2. These parameters including BE, macCSMABackoff, and macFrameRetries. The value of BE further depends on macMinBE and macMaxBE. We performed experiments for those combinations which p the limited delay with maximum reliability. Further, TMP selects the appropriate duty cycle values by considering the offered load up to 100 kbps. The TMP reduces the delay. AAOD, AMPE, and DCA showed higher delay values that are, more than two seconds. ADCA, DSAA and IEEE 802.15.4 performed comparatively better but did not fulfil the requirements of medical applications. The higher delay for these protocols is caused by the factors like higher values of BE and the selection of inappropriate duty cycle values. Higher values of BE cause more delay for nodes to access the channel and inappropriate values of duty cycles cause packet loss and increase delay.

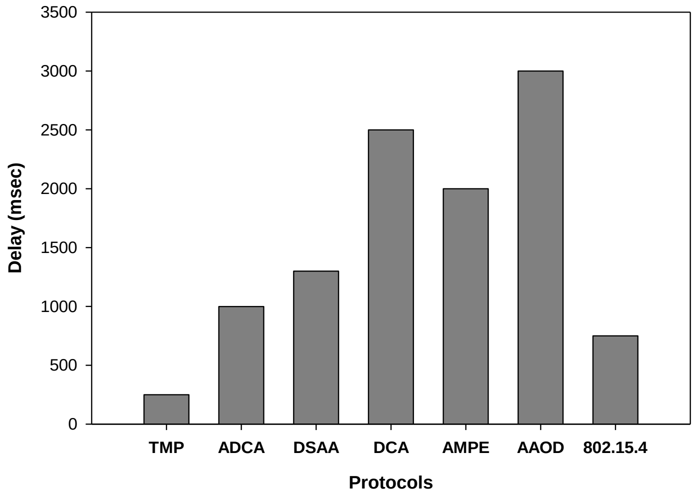

Figure 4- 2 Average end-to-end delay comparison

4.3.2. Packet delivery ratio analysis

Figure 4-3 describes the comparative analysis of PDR values of TMP in comparison with other protocols. It is noticed that TMP provides 76% better PDR. The main reason for the higher PDR is the consideration of the appropriate MAC parameter settings which contribute towards reliability: macCSMABackoff and macFrameRetries. We selected a suitable combination of these values from Table 4-2 and mentioned in Section 4.2.5. These combinations provide the reliability within the required time boundaries for medical applications. Further, the value of the duty cycle based on offered load gives an appropriate active period to transmit maximum data, which increases the PDR. The default IEEE 802.15.4, AAOD and AMPE provides PDR (within 250 ms) between 35% and 55%; whereas, ADCA, DSAA, and DCA provide less than 30%. The reason for less PDR within the limited time period includes lower values of BE which increase the collision rate, inappropriate values of the MAC layer parameters: macCSMABackoff and macFrameRetries [97].

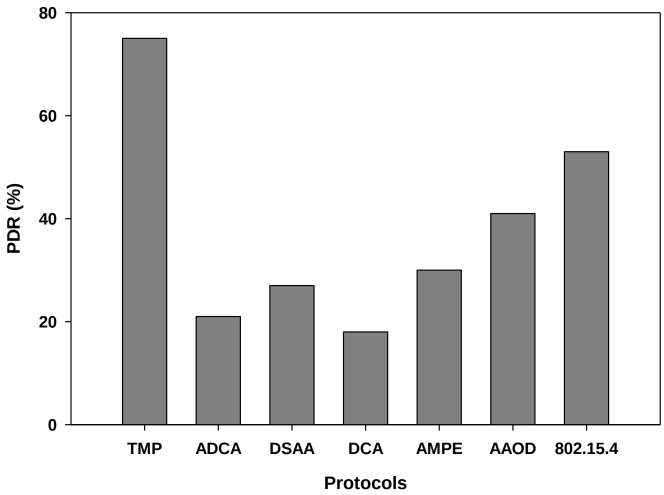

Figure 4-3 PDR comparison

4.3.3. End-to-end delay, PDR, and energy consumption analysis

Figure 4-4 shows the overall performance comparison of TMP with other protocols in terms of energy consumption, delay, and PDR. We used the energy model parameters described in Table 4-3. TMP performs better in all three aspects and provides its suitability for medical applications. The selection of an appropriate duty cycle by considering the offered load is the key element of its performance, which results in efficient energy consumption and reliable data delivery within a limited time. Other protocols do not provide the required performance in terms of delay, PDR, and energy consumption.

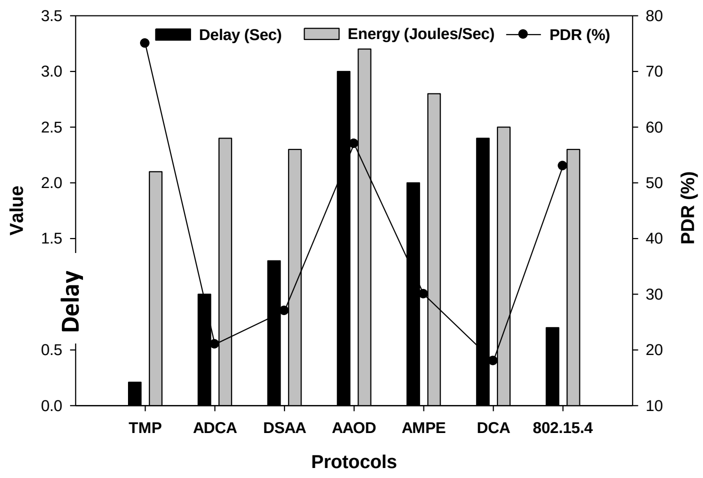

Figure 4-4 Delay, energy and PDR comparison

Figure 4-4 shows that TMP provides less delay that is 248 ms. TMP also provides better performance for energy consumption which is 2.3 Joules/sec. As discussed in Section 4.1, the protocols like AAOD, AMPE, ADCA, DSAA, and DCA use various computations and then select the value of duty cycle. These computations usually include buffer occupancy, collision rate, and packet reception rate. These computations lead towards some other procedures which require additional time. If the estimation goes wrong then there will be an inappropriate selection of active periods and duty cycle which causes low performance in the context of medical applications [97].

4.3.4. Duty cycle analysis

Figure 4-5 shows the different duty cycle values for various offered network traffic load for TMP. These duty cycle values provide optimal energy consumption with limited latency and reasonable reliability. Usually, patient monitoring systems consist of six to ten monitoring sensors and the total offered data load varies from 10 to 100 kbps collectively for all nodes. After simulations 17 % value of duty cycle is suitable for a maximum load of 100 kbps; whereas, for 20 kbps the recommended value is 8 %.

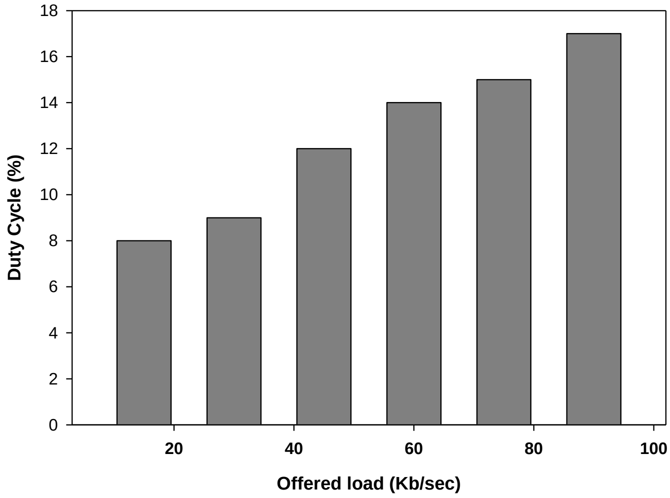

Figure 4-5 Duty cycle effect on offered load

4.3.5. Number of nodes variation effect on end-to-end delay, PDR and collision rate

Figure 4-6 shows the average end-to-end delay comparison of TMP with the other protocols by varying the number of nodes. As our focus is on medical applications, we assumed that a patient can carry maximum of 6 to 10 sensors nodes. We also checked the effect of a high number of nodes which is up to 16. However, our main concern is up to 10 nodes for discussion. It is observed that TMP performs well and the delay varies within 250 ms; whereas, the other protocols could not meet the strict criteria in the context of medical applications. The cause for required performance of TMP is the appropriate selection of SO and duty cycle which reduces the load on queues and provides fewer collisions. The default IEEE 802.15.4 and ADCA performed better than other protocols and provides delay up to 1000 ms with 14 nodes. The reason is that higher values of BE help to manage the channel access for nodes which reduces the collision chances. The reasons for the low performance of the AAOD, AMPE, DSAA, and DCA include lower values of BE and inappropriate duty cycle values which increase the waiting time and caused packet drop and collisions.

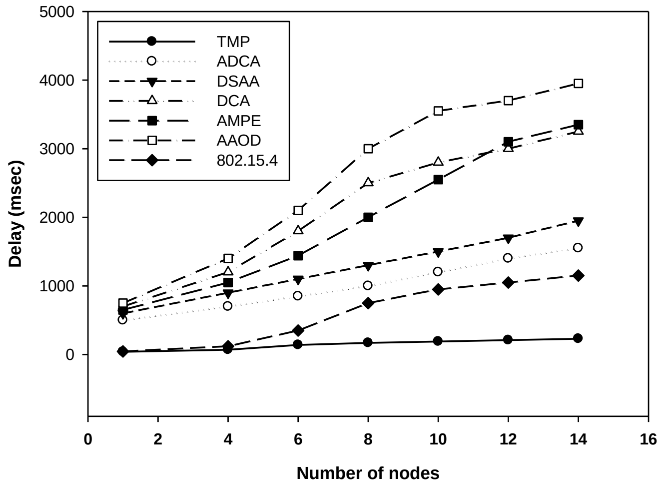

Figure 4-6 Delay vs number of nodes

Figure 4-7 shows the effect of varying the number of nodes on PDR values for TMP with the other protocols. TMP performed well and provides reasonable PDR values due to its consideration of appropriate reliability parameters. The default IEEE 802.15.4 and AAOD performed better than AMPE, ADCA, DSAA, and DCA because of reliability factors for the MAC layer, but their performance is lower than TMP due to inappropriate selection of SO and duty cycle values [97].

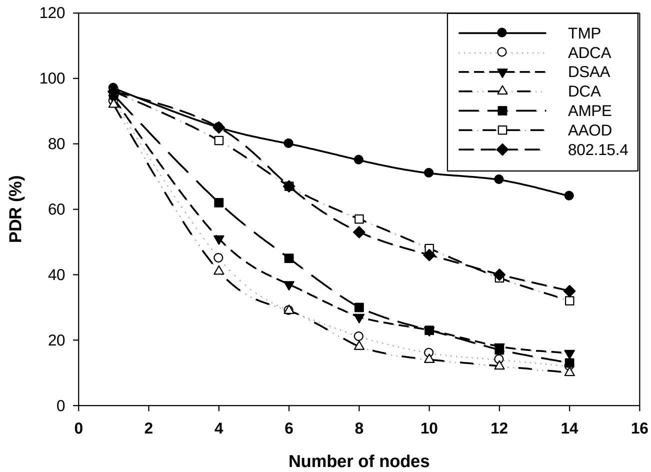

Figure 4-7 PDR and number of nodes

Figure 4-8 shows the comparison of the collision rate. It is observed that number of collisions increases by increasing the number of nodes. Although several packet collisions in AAOD is lower, but the value of energy consumption is the higher from all other protocols. The reason for the lower number of collisions for AAOD is the high range of backoff values which significantly reduces the collisions. The TMP provided collision rate almost equal to ADCA because of selective backoff values; however, ADCA showed higher delay and energy consumption than the ADCA [97]. The remaining protocols provided high collision rate due to their fewer backoff values.

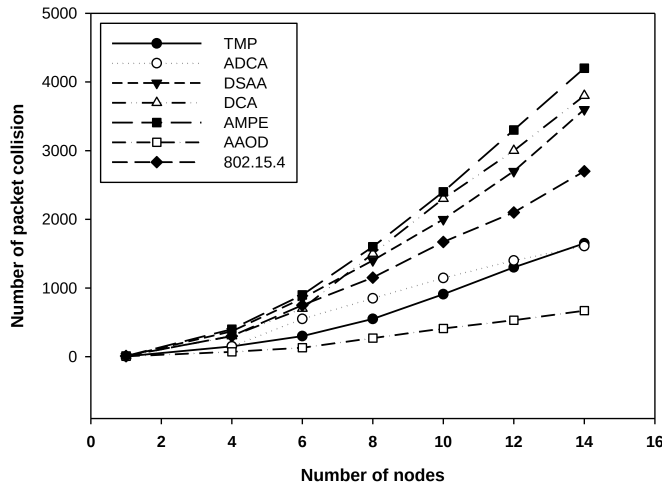

Figure 4-8 Collision rate

4.4. Conclusion

We proposed the TMP using the IEEE 802.15.4 slotted CSMA/CA with beacon-enabled mode for remote patient monitoring systems. TMP combines two popular optimization techniques: MAC layer parameter tuning and duty cycle optimization. Duty cycle is adjusted by three factors: offered network traffic load, delay and reliability factor (DRT) and superframe duration. TMP depends on the offered network load of the system, which is up to 100 kbps. In section 4.2.1, the time required to transmit 100 kbps is estimated which is used in calculating the superframe duration. To provide limited latency and reliability, the methods from section 4.2.3 are used which basically tune the MAC layer parameters. The superframe duration is computed by considering the mentioned factors: offered network load and delay and reliability factor. In section 4.2.5 the optimized duty cycle is computed by doing a series of the experiment. It is observed from experiments that DC value of 17% provides 2.3 Joules/Sec for energy consumption. It provides SD value of 983 ms which is sufficient to transmit 100 Kbps of data. The proposed TMP is optimized for the star topology and provides a limited delay which is within 250 ms, reliability (2 times retransmission) and throughput. Comparative analysis of the TMP protocol is conducted with existing protocols: AAOD, AMPE, ADCA, DSAA, DCA and default IEEE 802.15.4. The comparison parameters include end-to-end delay, reliability, collision rate, PDR, and energy consumption. Simulation is conducted in CASTALIA 3.2 by using the OMNet ++ platform. The TMP provides 76% PDR which is better than the other protocols. Further, the delay values remain less than 250 ms. The reason for the better performance is optimized DC mechanism. The DC value is computed using offered traffic load. Moreover, TMP is simulated by varying the number of nodes from 1 to 10. TMP performs better than the mentioned protocols in terms of time bounded data delivery with better reliability and efficient energy consumption. The partial work in this chapter has been published in the following journal

- Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "TMP: Tele-Medicine Protocol for Slotted 802.15. 4 With Duty-Cycle Optimization in Wireless Body Area Sensor Networks", Published in IEEE Sensors, vol 17, No 6, 2017, doi: 10.1109/JSEN.2016.2645612, Impact Factor = 2.54

Chapter 5: IEEE 802.15.4 Frame Aggregation Enhancement to Provide High Performance in Life Critical Patient Monitoring Systems

5.1. Introduction

This Chapter is the third step to achieve the MAC layer QoS. In this Chapter, we have used a different approach called frame aggregation mechanism to optimize the QoS in terms of delay, reliability, throughput, and energy.

In WBASNs, the QoS provision for time-critical applications is a challenging task. The periodic data from these applications generate a large number of small packets in a short time period which needs an efficient channel access mechanism. The IEEE 802.15.4 standard is recommended for low power devices and widely used for many wireless sensor networks applications. It provides a hybrid channel access mechanism at the MAC layer which plays a key role in overall successful transmission in WBASNs. There are many WBASN's MAC protocols that use this hybrid channel access mechanism in a variety of sensor applications. These protocols are less efficient for patient monitoring systems; however, life-critical data requires a limited delay, high throughput, and energy efficient communication simultaneously. To address this issue, this research proposes a frame aggregation scheme by using the Aggregated MAC Protocol Data Unit (A-MPDU) which works with the IEEE 802.15.4 MAC layer. To implement the scheme accurately, we developed a traffic pattern analysis mechanism to understand the requirements of the sensor nodes in patient monitoring systems. We mapped these requirements to the channel access mechanism to identify the performance. Based on the performance gap, frame aggregation mechanism is proposed. The mechanism is initially verified using numerical modelling and then the simulation is conducted using NS 2.29, Castalia

3.2 and OMNeT++. The proposed mechanism provides the optimal performance considering the required QoS.

The sensors periodically collect data from the body and send towards monitoring station through a coordinator node [34]. The periodic data from the sensors have distinctive characteristics in the context of delay and sensing rate [22].

The design of MAC protocols plays a vital role to provide appropriate communication services. Time-division multiple access (TDMA) and CSMA/CA are two basic channel access mechanisms used in WBASNs to support periodic and urgent traffic [18]. Usually, the CSMA/CA is considered to be appropriate for low, urgent, adaptive and scalable traffic patterns; whereas, the TDMA is recommended for periodic traffic [101-103]. Various hybrid MAC protocols are proposed [39-50, 104-113] based on the IEEE 802.15.4 and IEEE 802.15.6 standards. Table 5-1 shows the requirements of the bio-medical sensors [22].

Table 5- 1 Physiological signals: sampling rate, resolution, type, and location [114]

Physiological parameter	**Sampling rate (Hz) (min-max)**	**Sampling resolution (min-max bits)**	**Type of sensing device**	**Location**
ECG (per channel)	(100-1000)	(12-24)	Electrodes	Chest
EMG	(125-1000)	(12-24)	Electrodes	Muscles
EEG	(125-1000)	(12-24)	Electrodes	Head
Pulse oximeter	(100-1000)	(12-16)	Photodiode	Ear or finger
Blood pressure	(100-1000)	(12-24)	Pressure cuff	Arm or finger
Respiration	(25-100)	(8-16)	Elastic chest belt or Electrodes	Chest
Blood glucose	<0.01	(8-16)	Chemical	Skin
Skin temperature	<1 in 60 sec	(15-24)	Thermistor probe	Wrist/arm
Activity	(25-100)	(12-24)	Accelerometers	Chest

In this research, a different approach is used to address the above issues. A frame aggregation mechanism is proposed at the MAC layer which sends multiple MAC frames under the single PHY header. Aggregation mechanism will reduce the overheads particularly the waiting time before a successful channel access and underutilization of the channel capacity. The frame aggregation mechanism significantly reduces the delay and increases the throughput for patient monitoring systems. The network lifetime is increased due to overhead avoidance of aggregated packets. This research initially defines the traffic patterns for such biomedical sensor networks for patient monitoring systems. These traffic patterns provide the requirements based on how much and how frequent data is generated. Based on the obtained information a channel modelling is conducted to define the problem statement of the research work. The proposed frame aggregation uses the information achieved from the traffic patterns to clearly define the aggregation limits. In the later section, a detailed discussion is provided on how the proposed frame aggregation mechanism is incorporated with the superframe structure of the IEEE 802.15.4. The evaluation is conducted based on modelling and simulations [22].

To improve the IEEE 802.15.4, an enhancement is proposed for this standard. Mainly this enhancement introduces three modes to improve the channel access mechanisms of the IEEE 802.15.4 standard [115, 116]. These modes include Time Slotted Channel Hopping (TSCH), Deterministic and Synchronous Multi-Channel Extension (DSME) and Low-Latency Deterministic Networks (LLDN). TSCH is considered as a new efficient MAC protocol that incorporates time-slotted access with multiple channels and channel hopping. It is popular because of its interoperability with the Internet of things (IoTs). TSCH is more suitable for high coverage scenarios and particularly for the node-coordinator scenario. The DSME is proposed for applications which require time-bounded services and high reliability. It is the improved form of the IEEE 802.15.4 which provides the adoptability option for time-varying traffic which lacks in the original standard. DSME improves the performance of the 802.15.4 by increasing the number of GTS slots and operating frequency channels. Moreover, it introduces the concept of the multi-superframe structure which is capable of handling both periodic and aperiodic traffic. The best channel is selected to provide high reliability. In multi-superframe, various CFP and CAP periods are aggregated. That said, DSME does not provide its implementation due to its complex access mechanisms. Further, the nodes are required to stay in the active mode which increases the energy utilization. LLDN is a TDMA based mechanism and depends on a simple superframe structure where each node can get the exclusive access for a timeslot [117]. In spite of these considerations, LLDN is not suitable for time-varying traffic and it also requires the information regarding a number of nodes and packet size [22]. Due to above-mentioned limitations, this research proposed a frame aggregation mechanism with existing MAC of the IEEE 802.15.4 standard to optimize the performance of the standard in terms of time-bounded services, throughput, reliability, and energy efficiency.

5.2. Proposed design for frame aggregation mechanism

In the first step, we need to identify the traffic patterns for patient monitoring systems in WBASNs [98]. For this, nine types of bio-medical sensor nodes are used as mentioned in Table 5-1. Based on traffic patterns requirement in terms of data rate, we map these requirements to the MAC layer CAP mechanism of the IEEE 802.15.4 standard to find out the performance gap. Either existing standard is capable of managing such traffic patterns or not. We then propose the frame aggregation mechanism and incorporate it with the IEEE 802.15.4 superframe structure. We considered a star topology network with sensor nodes. The description of each sensor with its traffic pattern is presented below.

5.2.1. Traffic patterns identification

In this section, traffic patterns of different bio-medical sensor devices will be identified. ECG is a waveform that shows the transmission of electric potentials via heart muscle in the context of time. Overall, ECG waveform represents a non-invasive way of the viewing heart function. A standard ECG output is obtained through 12 leads.

From [114], considering the sampling rate 250Hz and sampling resolution 16 bits, we have Sample Interval Time (SIT)=1/250=4 ms and Maximum Possible Data Size (MPDS) = Sampling rate * resolution = 250 * 16 = 4 Kbps =500 bytes/sec. Thus, the Data Need to Send (DNS) in 4ms can be computed as

$$\text{DNS} = \text{MPDS} * 4 = 2 \text{ bytes} \qquad 5\text{-}1$$

Where MPDS = 500 bytes/second or 500 bytes/1000 ms

In this research, the minimum overhead of MAC header is considered as 9 bytes. Equation 5-2 shows a computation of packet size for ECG sensor.

$$\text{DNS after 4 ms including minimum MAC and physical (PHY)header} = 2\ (\text{data}) + 9\ (\text{MAC header}) + 6\ (\text{physical layer header}) = 17 \text{ bytes} = 136 \text{ bits} \qquad 5\text{-}2$$

Equation 5-3 computes the required data rate

$$\text{Data rate required by ECG packet} = \text{Sampling rate } (250) * \text{packet size } (136) = 34 \text{ Kbps} \qquad 5\text{-}3$$

In the slotted CSMA/CA, whenever a node gets the channel, it only transmits the single packet if the remaining CAP is enough to transmit that packet [22].

Table 5-2 presents the summary of traffic patterns for bio-medical sensor nodes.

Table 5-2 Traffic pattern summary

Physiological parameter	**Data generation Interval**	**Data generation (bits)**	**Packet size (bytes)**	**Required data rate (kbps)**
ECG	4 ms	16	17	34
EMG	6 ms	11	17	20
EEG	4 ms	11	17	20
Pulse oximeter (SpO2)	10 ms	12	17	14
BP	10 ms	12	17	14
Respiration	40 ms	8	16	14
Blood glucose	250 sec	0.032 (1 bit)	16	1
Skin temperature	60 sec	0.266	17	3
Activity	10 ms	11	17	4

5.2.2. Problem formulation using traffic patterns

We selected the IEEE 802.15.4 standard for the experiments because of its simple hybrid channel access mechanisms. IEEE 802.15.4 operates under a superframe which is divided into active and inactive mode. The active mode consists of two basic periods including CAP and CFP [22]. CAP consists of time slots which can be acquired through slotted CSMA/CA; whereas, CFP provides GTS slots and works in TDMA manner. Both the periods work in an energy efficient by involving synchronization mechanisms [1, 34]. CAP follows several steps in the contention process. In the first step, the slotted algorithm for CSMA/CA initializes the values of backoffs (NB), CW and backoff exponent (BE). The node waits according to its selected backoff period and then performs CCA process. In the first attempt, if the channel is found idle then CW value is decremented from 2 to 1 and the node performs the 2nd CCA. If the channel is idle in the 2nd CCA, then the value of CW decremented from 1 to 0 and CCA is assumed to be successful. In case the channel is sensed busy in both CCA attempts, NB and BE are incremented by one; whereas, the value of CW is initiated from 2. If both modes: CAP and CFP are used together, then in the CFP mode, GTS slots are assigned to important periodic data like ECG, EMG, and EEG. Then other nodes which require event bases or emergency data use the CAP mode [22].

The IEEE 802.15.4 standard supports the maximum frame size up to 127 bytes including 25 bytes of MAC header and 102 bytes of payload. Figure 5-1 describes the frame structure of the IEEE 802.15.4. A successful packet transmission of the IEEE 802.15.4 based node with its overhead is illustrated in Figure 5-2. By analyzing the single successful packet transmission mechanism, overhead for a successful channel access at various stages can be observed. It includes random backoff delay, two times CCA, 802.15.4 header with each frame, SIFS and acknowledgement transmission time [34].

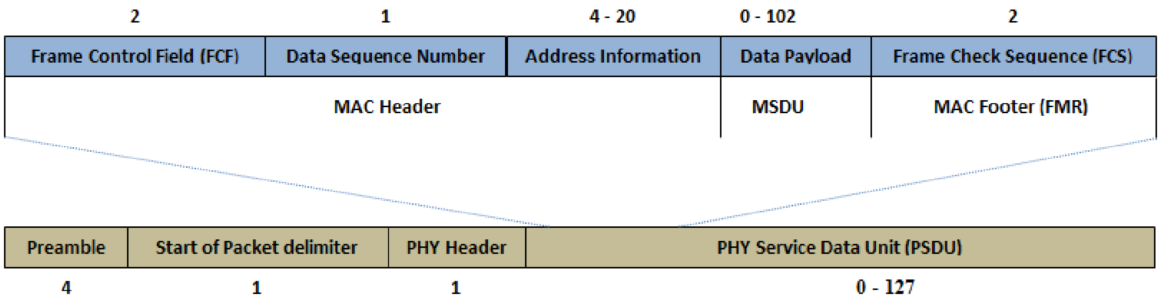

Figure 5-1 Frame structure of IEEE 802.15.4 [1]

The maximum packet size for these bio-medical sensor devices used is 17 bytes for a single frame including headers. The size is almost the same for other devices; therefore, we considered the total packet size for these devices as 17 bytes in our experiments.

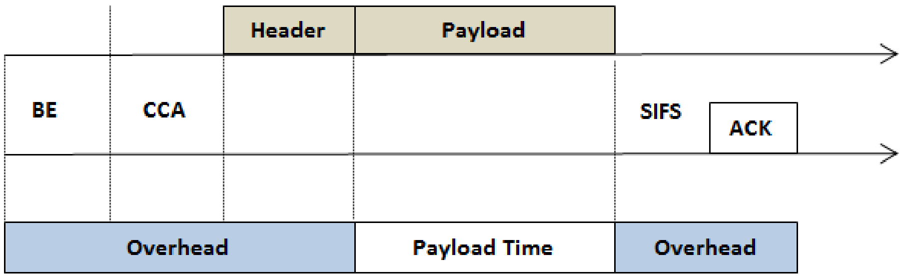

Figure 5-2 Overheads in successful packet transmission [2]

Each frame will content for the channel to send the data. A node which wins the channel transmits a packet and for the next packet transmission, it needs to content for the channel again. The common characteristic of these biomedical sensor devices is that they generate many small packets in a limited time. Furthermore, the generated data from these devices requires a combined set of QoS including limited delay, specified throughput, reliability, and energy efficiency. By analyzing the packet transmission process of the IEEE 802.15.4. It is noted that CFP and CAP provide inefficient channel utilization for the patient monitoring biomedical sensor devices, especially when the duty cycle mechanism is used [36]. Additionally, in patient monitoring systems the traffic pattern of sensor nodes is periodic which means these nodes generate many packets continuously in the limited time. A node has multiple packets in the queue for transmission; whereas, if it gets a successful channel access it can transmit one packet. Therefore, on getting a channel access, a transmitting node is underutilizing the available maximum packet size capacity which is 127 bytes for a MAC frame and only transmits up to 17 bytes shown in Figure 5-1.

5.2.3. Proposed solution

Following the discussion in section 5.2.2, it is observed that wireless biomedical sensors generate many small packets in a limited time period which poses challenges for the MAC layer, especially on channel access process. To address these issues, we proposed the frame aggregation mechanism, which sends multiple MAC frames under a single PHY header within a single channel access. The concept of frame aggregation is successfully used in the IEEE 802.11n [118, 119].

This helps to reduce the overheads, particularly the waiting time before a successful channel access. As in a single channel access, multiple frames are transmitted in the cost of a single frame overhead with lesser PHY header overhead. Moreover, aggregating the frame under a single PHY header almost fully utilizes the channel. In the following section, we present the proposed design and its performance evaluation. Figure 5-3 presents the design of the frame aggregation mechanism at the MAC layer. Initially, the data is received in the form of MAC Service Data Unit (MSDU). After applying the MAC headers, it becomes MPDU. The combination of multiple MPDUs creates A-MPDU. The MAC does not wait for a certain number of MPDUs to create A-MPDU; hence if a node gets a channel access, the MAC layer takes available MPDUs to make A-MPDU for transmission. The destination of all MPDUs must be same. The maximum size for A-MPDU frame must not exceed than 127 bytes. Each encapsulated MPDU consists of a delimiter and padding bits [22]. The purpose of the delimiter is to define a boundary of MPDU in A-MPDU.

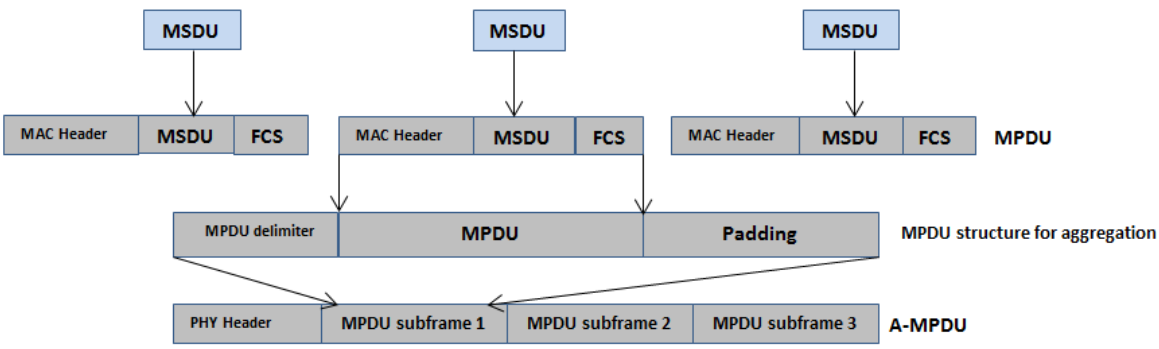

Figure 5-3 Frame aggregation mechanism

The delimiter represents the information including MPDU length, reserved bits, cyclic redundancy checks (CRC) and unique pattern. MPDU Length field represents the length of the MPDU. CRC design uses reserved and MPDU length fields for its calculation. The unique pattern is helpful to find the next delimiter. Figure 5-4 presents the delimiter structure.

	Reserved	MPDU length	CRC	Unique pattern
Bits	4	12	8	8

Figure 5-4 Delimiter structure

In this aggregation mechanism, selective retransmission is possible due to the presence of individual FCS for each MPDU. All the MPDUs in an A-MPDU have same traffic identifier (TID) to effectively work with block acknowledgement (BA) mechanism. In the de-aggregation process, the receiving node first validates the CRC integrity, in the case of successful CRC check, the A-MPDU is de-aggregated and data is passed to the application layer [22].

The block acknowledgement mechanism is widely used with the IEEE 802.11n to support the frame aggregation mechanism. The IEEE 802.15.4 already gives the option to use a block acknowledgement [115]. The A-MPDU can enhance channel access performance significantly; however, in the wireless environment. It follows that, if the Bit Error Rate (BER) is higher than the probability of packet loss rate is also high. To resolve this issue, the block acknowledgement mechanism is used to support the A-MPDU frame. The receiving node receives the A-MPDU and only sends a collective acknowledgement against those MPDUs which are received correctly. The sending node will only retransmit the specific MPDU. Figure 5-5 shows the example of block acknowledgement mechanism.

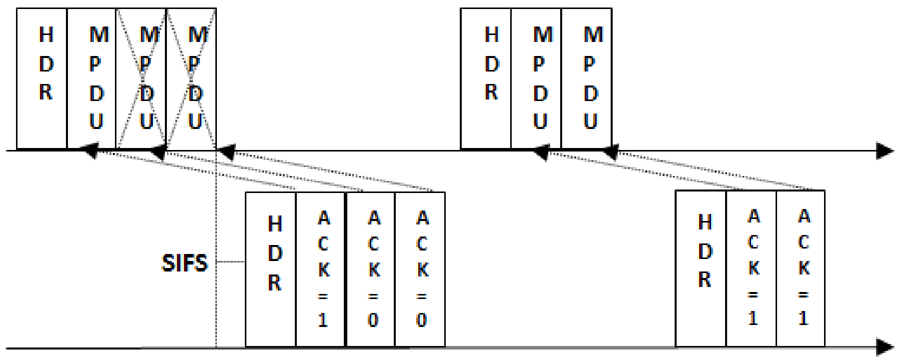

Figure 5-5 Block acknowledgement procedure

5.2.4. Numerical analysis

In the following, frame aggregation analysis on the performance of the IEEE 802.15.4 by incorporating traffic patterns of patient monitoring systems is conducted. The required frame size of MPDU with minimum header overhead is

$$\text{MPDU Size} = 2\ (\text{data}) + 9(\text{Minimum MAC layer header}) = 11\ \text{bytes} \qquad 5\text{-}4$$

Where 2 bytes of data is computed in equation 5-1, which is the data generated by the ECG node after every 4 ms

The size of single A-MPDU is

$$\text{A} - \text{MPDU frame size} = 4\ \text{bytes (delimiter size)} + 11\ \text{bytes (MPDU)} + 4\ \text{bytes (padding)} = 19\ \text{byte} \qquad 5\text{-}5$$

The total A-MPDU packet size is

$$\text{A} - \text{MPDU packet size} = 19\ \text{bytes} + 6\ \text{bytes (PHY header)} = 25\ \text{bytes} \qquad 5\text{-}6$$

Similarly, size of A-MPDU with two frames is

$$\text{A} - \text{MPDU} = 19\ \text{bytes} + 19\ \text{bytes} + 6\ \text{bytes (PHY header)} = 44\ \text{bytes} \qquad 5\text{-}7$$

Considering the maximum packet size capacity 127 bytes and the size of single A-MPDU from equations 5-5 and 5-6, we aggregated the maximum six MPDUs in a single A-MPDU. Therefore, the size of the maximum A-MPDU is

$$\text{Total size of A} - \text{ MPDU } = (6 * 19) + 6 \text{ bytes (PHY header)} = 120 \text{ bytes} \quad 5\text{-}8$$

The transmission time of a maximum-sized A-MPDU [36] is

$$T_{frame} \text{ for A} - \text{MPDU} = \frac{(120)*8}{\text{data rate}} = 3.84 \text{ ms} \quad 5\text{-}9$$

In the following, we compute the value of total delay using [34, 36]

$$\text{ED} = \text{macMaxFrameRetries} * (T_{WT} + T_{frame} + T_{Ack} + T_{SIFS} + T_{\tau A}) \quad 5\text{-}10$$

For the scenario mentioned in Figure 5-1 where multiple nodes try to access the channel, we compute the value of delay by considering the default MAC attribute values mentioned in Table 5-3.

It includes total waiting time (T_{WT}), where T_{WT} represents the backoff period which is assigned to a node before going to channel access attempt. Equation 5-10 also includes frame transmission time (T_{frame}), acknowledgement receiving time (T_{Ack}), short interframe space time (T_{SIFS}) and turnaround time ($T_{\tau A}$). For analysis, we considered the bit rate of 250 kbps (2.4G Hz frequency band is considered with BPSK modulation and a symbol represents 4 bit). T_{BOslot} denotes the time for a single backoffslot.

$$T_{WT} = \text{macMaxCSMABackoffs} * (T_{BE} + T_{CCA}) + T_{CW} \quad 5\text{-}11$$

where T_{BE} is random backoff time, T_{CCA} is clear channel assessment time and T_{CW} is contention windows time. The random backoff time (T_{BE}) is the waiting time for channel access which is computed as:

$$T_{BE} = (2^{macMinBE} - 1) * T_{symbol}\ (aUnitbackofftime) \quad 5\text{-}12$$

Table 5-3 MAC layer parameters and values [34, 36]

Parameters	Value
$T_{\tau A}$	0.192 ms
T_{SIFS}	0.192 ms
T_{Ack}	0.864 ms
T_{CCA}	0.128 ms
T_{CW}	0.64 ms
T_{symbol}	0.32 ms

Using equation 5-12 with ideal channel conditions, Figure 5-6 presents a comparative analysis of total delay for the transmission of the number of frames with aggregation and without aggregation. It is noticed that without aggregation, delay continuously increases because every frame takes a separate channel access attempt. We assumed that a node gets channel access attempt at the transmission time. On the other hand, for the A-MPDU, a node sends multiple packets in single channel access attempt, only the packet size varies by increasing the frame aggregation size. It can be concluded that if there is a need to send six frames, an A-MPDU can send it in one channel access with a minimum delay [22].

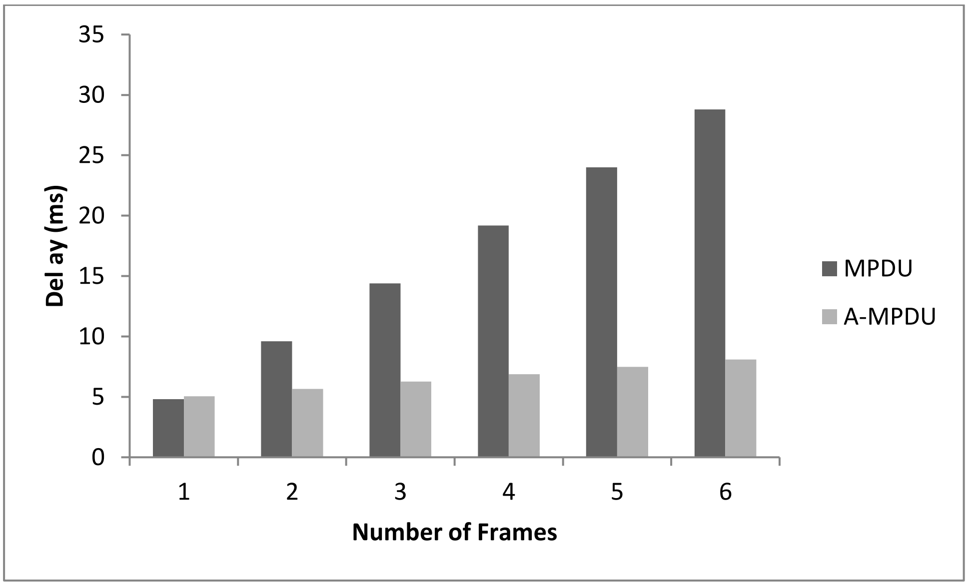

Figure 5-6 Delay comparison between MPDU and A-MPDU

Figure 5-7 presents the MT analysis for the same scenario mentioned in Figure 5-6. It is noticed that MT increases with the increase of aggregation level like from two frames in an A-MPDU to a maximum of six frames. Therefore, it is concluded that frame aggregation mechanism enhances the packet delivery which is helpful to reduce the delay. The MT is considered as the ratio of payload size (bytes) to the transmission delay for specific payload size and is computed as:

$$MT = \frac{(\text{payload size in bytes}) * 8}{\text{transmission delay}} \qquad 5\text{-}13$$

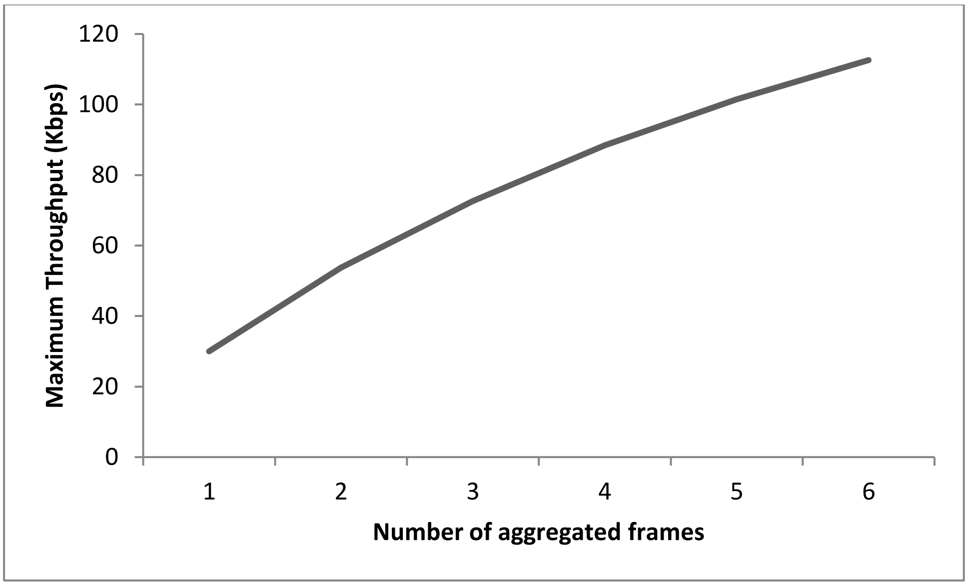

Figure 5-7 Maximum throughput analysis

5.2.5. Mapping of proposed A-MPDU mechanism with the superframe

To adjust the aggregation mechanism with superframe, we need to compute such SD where at least one or more than one A-MPDU could transmit. The maximum size in our scenario is 120 bytes as mentioned in 5-8 and the transmission time for a single A-MPDU is 3.84 ms as mentioned in equation 5-9.

The superframe duration SD represents the duration of superframe which consists of 16-time slots [36] is:

$$\text{SD} = \text{aBaseSuperframeDuration} * 2^{SO} \text{ symbols} \quad \text{5-14}$$

where superframe order is represented by SO. aBaseSuperframeDuration is calculated as:

$$\text{aBaseSuperframeDuration} = \text{aBaseSlotDuration} * \text{aNumSuperframeSlots} * \text{symbolTime} \quad \text{5-15}$$

Symbol time using 2.4GHz frequency band and symbol rate 4 is:

$$\text{symbolTime} = 1 / (\text{phyDataRate} * 1000 / \text{phyBitsPerSymbol}) \quad \text{5-16}$$

The single slot time should be at least 3.84 ms as mentioned in equation 5-9, using equation 5-14, a suitable value for SD is computed which fulfils the slot duration requirement. SD is computed using 5-14 as:

$$\text{SD} = 15.36 * 2^2 = 61.44 \text{ ms}$$

Where the value of SO=2, the single slot duration is computed as:

$$\text{Single slot duration} = \text{Total SD time/Number of slots} \quad \text{5-17}$$

It is noted that 3.84 ms is the same time as computed in equation 5-9, which means that SO should be at least 2 or greater than 2 so that a complete A-MPDU could be transmitted.

5.3. Performance evaluation of the proposed frame aggregation mechanism

The aim of the frame aggregation mechanism is to provide a combined set of QoS for the periodic data generated by bio-medical sensor devices [98]. Here, the QoS set refers towards provision of delay, appropriate throughput, reliability, and energy efficiency. The delay shown in the Figure 5-6 represents the average delay. Some of the bio-medical sensors like ECG and EEG generate many small packets in a short time interval. The aggregation mechanism for the IEEE 802.11n is implemented in NS-2.29 at the MAC layer. We conducted the capacity analysis of different aggregation levels in NS-2.29 and later, we used the results while doing our evaluation in Castalia 3.2 and OMNeT++. A star topology is considered where it is assumed that there are 10 nodes initially. Node 0 is configured as the coordinator node and located in the center. We used both available modes for the channel access including CFP and CAP. Table 5-4 provides the values for simulation parameters [22].

Table 5-4 Simulation parameters

Parameters	**Value**
Number of nodes	Varies from 6-10
MAC	IEEE 802.15.4
Channel mode	Log Shadowing Wireless Model
Seed value	11
Frequency band	2.4 GHz
Data rate	250 kbps
Evaluation Criteria	Delay, PDR, Energy consumption
T_{SIFS}	0.192 ms
T_{Ack}	0.864 ms
T_{CCA}	0.128 ms
T_{CW}	0.64 ms
T_{symbol}	0.32 ms
Simulation time	100-2000 seconds

Figure 5-8 provides the received packets analysis of the IEEE 802.15.4 with the aggregated-802.15.4. The focus of evaluation is to explore the capacity of different level of aggregations. In the simulation, for aggregated-802.15.4, we used different frame levels including Agg_2 802.15.4 (two frames in an A-MPDU), Agg_4 802.15.4 (four frames in an A-MPDU) and Agg_6 802.15.4 (six frames in an A-MPDU). The purpose of using different levels of aggregation is to conduct a detailed performance analysis of the aggregation mechanism. As duty cycle (DC) mechanism is an integral part of the IEEE 802.15.4 which provides energy efficient data transmission [18, 36]. The beacon order (BO) represents the total duration of a superframe including active and inactive periods. Therefore, different combinations of the duty cycle are considered including 2/4 (25%), 2/8 (2%), 4/6 (25%), 4/8 (6.25%), 6/8 (25%), 6/10 (6.25 %) and 8/10 (25%). The value 25% means that a node stays awake for 25% in the superframe duration. In all combinations, we set SO = 2 or more than 2 to achieve the appropriate superframe duration. Moreover, we also used a variety of SO values like 2, 4, 6 and 8 to see the optimal results as superframe duration is an important aspect for throughput. In Figure 5-8, we considered slotted CSMA/CA mode of CAP with a different combination of duty cycles and evaluated the number of received packets with and without aggregation mechanisms. Initially, DC with 25% value shows the higher number of received packets near 3000. It is obvious that data generation is higher at the application layer; however, due to duty cycle mechanism, a node stays awake for a limited time. The packets keep coming to the queue, but a limited number of packets are sent from the queue. This behavior creates the performance bottle-neck for patient monitoring systems. To overcome this issue, we used the different levels of proposed aggregated mechanisms. Overall, aggregation mechanism is helpful to increase the number of received packets. For the first combination 2/4 (25%), the value of received packets for non-aggregated 802.15.4 is 3000 which increase up to 5566, 10443 and 15771 for Agg_2 802.15.4, Agg_4 802.15.4 and Agg_6 802.15.4. Similarly, a significant increase is noticed for the other DC options with aggregated-802.15.4. The reason for this improved throughput is the better channel utilization through aggregation mechanism. In the IEEE 802.15.4, due to channel access overheads, packets start dropping from the queue, which affects the throughput. The other major reason for low throughput for this scenario is inefficient channel utilization, where a node gets a channel to transmit only a small packet and then again it needs to contend. The aggregation mechanism provides an opportunity to send multiple MPDUs in a single channel access [22].

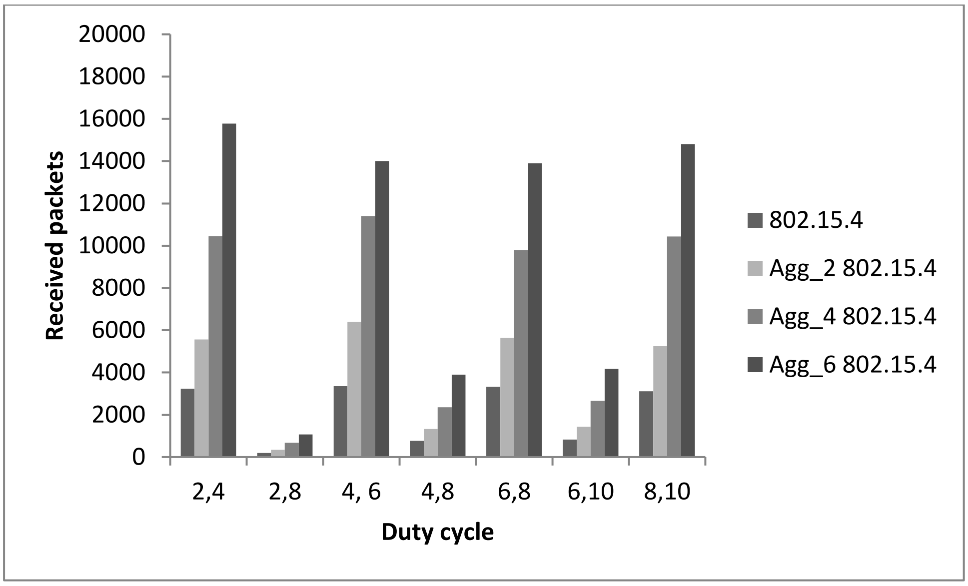

Figure 5-8 Received packets comparison

Figure 5-9 provides the delay comparison of the similar scenario provided in Figure 5-8. All the DC options for non-aggregated 802.15.4 provide the average delay values up to 500 ms or higher. For the patient monitoring system, the end-to-end delay must be under 250 ms so that meaningful information could be generated [1, 18, 41, 60, 114]. It is observed that the average end-to-end delay reduces by increasing the aggregation levels. Although the Agg_2 802.15.4 level gives the delay values more than 250 ms for few DC options, which include 2/8, 4/8 and 6/10, the Agg_4 802.15.4 and Agg_6 802.15.4 aggregation levels provide average delay within 250ms for all the DC options. The main reason for the reduced delay is that the multiple packets are received collectively instead of a single packet. The channel access overheads include random backoff delay, two times CCA, SIFS and acknowledgement transmission time. Therefore, if a node sends six packets in single channel access, then it significantly reduces the overheads for the five packets.

The efficient energy consumption for the WBASNs is considered as an integral performance aspect. IEEE 802.15.4 provides a complete synchronization mechanism among coordinator and the network nodes [18, 44]. The nodes know their awaken timing where they could content for the channel. DC mechanism is incorporated to adjust sleep and awaken timings [22].

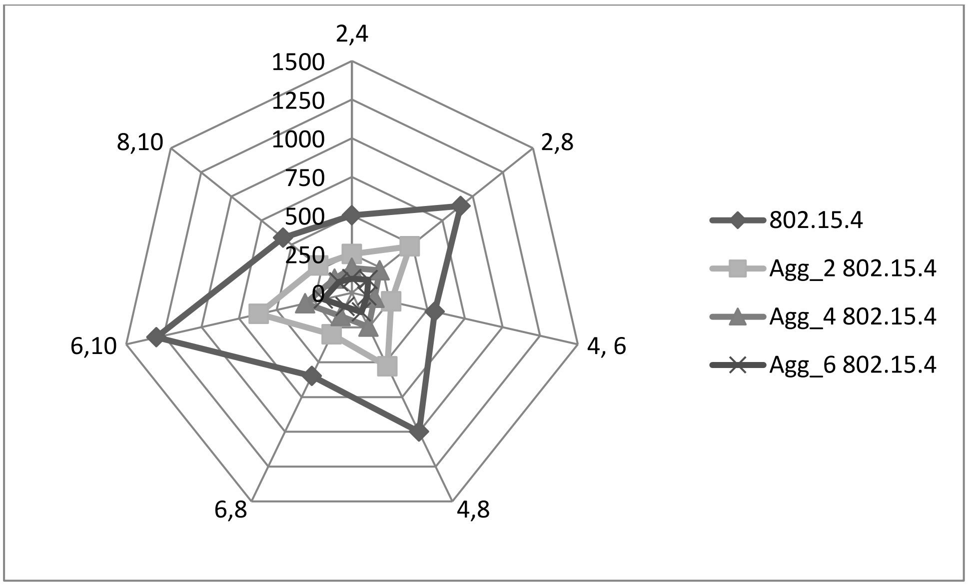

Figure 5-9 Average delay comparison

Figure 5-10 shows energy consumption analysis of different aggregation levels by considering the number of received packets. For this analysis, we used the DC combination 2/4 (25%). A continuous increase in energy consumption is observed with the increase in aggregation levels. The reason for this increase is the increased packet size which takes more transmission time as the radio remains on. This marginal increase in the energy consumption is affordable with the significant increase is in the received packets which varies from 12500 with Agg_4 802.15.4 to 14701 with Agg_6 802.15.4 aggregation.

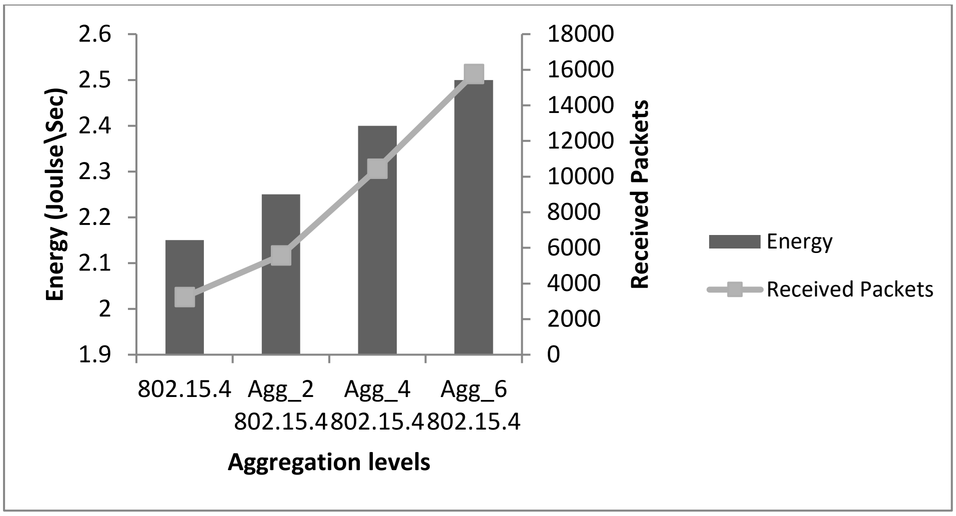

Figure 5-10 Energy consumption analysis of aggregation with received packets

Figure 5-11 shows energy consumption analysis of aggregation levels by considering the DRT profile. The scenario and parameters are the same as mentioned in Figure 5-10. It is observed that the energy consumption increases by increasing the aggregation level but at the same time the average end-to-end delay significantly reduces and come under 250 ms. As the aggregation mechanism reduces the waiting time and transmission overheads, therefore, average delay significantly reduces. Moreover, the use of block acknowledgement also contributed to reducing delay. Only one acknowledgement is sent for A-MPDU which consists of maximum six MPDUs. In case of higher BER, there is the probability of packet loss. The use of block acknowledgement makes a receiving node capable to send a collective acknowledgement against those MPDUs which are received correctly. The sending node only retransmits the lost MPDUs [22].

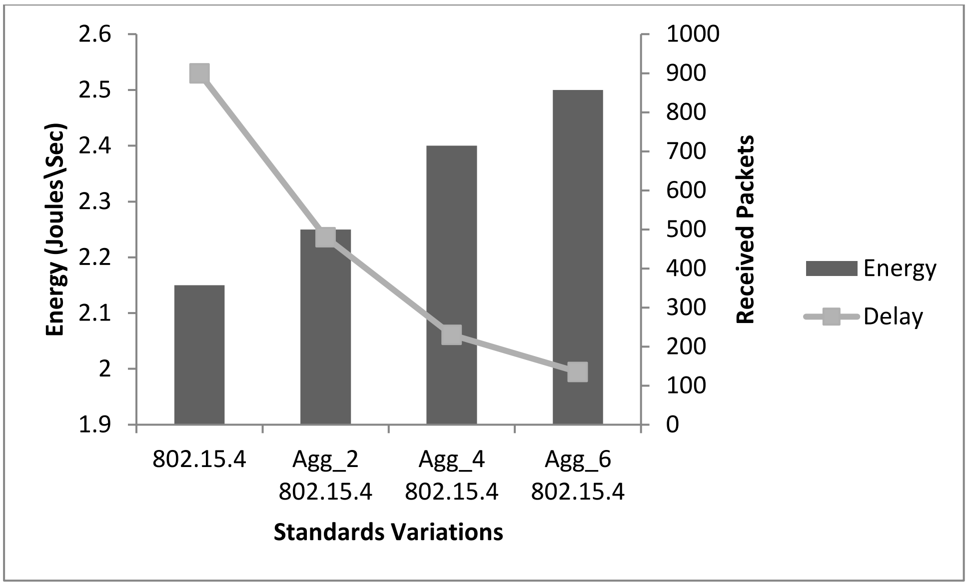

Figure 5-11 Energy consumption analysis of aggregation with delay

It is noted that performance optimization is achieved in terms of received packets and average delay by using different levels of frame aggregation for slotted CSMA/CA in CAP. For the proposed patient monitoring system, ECG and EEG nodes requested for three GTS slots. A coordinator can assign maximum seven GTS slots. Figure 5-12 provides a comparative analysis of received packets between GTSon (where two nodes requested for GTS slots) and GTSoff (all nodes use CAP). The different DC options are used to evaluate the performance of these modes. From Figure 5-12, a significant improvement in GTSon mode is observed for the number of received packets from 6000 to 10500 with DC option 2, 4. The reason is that the nodes with high-periodic traffic get a guaranteed time slot in superframe duration, so there are fewer chances of data loss. Figure 5-12 clearly shows that the hybrid scheme involving CFP and CAP is more suitable option for the patient monitoring systems [98].

Figure 5-12 proves that a hybrid (combination of CFP and CAP mode) MAC mechanism fulfils the requirement of the proposed patient monitoring system. Therefore, to further improve the performance in terms of received packets, we apply the proposed aggregation mechanism to check the full capacity of aggregation mechanism with GTSon mode.

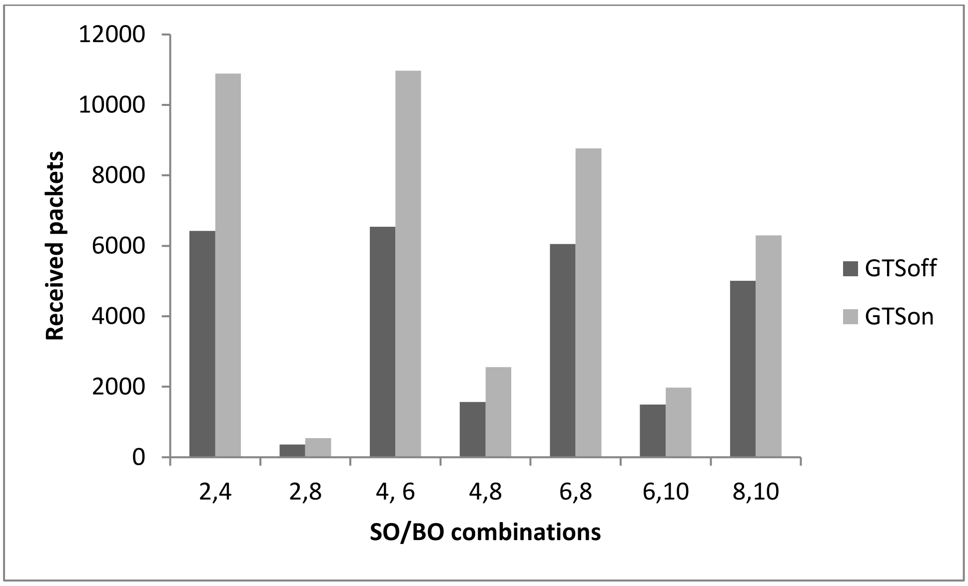

Figure 5-12 GTSon vs GTSoff comparison

Figure 5-13 presents a comparative analysis of the received packets with the non-aggregated GTSon mode. A significant improvement can be seen with the frame aggregation levels. The frame aggregation mechanism significantly increases the number of received packets by reducing the delay. For example, with DC option 2, 4, if we use third level aggregation, then the maximum capacity goes from 10000 to 24000. It is concluded from the results of Figure 5-13 that patient monitoring systems work well with the hybrid channel access mode (GTSon). Furthermore, with the help of frame aggregation mechanism, their performance can be further optimized.

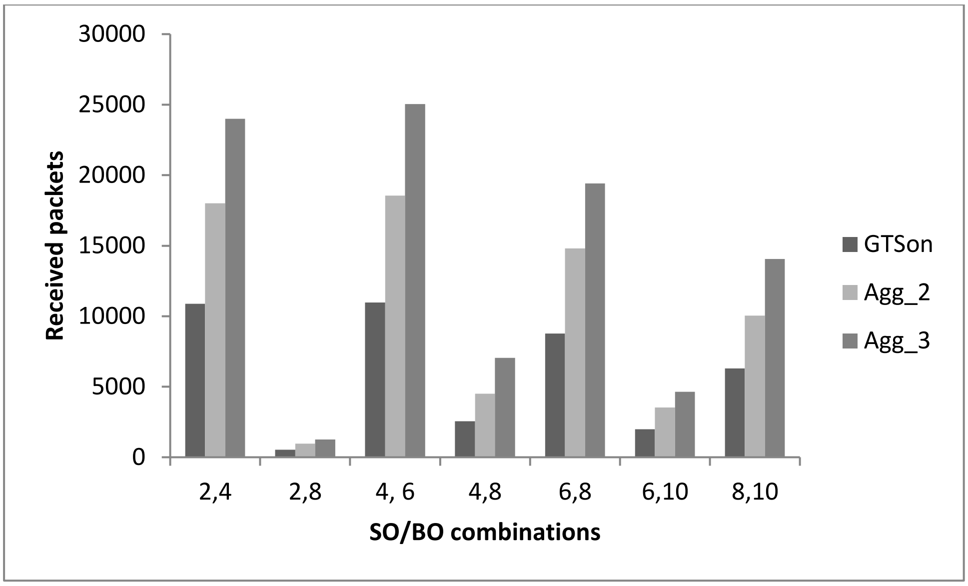

Figure 5-13 Received packets analysis for aggregation in GTSon mode

Figure 5-14 presents the energy consumption analysis for the scenario mentioned in Figure 5-13. Overall, the GTSon mode provides slightly better energy consumption with the less delay [22]. The reason is that the nodes contend for fewer slots in the GTSon mode as compared to the GTSoff mode.

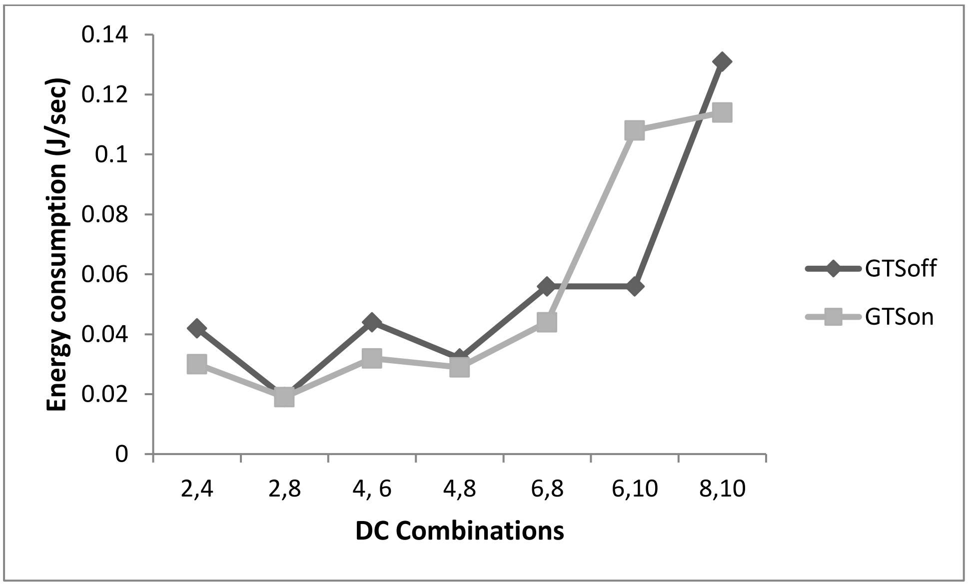

Figure 5-14 Energy consumption analysis

Figures 5-15, 5-16 and 5-17 provide an analysis of the number of packets received by the coordinator from an individual node. Figure 5-16 provides a comparative analysis of received packets with GTSon and GTSoff mode. In GTSon mode, we assigned three GTS slots to an ECG sensor and three GTS slots to an EEG sensor. The remaining seven nodes used slotted CSMA/CA in CAP mode. Figure 5-15 provides comparative analysis when nodes are 100% active (with DC value 100%). It is noticed that ECG and EEG nodes provide 90% packet delivery ratio in GTSon mode; whereas, their performance is low in GTSoff mode. The reason is that these nodes are generating a high number of small packets in limited time and there is no guarantee whether they get a channel access or not. Therefore, the packet loss ratio is high on queues due to waiting time and limited space in queues. On the other hand, when GTS mode is used for ECG and EEG, they provide a high number of received packets as in every superframe they get three GTS slots each. It is also observed that in the hybrid mode (with the usage of GTS slots) the node which is not using GTS provides a lower number of received packets in comparison with a node which only uses slotted CSMA/CA like SaO2 sensor node. The reason for low received packets in hybrid mode is that the superframe is divided into sixteen slots, where GTS uses six slots (3 for ECG and 3 for EEG) and ten slots left for seven remaining nodes. These nodes contended for the channel and got less number of channel accesses. On the other hand, in the non-hybrid mode (all nodes use slotted CSMA/CA for channel access), nine nodes contended for all the available slots, where SaO2 got more number of slots than in the hybrid mode. The other remaining sensors including BP, respiration, diabetes, temp, and accelerometer send data at a low rate, which indicates that there is no critical issue involved with them. Figure 5-16 provides the analysis regarding the suitability of a hybrid MAC for the proposed patient monitoring system. However, the DC mechanism is not considered in the scenario related to Figure 5-15. Figure 5-16 provides the similar scenario in Figure 5-15 but with DC value 2/4 (25% active). It is noted that because of the usage of DC mechanism in hybrid mode, the number of received packets reduce almost to 50%. The reason is the less duty cycle value of the nodes [22]. The overall received packet rate for each sensor is affected because of DC mechanism.

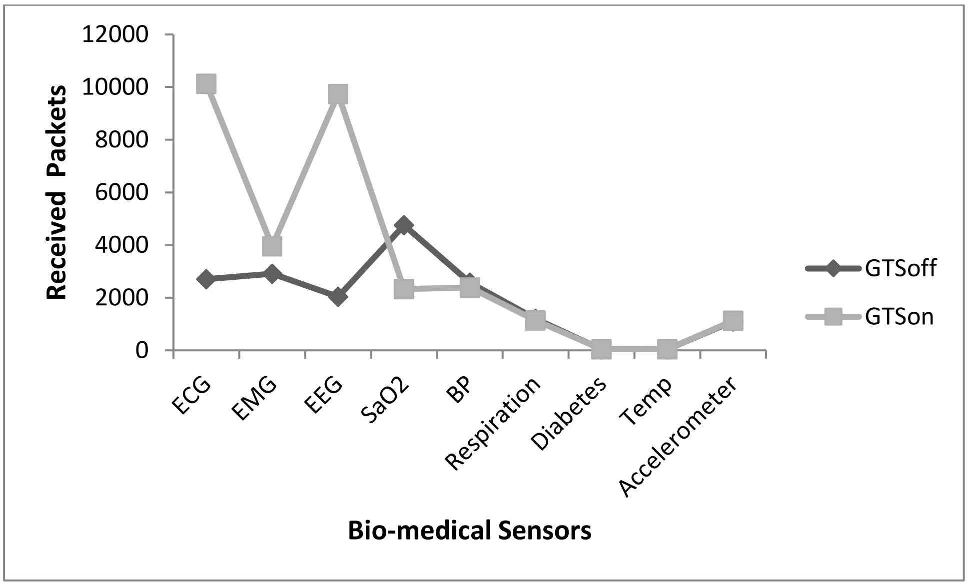

Figure 5-15 Received packet analysis from an individual node without DC

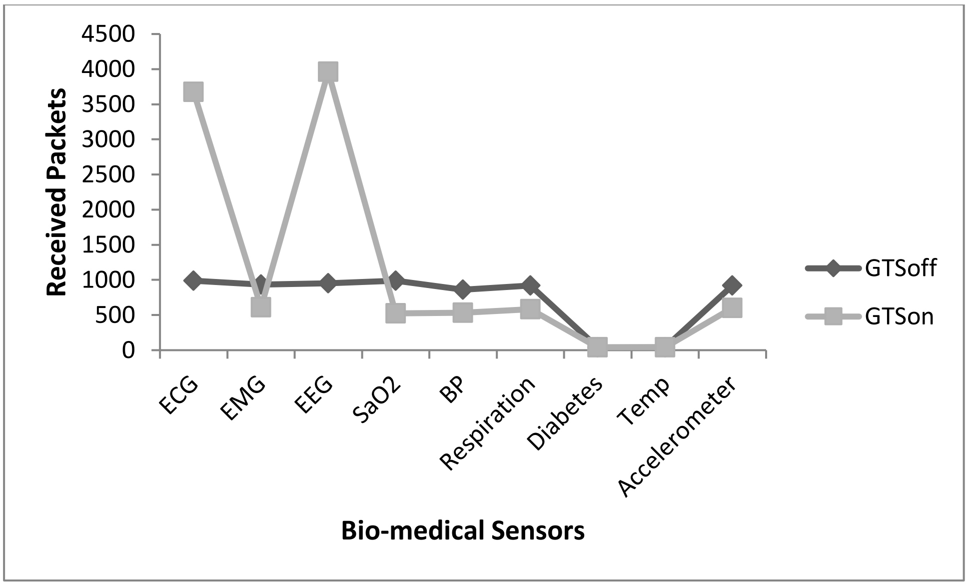

Figure 5-16 Received packet analysis from the individual node with DC

To overcome the issue presented in Figure 5-16, we apply the frame aggregation mechanism. Figure 5-17 provides a comparative analysis for received packets of individual sensors with the modes: GTSoff, GTSon, GTSon_Agg_2, and GTSon_Agg_4. Moreover, the DC mechanism is considered with the value of 25%. It is noted that the frame aggregation mechanism increases the number of received packets significantly for each node.

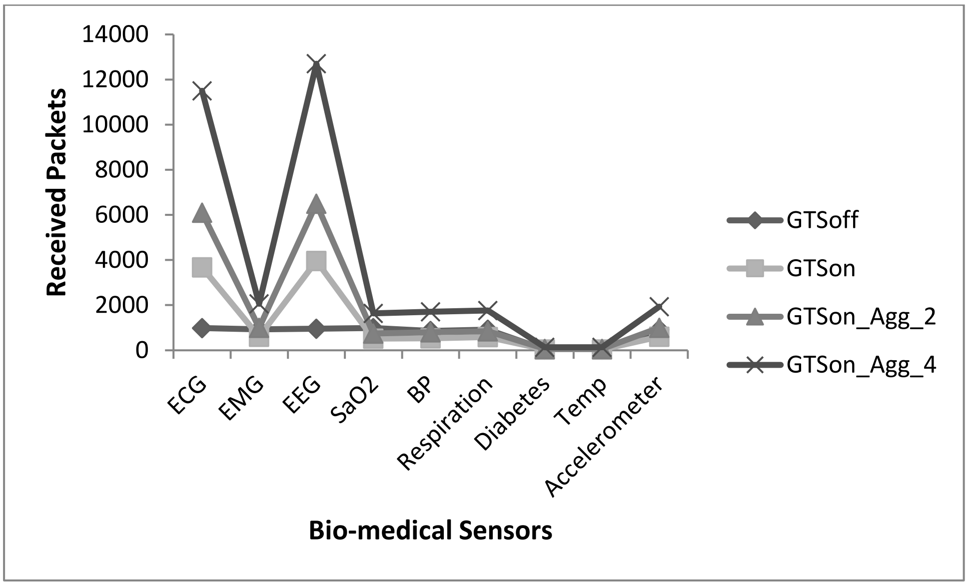

Figure 5-17 Received packet analysis for an individual with aggregation and DC

We used the IEEE 802.15.4 with operating band of 2.4 GHz that may also receive signals as interference from coexisting IEEE 802.11 deployed wireless networks [22].

5.4. Conclusion

Aiming the patient monitoring applications of WBASNs, frame aggregation mechanism is proposed at the MAC layer to improve the channel access mechanisms as well as to achieve strict time deadlines, reliable data delivery, and energy efficiency requirements at the same time. For patient monitoring systems, we have selected ten different bio-medical sensor devices including a coordinator. These nodes are deployed in a star topology. The devices include ECG, EEG, EMG, accelerometer, gyroscope, pulse oximeter, blood pressure, temperature, barometer and heart rate monitoring. The sensors periodically collect data from the body and send towards monitoring station through the coordinator node. The high prioritized and emergency data demand a different set of QoS. To address the mentioned challenge, initially, we have provided traffic pattern analysis of these devices to understand their transmission requirements. From the traffic pattern analysis, it is observed that these biomedical sensor devices generate many small packets in limited time. The IEEE 802.15.4 standard supports the maximum frame size up to 127 bytes including 25 bytes of MAC header and 102 bytes of payload. The maximum packet size from these bio-medical sensor devices used in the patient monitoring system is 17 bytes for a single frame including headers. On getting a channel, a node underutilizes the channel in terms of packet size for a MAC frame and only transmits up to 17 bytes. To address the issues, we proposed the frame aggregation mechanism, which sends multiple MAC frames with a single PHY header. The concept of frame aggregation makes a huge difference in throughput and delay the performance by efficiently utilization the channel access mechanism. The proposed mechanism is initially evaluated through numerical modelling. In the next step, simulation is conducted using NS 2.29 and CASTALIA 3.2 with OMNeT++. The evaluation is conducted for both modes: CAP and CFP. The evaluating parameters include the number of received packet, average delay, and energy consumption. Three types of aggregations levels are tested in the simulations: aggregation of two packets (Agg_2), aggregation of four packets (Agg_4) aggregation of six packets (Agg_6). It is observed that higher the aggregation level, the higher the number of received packets. In Agg_6, the number of received packets reached near 16000. Similarly, the delay decreases by increasing the aggregation level, with the Agg_6 the delay value is 100 ms. Moreover, Agg_6 provides energy consumption up to 2.4 J/sec, which is slightly high in comparison to Agg_2 and Agg_4. This slightly higher value can be ignored, however, since Agg_6 provides a higher number of packet received (16000) with less delay (100 ms). Another consideration is that the aggregation mechanism tested for GTSon and GTSoff mode. Hence frame aggregation mechanism is very useful for life-critical applications. Various constraints are considered in the simulations including SO/BO combinations, GTSon and GTSoff.

Part of the work in this Chapter has been published in the following journal and conference paper

- Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "IEEE 802.15. 4 Frame Aggregation Enhancement to Provide High Performance in Life-Critical Patient Monitoring Systems", MDPI Sensors, vol 17, No 2, 2017, doi: 10.3390/s17020241, Impact Factor = 2.67

- Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "A holistic simulation model for remote patient monitoring systems using Wireless Body Area Sensor Networks (WBASNs)", In proceeding of 9th International Conference on Software, Knowledge, Information Management and Applications, 2015, doi: 10.1109/SKIMA.2015.7399990 (Published)

Chapter 6: Investigation of LQI and RSSI for WBASNs/IoTs in a Hospital Environment

6.1. Introduction

This Chapter presents research work on the network layer of WBASNs as mentioned in Chapter 1: Section 1.1. The tremendous popularity of WBASNs in combination with the Internet of Things (IoTs) based routing protocols leads toward potential low-cost, low-power, smart and ubiquitous remote healthcare solutions. The low-power radios used in the sensors are sensitive to interference, distortion, and noise. Therefore, they experience a link unreliability problem. The Performance of a routing protocol in WBASNs/IoTs is highly dependent on accurate link quality status information of the neighbouring nodes. Most of these protocols are compliant with the IEEE 802.15.4 and IEEE 802.15.6 standards and obtain the link quality information in the form of Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI). Most of the link quality investigation studies are focused on office or factory environments; whereas, a hospital environment is partially discussed. Therefore, for the efficient deployment of WBASNs/IoTs based routing protocols with low-power radios, a detailed empirical reliability assessment is required for a hospital environment. To address the mentioned issues, this research proposes a solution in three steps: 1) identification of suitable WBASNs/IoTs based routing protocols for patient monitoring systems using simulation in Castalia 3.2 with the OMNet++ platform; 2) a detailed discussion and analysis regarding link quality mechanisms used; 3) a test-bed to perform empirical experiments to find the actual link quality estimation for different hospital environments. This research provides a detailed investigation of the crucial communication properties including RSSI, LQI, packet reception and error rate over a long period of time using test-bed in a hospital. Moreover, we divided the communication in a hospital into four environmental scenarios including inside ward, corridor, ward to corridor and ward to ward. Both mobile and static scenarios are considered with LOS and NLOS. A strong correlation is noticed between LQI and packet reception rate in most of the scenarios; whereas, a weak correlation is found between RSSI and packet reception rate. These correlations are helpful to design a routing algorithm. The outcome of this empirical investigation provides useful values of LQI and RSSI for WBASNs/IoTs based routing protocols in different hospital scenarios.

6.2. Proposed benchmark routing architecture

In this section, we proposed a cross-layer design for WBASNs/IoTs based routing protocols. The proposed design provides guidelines to increase network lifetime, packet delivery ratio and reduce retransmissions in dense and populated scenarios. Figure 6-1 shows the proposed cross-layer architecture of proposed routing protocol. The routing decisions are made using the information about residual energy, queue status and signal quality of the next hop. All this information will be used by the Hello protocol for neighbour discovery mechanism. The network layer consists of two major components including Hello protocol and a Routing module. Hello protocol composes Hello messages which are used in neighbour discovery mechanism. Further to this process, a pattern-based Hello message is proposed to make the neighbour discovery mechanism simple and efficient. Similarly, when a packet is received by network layer, if it is a Hello message then the neighbour table either update its entry or add a new entry of a node. The purpose of neighbour table is to construct the routing table.

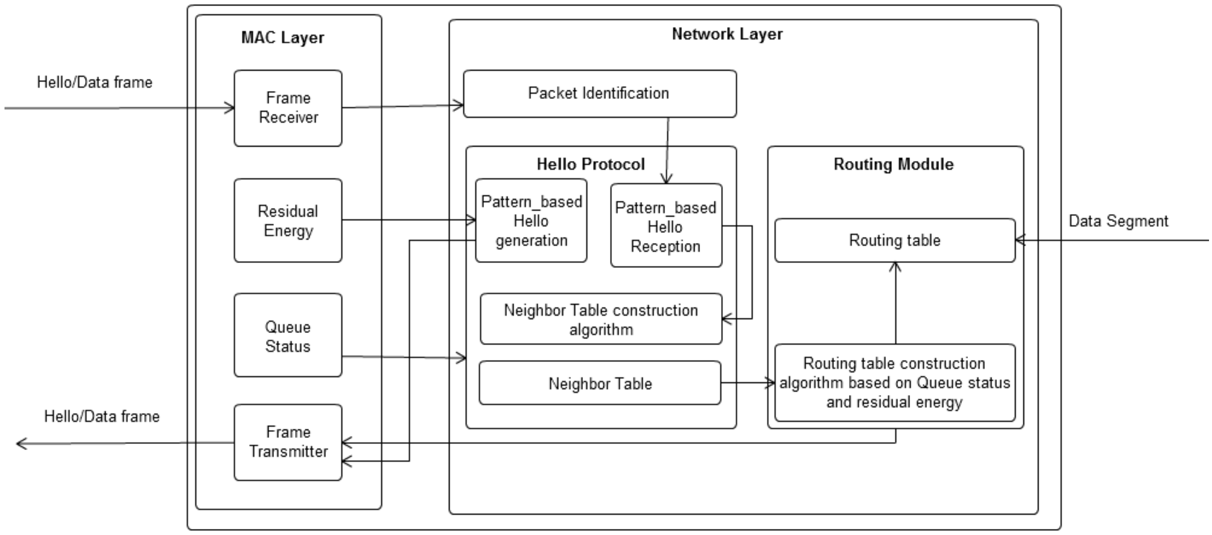

Figure 6-1 Proposed cross-layer architecture for routing protocol

6.2.1 Pattern-based hello/update dissemination

The location of the sink is fixed, whereas the other nodes can be mobile as well. We have proposed Hello message of 10 bits as shown in Figure 6-2. It works well for a network of four nodes; however, if we want to increase the number of nodes then we need to change the assigned bits of ID from 2 bits to required number of nodes. Figure 6-2 shows the meaning of the pattern bits with its sequence. The neighbor discovery mechanism is based on following dissemination rules:

- Each node broadcasts Hello message to its one-hop neighbor;
- Hello message interval is yet to be decided;
- A node will generate update message only when there is some significant change in following three components
  - Location
  - Energy levels
  - Congestion status

0 11 111 11 11

Bit/Bytes	Meaning
0	Message type (0 for Hello/ 1 for Update)
11	ID of the sender
111	Location of the sender
11	Residual Energy Level of sender
11	Congestion level

Congestion levels	
00	Low
01	Medium
10	High
11	Critical

Energy levels	
00	Low
01	Medium
10	High
11	Critical

Figure 6-2 Pattern-based Hello message

On receiving Hello message, a node will compare the information with existing neighbor table for updates.

6.3. Initial simulation for existing routing protocols

To validate the performance of REL [120], LABILE [121] and AODV [122] routing protocols of WBASNs in IoTs scenario, simulations are reproduced [120] using the Castalia 3.2 framework. The simulation provides the comparison of delay and Packet Error Rate (PRR) in 100 m x 100 m. Table 6-1 provides simulation parameters.

Table 6-1 Simulation parameters

Parameters	**Value**
Simulation time	1 hour
Area	100 m x 100 m
Packet interval	1 to 2 sec
Initial energy	18,729 J (2 AA batteries)
Threshold for LQI	220
Radio model	CC2420

Figure 6-3 provides a comparative analysis of the received packets which arrived within 120 ms. The benchmark for acceptable latency is set to 120 ms as it is the requirement of remote patient monitoring systems [1]. The purpose of the simulation is to validate the performance of existing protocols for patient monitoring systems. The protocols based on link quality REL and LABILE performed better than AODV. AODV performs well up to 30 nodes by providing acceptable packet reception. The reason for the better performance of REL and LABILE is the link reliability consideration for selecting the next hop; whereas, AODV selects the next hop on a single factor that is minimum hop count. It is also notable that REL shows more stability than LABILE in terms of packet reception rate. The reason for this better performance is the consideration of multipath routing; whereas, LABILE only considers the link quality in terms of LQI.

It can be concluded from the simulations that for WBASNs/IoTs applications, link-based routing protocols can provide better performance. The mentioned routing protocols mostly consider the static inside office environment for link reliability by using RSSI and LQI values. For WBASNs/IoTs applications, link reliability is considered as most important selection criteria for the next hop selection. The wireless interface for low-power radios experience fluctuations which cause the unreliability problem. These low-power radios are very sensitive to noise, fading, and interference, therefore the performance of the routing protocols is dependent on the link quality. The link reliability considers the signal strength and packet delivery ratio to select next hop.

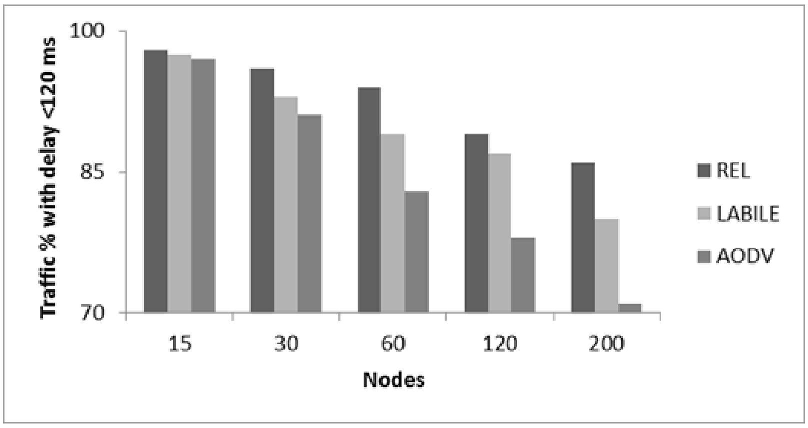

Figure 6-3 Comparative analysis of routing

6.4. Existing link quality techniques

The link aware protocols consider metrics like residual energy (how much energy a node have in joules/sec) and congestion level of neighbouring nodes. There are many studies to estimate the link quality in different environments including inside hospitals, factories and outdoor [123-134]. These studies mostly provide empirical analysis by considering the temporal and spatial scenarios.

In [123, 124], a wearable remote patient monitoring system is suggested for the indoor environment. To evaluate the performance of health-care monitoring system, it is important to estimate accurate radio propagations values. An algorithm is proposed to estimate the quality of the link. A human model is also developed which consists of sensor nodes at different parts of the body. Few studies provide the small-scale fading modelling to improve the channel characterizations and link quality for indoor environments. In [125, 126], the small-scale fading is modelled in the real indoor environment by considering the mobility of a node. For experiments two dimensional measurements are used which provide data from two dimensions: x and y-axis. Multiple scenarios are considered including LOS, NLOS and two waves diffuse power. Additionally, several obstacles such as walls, cabinets, and metallic reflectors are used in these cases. The results show that the two-dimensional technique outperforms the traditional single direction techniques in terms of accurate interference patterns and channel quality. These calculations are helpful for designing efficient data collection systems for wireless sensor networks. One consideration, however, is two-dimension calculations that demand more computation and energy resources, which is a challenging task for WBASNs. Moreover, only fading scenarios are discussed, while actual link quality and interference variations are ignored. A couple of studies discuss the behaviour of the wireless channel in the industry while comparing it with the home environment [127, 128]. Statistical characterization for 2.4 GHz radio channel is discussed for indoor office environments [129]. Empirical investigation is conducted to identify wireless channel characterization which is related to the indoor environment [130]. It is noticed that these wireless channel characteristics are different for the house and indoor office environment due to metallic piping and multipath environment.

Rappaport [131] performed numerous experiments on various factory environments using a variety of material to compute average path loss. The author concluded that noise caused by the human factor is ignorable in an indoor environment where the frequency is higher than 1 GHz. The link quality changes with time [132-134], the link quality variances are high at the edge of the network, whereas very low variance is noticed near the sending node. Furthermore, link asymmetry is also noticed. The reason for this asymmetry is either the large distance or low power. The mentioned studies [123-134] provide various analysis of wireless channel characterization in multiple environments including indoor office, indoor/outdoor factory, hospital indoor/outdoor.

6.5. Experiment and design for Test-bed in a Hospital Environment

6.5.1. Hardware and system architecture

There are mainly two radio modules of the IEEE 802.15.4 standard available in the market including transceiver-only modules and integrated Microcontroller (MCU) transceiver modules. Transceiver-only modules are low price and composed of RF transceivers and do not include MCU, therefore to handle a protocol stack an external Integrated Chip (IC) can be used. MCU transceiver modules are also called ready-to-use modules. These modules consist of a transceiver, MCU, and an antenna. ZigBee, WirelessHART, and Thread are popular examples of ready-to-use modules.

For the experiment, we selected a ready-to-use module, the Series 2 XBee-PRO S2B of Digi International which consists of ZigBee stack. It uses Ember (Silicon labs) EM250 module as radio chip which is the IEEE 802.15.4-compliant transceiver. It works at 2.4 GHz ISM band and provides 250 kbps data rate. The XBee-PRO S2B module incorporates different sub-modules including MCU core (16-bit, 12 MHz, RISC), RAM (5 kB) and flash (128kB). The radio operates using direct sequence spread spectrum with receiver sensitivity of -102 dBm. The module supports various network topologies including point-to-point/multipoint, peer to peer and mesh.

We used XCTU 6.3.2 which is an open source multi-platform application designed with the graphical user interface for Digi RF modules. XCTU is very useful for configuration and testing process of XBee modules. These modules can be configured as a coordinator, a router and as an end device. In experiments, we consider two metrics to estimate the link quality that is, RSSI and LQI.

In EM250 silicon, the LQI is computed based on the chip error rate of the packet. The IEEE 802.15.4 specification describes 64 chips per byte. The LQI value is represented through an 8-bit integer value which varies from 0 to 255, where 255 shows the best link quality. This LQI value is used to calculate link cost for the routing process. The communication scope of LQI is limited up to the next hop. Figure 6-4 shows the LQI value categorization to estimate the link quality. Higher values are representing better link quality and vice versa.

Quality	Maximum	Minimum	Units	Color
Very strong	256	195	LQI	(0,125,0)
Strong	195	130	LQI	(12,150,159)
Moderate	130	65	LQI	(212,105,0)
Weak	65	0	LQI	(231,0,0)

Figure 6-4 LQI value categorization in XCTU [135]

The RSSI values of XBee PRO S2B show the signal strength of last received packet over the link. In the context of a mesh network, the RSSI value represents the signal strength of the last hop; it does not provide any indication for the signal strength of a complete end-to-end link. The value of RSSI is associated in hardware with pin number 6. The RSSI value is obtained through an 8-bit integer.

Figure 6-5 defines the default values of RSSI based on different values link quality, where -69 dBm shows strong link quality and -100 dBm indicates the weak quality.

Quality	Maximum	Minimum	Units	Color
Very strong	0	-69	dBm	(0,125,0)
Strong	-69	-80	dBm	(12,150,159)
Moderate	-80	-90	dBm	(212,105,0)
Weak	-90	-100	dBm	(231,0,0)

Figure 6-5 RSSI value categorization in XCTU [135]

6.5.2. Classification of hospital scenarios

The Royal Bournemouth Hospital (RBH) is considered as the experimental environment. Figure 6-6 shows the west wing of the hospital which consists of one long corridor (blue line) surrounded by several standard size wards.

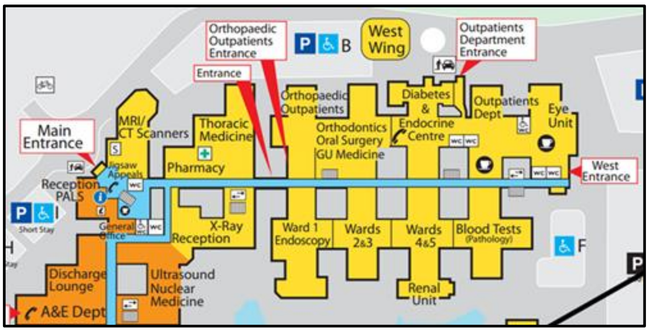

Figure 6-6 Floor map of the hospital [136]

The size of the room of each ward is approximately 12 m x 8 m and it consists of 6 electrically operated beds as shown in Figure 6-7. Each bed is surrounded by different medical and plastic equipment including Sonosite 180 Plus Portable Ultrasound System, drip stand (metallic), ECG monitor, patient entertainment system and bedside computing system, urine volume measurement instrument PBSV3.1 and a long metallic rack for small medical equipment. The rooms are separated by10 cm plaster wall. The columns inside building, floor, and ceilings are made of concrete. We designed a sample test-bed as shown in Figure 6-8 where one node is a coordinator and other two nodes are routers. The coordinator is managing this small network by controlling the communication of the nodes. In the hospital, the nodes are considered as sensor nodes and they send data towards coordinator.

Figure 6-7 Hospital ward equipped with medical devices

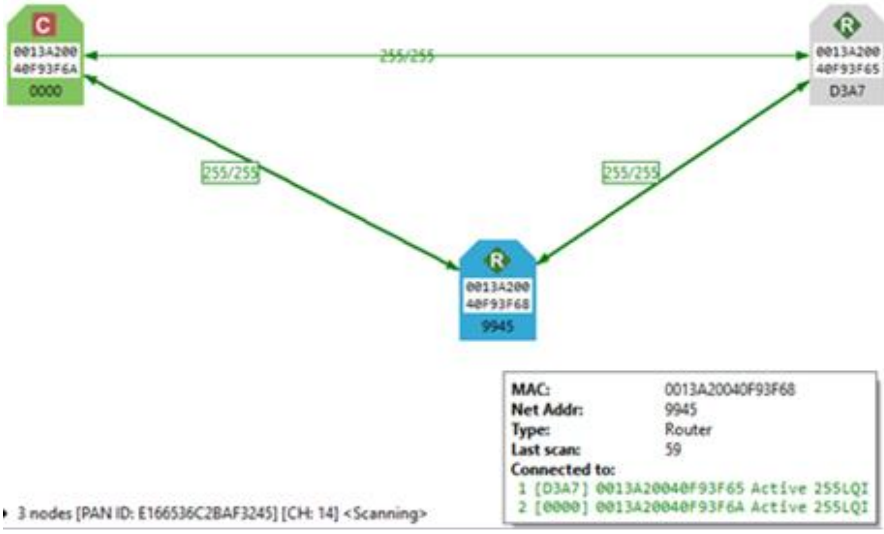

Figure 6-8 Sample deployed Test-bed topology

Classification of the hospital environment is done as follows:

1) Inside-ward: Inside ward communication involves metallic and plastic equipment. LOS exists in this scenario;

2) Corridor communication: The corridor of the hospital is approximately 250 meters long, four meters wide and surrounded by the wood walls. This scenario is important in terms of patient's mobility scenario in hospital. LOS exists in this scenario;

3) Ward to corridor: In a mesh topology, the patient equipped with sensor nodes moving in the corridor might only get chance to transmit the sensed data to the coordinator using any nearby node. NLOS exists in this scenario;

4) Ward to ward: A node form one ward might find next-hop in the nearby ward to send the data to the coordinator. In this scenario, the interference generated from both wards is important to consider. NLOS exists in this scenario.

6.6. Temporal experiments and analysis

Most of the propagation models are developed on the basis of empirical and analytical studies [137]. These studies are established by considering specific environments, frequencies, and surroundings. Therefore, these models may not be suitable for every environment. Before starting the empirical experiments, it is important to understand wireless channel characteristics and reasons for fluctuations and data loss in wireless communications in a hospital environment. There are mainly four reasons for fluctuations and data loss including high distance, attenuation with mobility, shadowing and fading. The difference between transmitted power and the received power is known as path loss. This same term also describes the signal attenuation which is helpful for link analysis purposes. To understand the wireless channel model in a hospital environment, two categories of channel models are used including LOS channel model and NLOS.

6.6.1. Inside ward

As the ward is of small size (12 m * 8 m approximately) and open, therefore, there is a high probability that LOS exists among the communicating nodes. For temporal experiments, we selected two points for communication inside the ward. The experiments are performed for 48 hours, starting from Thursday 20:00 pm to

Saturday at 20:00 pm. These days and timings are selected to analyze the variations of RSSI, LQI and packet reception at different peak (more human activity) and non-peak (less human activity) hours. The packet size of 100 bytes is sent in a loop after every 100 ms. We divided the scenario in four cases as shown in Table 6-2.

Table 6-2 Inside ward cases

Case #	**Intensity**	**Timing**
1	Off-peak	20:00 pm - 9:30 am (Thursday to Friday)
2	Peak	9:30 am - 20:00 pm (Friday)
3	Off-peak	20:00 pm - 11:30 am (Friday to Saturday)
4	Peak	11:30 am - 20:00 pm (Saturday)

Figure 6-9 shows a description of the RSSI values analysis of 48 hours both for the sender (red) and receiver (green) with packet reception rate. In case 1, the off-peak scenario is considered. Less human movements are noticed in the ward because of night hours. In this circumstance, the movement of the staff is also low. The RSSI values show a stable trend since the values are between -60 dBm to -66 dBm. The stable term is used here for less variation in RSSI values. In less interference scenario with the value of RSSI is -37 dBm for Series 2 XBee-PRO S2B. However, the value -60 dBm is still higher, although there is less human movement but the interference of medical equipment in the ward is still there which increases the value of RSSI. The interference from medical devices affects the successful packet rate in case 1.

In case 2, the peak scenario is presented which assumes the high human involvement inside the ward. It is observed that the RSSI values brought a large variation, with the values being between -60 dBm to -98 dBm. The reason for this variation is active human movements inside ward which caused interference. Further, the packet received ratio also dropped from 100% to 96%. In case 3, the off-peak scenario is described with less human movements as mentioned in case 1. Case 4 is the most interesting case as it takes place on a Saturday.

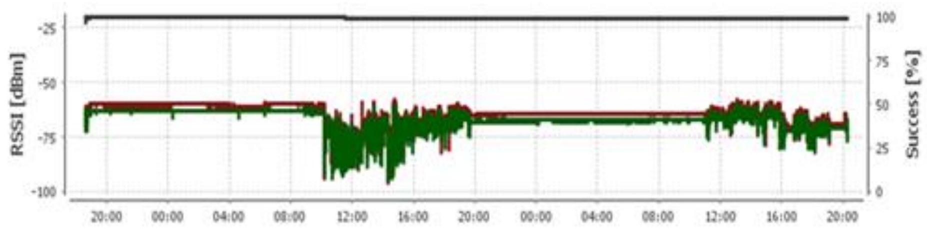

Figure 6-9 RSSI evaluation with temporal experiment

The value varies from 69 dBm to 79 dBm. The reason for less variation in the low human movement due to Saturday. Overall, it is noticed that the scenarios inside ward are mainly affected by two types of interference including medical equipment and human movements. The interference generated by the medical equipment is almost constant and dependent on the number of equipment. The interference generated by humans caused high variations.

In the next step, we performed a preliminary temporal experiment to find the correlation between LQI and Packet Reception Ratio (PRR). Figure 6-10 shows the comparison of average LQI and PRR. PRR represents the successful receive packets to the total number of transmitted packets. A strong correlation of 0.9 is found between PRR and LQI. In the temporal experiment of 24 hours, the variation is noticed for LQI. This variation is due to interference in the peak hours of the ward. The lowest LQI value is 205 with the PRR at 87 %. The LQI shows the error rate of the link, for wireless transmission where PRR should be 80%. If the value of LQI is more than 200 then it is acceptable as a routing metric.

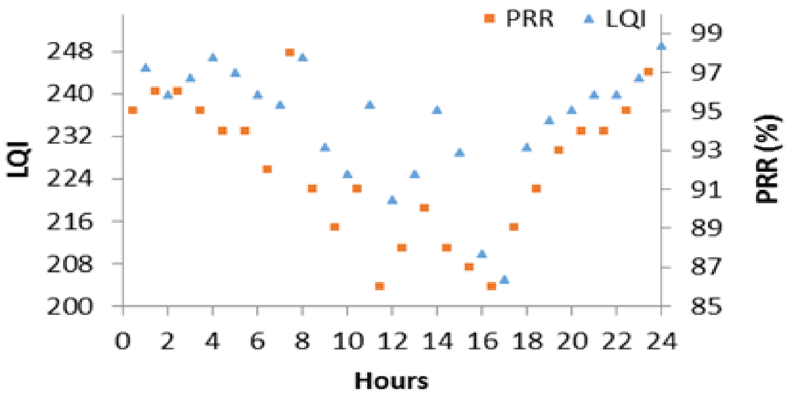

Figure 6-10 LQI temporal evaluation with PRR

6.6.2. Corridor communication

The corridor communication is an important scenario to consider in a hospital environment. We performed the temporal experiments in both cases including static (patients sitting/standing on different points in the corridor) and mobile scenarios. Figure 6-11 shows the analysis of RSSI and successful packet rate for a static scenario where patients are sitting in two different locations at the distance of 40 meters. The average RSSI value remained -75 dBm to -78 dBm from 14:20 pm to 16:00 pm. However, the high signal fluctuation is noticed from -80 dBm to -98 dBm is noticed from 16:00 pm to 17:00 pm. The reason for such fluctuation is higher human movement due to the shift change poses of doctors and nurses. After 17:00 pm, a stable trend of RSSI is observed from -77 dBm to -80 dBm. From this experiment, it is concluded that the RSSI value is very sensitive to human movement.

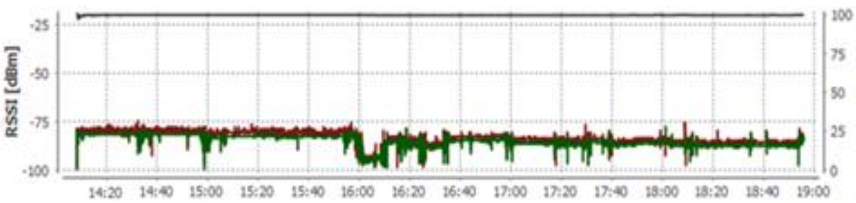

Figure 6-11 Analysis of RSSI and successful packet rate

The purpose of the experiment mentioned in Figure 6-12 is to find a correlation between RSSI value and distance. The distance varies from one meter to seventy meters. It is observed that the value of RSSI is increased by increasing the distance. The reason is that with the high distance the signal strength decreases. The correlation is computed based on Figure 6-12 which gives the value of 0.7 which considered as a good correlation value. It is concluded that a good correlation existed between distance and RSSI.

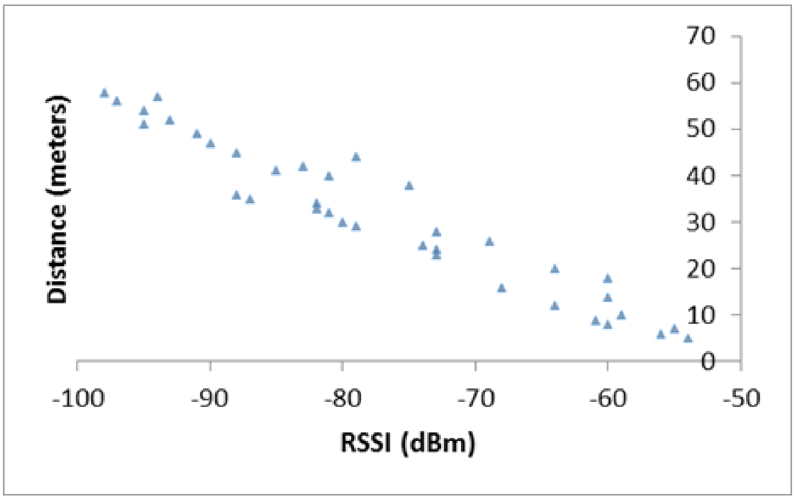

Figure 6-12 Correlation between RSSI value and distance

Figure 6-13 shows the relationship between RSSI and successful packet received ratio at the distance of 70 meters. The RSSI gives a stable trend from -80 dBm to -84 dBm; whereas, the received packet ratio dropped from 100% to 5% in the same duration. Therefore, it is concluded that RSSI did not show the useful information when the signal is weak. RSSI can be, however, used as a quality indicator, in the case when its value passes the maximum threshold value of -98 dBm which means very weak link quality.

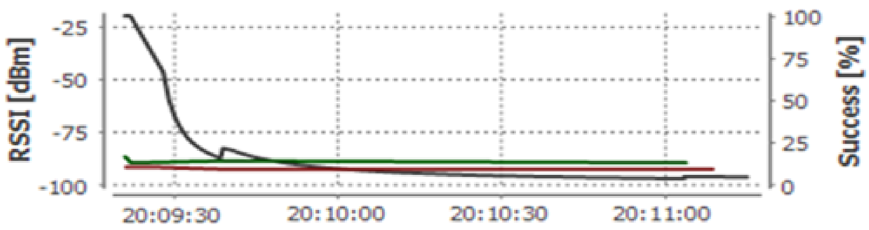

Figure 6-13 Relationship between RSSI and successful packet received ratio

The purpose of this experiment is to identify the effect of mobility on the average RSSI values and average packet received ratio. Figure 6-14 shows the temporal RSSI values and packet reception analysis of the corridor where one node is mobile and other is static. A continuous variation in RSSI value is noticed. Initially, it was from -64 dBm to -82 dBm. When the node moved from coordinator range then a straight line of time is observed. A strong RSSI value (-37 dBm) is noticed when a mobile node passed by the receiving node. Mobility does not significantly affect the received packet ratio; however, when the mobile node went out of the communication range than average received packet ratio significantly dropped.

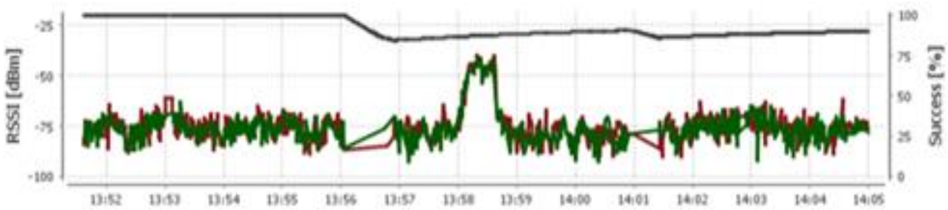

Figure 6-14 Temporal RSSI and packet reception analysis with mobility

The purpose of the evaluation in Figure 6-15 is to validate that either LQI or RSSI can be used as link quality metrics or not. Figure 6-15 provides a comparative analysis of a temporal experiment to identify the correlation between RSSI and LQI by considering the PRR. In the corridor, the packet size of 100 bytes is transmitted in a loop at different locations by varying the distance. A linear trend is observed between LQI and PRR with high LQI values being present at the same time as high PRR values and vice versa. In wireless networks, usually 80% PRR is considered as an acceptable quality of a link, below than 80% the link is not considered as a reliable communication link. The experiment shows that LQI is a strong candidate to be used as link quality metrics. Here, a threshold can be created for LQI to represent the link quality, such as the LQI value of 170 representing 81% of PRR which is the maximum threshold. If the value of LQI is below than 170 then the link is assumed to have a poor quality and should not be selected for communication. On the other hand, the RSSI values could not provide a clear trend in the context of PRR. That is even the lower values of RSSI represent the higher PRR. Moreover, a weak correlation of 0.40 is observed between RSSI and LQI, whereas, a strong correlation is noticed between LQI and PRR.

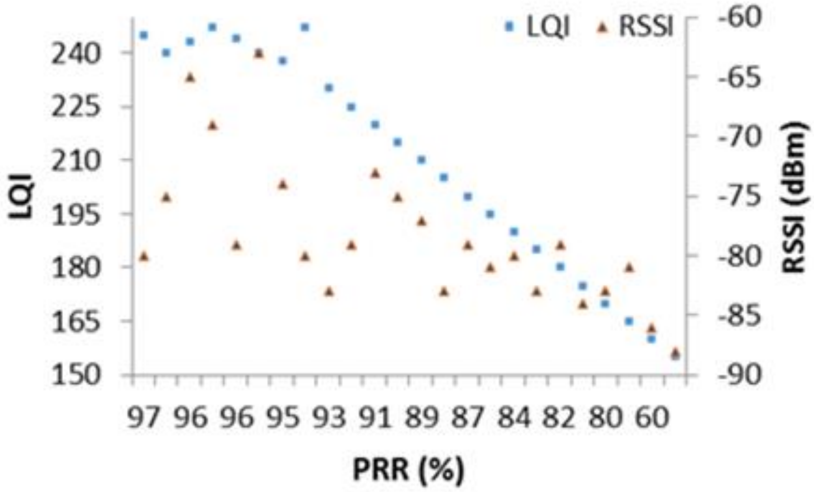

Figure 6-15 LQI and RSSI comparison in the context of PRR

6.6.3. Ward to corridor

This scenario is important to analyze, specifically in the mesh topology context where a node inside ward selects corridor's node as the next hop to send data towards a coordinator node. NLOS is considered for this scenario. This type of communication involves two types of interference, such as interference of the medical devices inside ward and interference in the corridor environment. To evaluate this scenario, the sensor network was deployed in the manner that a node inside the ward should select the next hop from one of the nodes presented in the corridor. Multiple temporal experiments are performed. Figure 6-16 shows one of the significant temporal experiments (from 15:45 pm to 19:45 pm) by varying distance from 5 meters to 40 meters. NLOS exists between communicating nodes. The experiments showed that the RSSI variations were from -60 dBm to - 98 dBm. The reason for this variation is the increment of the distance with NLOS. It is noticed that maximum transmission range limits up to 35 meters in NLOS for the ward to the corridor scenario. It is also observed that human movements have a strong impact on RSSI values, for instance, there are high variations in human movements from 18:30 pm to 19:30 pm.

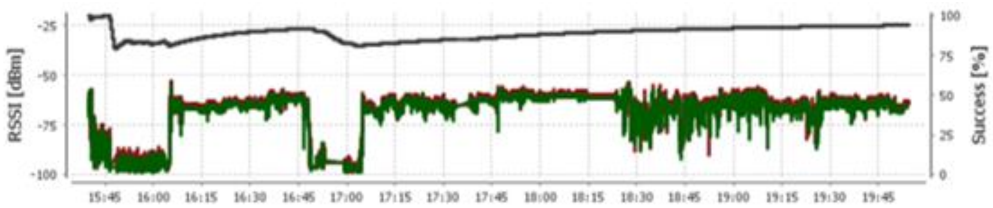

Figure 6-16 Temporal experiment analysis for NLOS

Figure 6-17 shows the correlation between LQI and PRR in the existence of LOS by considering the distance. It is also important to identify the same correlation for NLOS which exists in the ward to corridor scenario. LQI and PRR both decrease by increasing of the distance in NLOS; however, LQI shows the more linear trend. Moreover, the correlation of 0.65 is found between LQI and PRR. It is noticed that the LQI value of 210 provided PRR up to 80 % which meant to represent a reliable link. From this experiment it can be inferred that in NLOS, the LQI can be used to determine the link quality; however, in such case, the threshold value of LQI should be considered as 210.

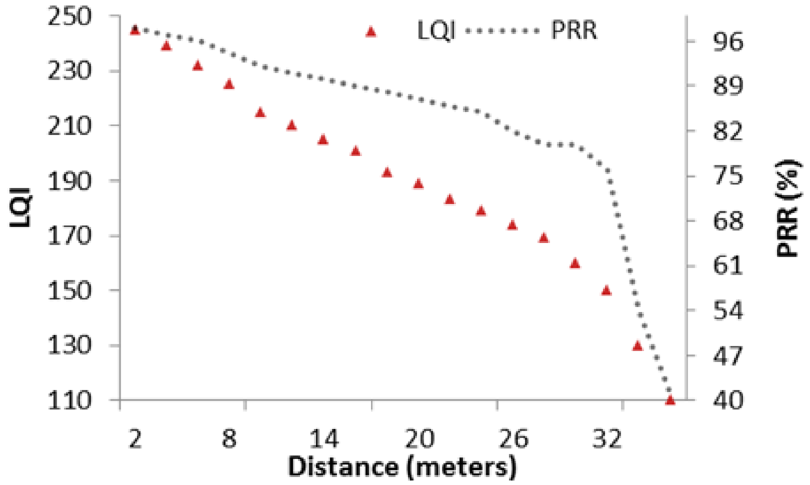

Figure 6-17 Correlation between LQI and PRR in the existence of LOS

6.6.4. Ward to ward

Ward to the ward communication is applicable in the mesh topology where a node may select another node as the next hop from the nearby ward. Figure 6-18 provides RSSI value analysis for the ward to ward communication scenario which involves the interference of medical devices from both the wards. The RSSI value started from -77 dBm, the reason for such low RSSI is the presence of interference of medical devices from the wards. Moreover, a short variation of RSSI is noticed from -80 dBm to -94 dBm, the reason is human movement.

Figure 6-18 RSSI value analysis for the ward to ward communication

6.7. Conclusion

The purpose of this study was to identify the appropriate channel link quality estimation so that it could be used as useful input in terms of reliability for route selection mechanism. In such a multi-hop environment, the coordinator is placed at a central location. The nodes send data using multi-hop communication. The values of RSSI and LQI change according to space and time. In the analysis section, we provided the details regarding different time periods. It is noticed that the characteristics of the low-power wireless radios are highly dependent on deployed environment. For the inside ward scenario, it is found that fluctuation is mainly due to interference generated by medical equipment and human movements. The interference generated by the medical equipment created a predictable effect on signals. A weak correlation is found between RSSI and packet reception which means that RSSI is not a reliable metric for link quality estimation. For inside ward scenario, a strong correlation of 0.9is noticed between LQI and packet reception. We suggest a threshold value of 200 for LQI which means if a link shows LQI value 200 or above then the link should be considered as a reliable link.

For the corridor scenario, there are two sub-scenarios: static and mobile. For the static scenario, the average RSSI value is noticed from -75dBm to -80 dBm and a weak correlation is also found between RSSI and packet reception. A medium correlation (0.65) is found between RSSI and distance which means that RSSI could be a useful input for routing protocol to determine the distance among nodes. For the mobility scenario, the average RSSI value shows a continuous fluctuation which is from -77 dBm to -85 dBm. For the mobility scenario, it is not recommended to use RSSI as link quality metric for routing protocols. For corridor scenario, a good correlation of 0.7 is found between LQI and packet reception. Further for routing decision, in the corridor, we suggested a threshold value of 180 for LQI. For the ward to corridor scenario, the NLOS model is considered. It is noticed that packet reception ratio decreases with the distance and it becomes zero after 35 meters. The average RSSI value is from -80 dBm to -85 dBm which shows a poor quality for the signals. It is not suggested to use RSSI as a quality metric in NLOS scenarios. A medium correlation of 0.65 is found between LQI and packet reception, we recommend a threshold value of 210 for LQI. For the ward to ward scenario, the average RSSI values remain from -80 dBm to -87 dBm and the reason for these low values is the interference from both metallic objects and human movements. Overall, it is concluded that LQI and RSSI value are dependent on the surrounded environment, therefore while using these metrics in routing algorithms; the threshold should be defined carefully to get the optimal performance.

The partial work in this Chapter has been submitted to the following journal for publication

- Akbar, Muhammad Sajjad, Hongnian Yu, and Shuang Cang, "Channel Characterization and Link Quality Validation of IEEE 802.15.4-based Routing Protocols for WBASNs/IoTs in Hospital Environment", (submitted in IEEE Transactions on Wireless Communications, 25 November 2017)

Chapter 7: Conclusion and Future Work

7.1 Conclusion

The main contribution of this thesis is to provide modelling, analysis, and design for WBASNs protocols at MAC and network layer. We used mathematical and numerical modelling to minimize the energy consumption of the nodes while considering the stringent QoS requirements of remote patient monitoring applications in terms of delay, reliability, throughput, efficient channel access and prioritized data transmission. We identified five main objectives for this thesis. The details of these objectives are mentioned in Chapter 1.

To achieve the first objective, in Chapter 3, the DRT profile is proposed based on end-to-end delay (ED) model. The DRT profile provides multiple delay values, these values considered three variables including BE, macMaxCSMABackoffs and MacMaxFrameRetries. The values of BE and macMaxCSMABackoffs represent delay; whereas, MacMaxFrameRetries values are used for reliability. By using parameter tuning approach, different combinations of these variables are applied in numerical computations by considering the multiple frequency bands including 420 MHz, 868 MHz, and 2.4 GHz. The numerical model is validated using Castalia 3.2 simulator. Moreover, simulations are conducted to evaluate the delay, PDR, and MT by varying the packet size, several nodes, frequency bands and data rates. The implementation of the DRT does not require any modification of the IEEE 802.15.4 standard. It is concluded from the simulations that DRT profile is suitable for WBASNs applications in terms of delay, reliability, and throughput.

To achieve the second objective, in Chapter 4, TMP protocol is proposed using the IEEE 802.15.4 slotted CSMA/CA with beacon-enabled mode for remote patient monitoring systems. TMP uses two popular optimization techniques including MAC layer parameter tuning and duty cycle-based. The Duty cycle is adjusted using three factors offered network traffic load, DRT profile, and superframe duration. The TMP performs better than comparative protocols including AAOD, AMPE, ADCA, DSAA and DCA protocols in terms of time delay, reliability, and energy consumption for slotted CSMA/CA. The reason for the better performance of TMP is the optimized duty cycle mechanism. TMP provides 76% of PDR which is better than the comparative protocols. Similarly, TMP provides better efficient energy consumption that is, 2.3 Joules/Sec for the proposed patient monitoring system.

To achieve the third objective, in Chapter 5, frame aggregation mechanism is proposed to obtain high throughput for life-critical applications at the MAC layer. Three types of aggregations levels are tested in the simulations and these are an aggregation of two packets (Agg_2), aggregation of four packets (Agg_4) and aggregation of six packets (Agg_6). It is observed that higher the aggregation level, higher the number of received packets. Similarly, the value of delay decreases by increasing the aggregation level. Moreover, Agg_6 provides energy consumption of 2.3 Joules/Sec, which is slightly high in comparison to Agg_2 and Agg_4. However, this slightly higher value can be ignored as Agg_6 provides a higher number of packet received with less delay. Further, the proposed aggregation mechanism is tested for GTSon and GTSoff mode. Simulation is conducted in NS 2.29 and CASTALIA 3.2 with OMNeT++. The evaluation is done for both modes including CAP and CFP. The evaluating parameters include several received packet, average delay, and energy consumption. Frame aggregation mechanism is proved to be useful for life-critical applications which require high throughput and less delay.

To achieve the fourth objective, in Chapter 6, the intelligent routing metrics are identified for WBASNs/IoTs based routing protocols. For inside ward scenarios, empirical experiments show a weak correlation between RSSI and packet reception which means RSSI is not a reliable metric for link quality estimation. For inside ward scenario, a strong correlation (0.9) of LQI and packet reception is found. For the corridor scenario, a medium correlation (0.65) is found between RSSI and distance which shows that RSSI can be a useful input for routing protocol to determine the distance among nodes. For the mobility scenario, the average RSSI value shows a continuous fluctuation which is from -77 dBm to -85 dBm. For the ward to corridor scenario, the average RSSI value is between -80 dBm to -85 dBm which shows a poor quality of signals. A medium correlation (0.65) is found between LQI and packet reception. For the ward to ward scenario, the average RSSI values remain between -80 dBm to 87 dBm. The reason for these lower values is the interference from both metallic objects and human movements. Overall, it is concluded that LQI and RSSI value are dependent on the surrounded environment. Therefore, while using these metrics in routing algorithms; the threshold should be defined carefully to operate at the optimal performance.

To achieve the fifth objective, an IETF draft is proposed which highlights the problem statement and solution for the integration of IPv6 network with the IEEE 802.115.6 standard. The core problems include MTU difference and auto-configuration of WBASNs nodes in the IPv6 network. For this purpose, an adoption layer is proposed which defines the fragmentation and reassembly mechanism by using header compression mechanism. Furthermore, it also specifies the addressing mechanism which supports the auto-configuration mechanism.

7.2 Future work

There are interesting future research directions which can be considered as the extension of this research work for WBASNs.

1. As there are many healthcare monitoring applications which require diverse QoS from the underlying communication infrastructure. Hence, an important research domain is to identify the suitable combination of MAC and routing protocols which could address these diverse QoS requirements. To address this challenge, a cross-layer framework should be proposed. This cross-layer framework will be applicable for many healthcare monitoring applications.
2. Another promising area is the integration of telemedicine solutions with patient monitoring systems using the IEEE 802.15.6 standard. The communication methods in IEEE 802.15.6 are not sufficient to demonstrate a complete MAC protocol. It only describes the interoperability mechanisms amongst the IEEE 802.15.6 standard devices by giving the message exchange formats. The aspect like topology changes with respect to human movements should be part of a MAC protocol of WBASNs. Moreover, research can be done to make IEEE 802.15.6 MAC more robust so that it could support multiple WBASNs in parallel.
3. The existing routing protocols of WBASNs should be extended in the context of fault detection and prevention. The coordinator node should send a malfunction message to the corresponding node. Similarly, if we integrate WBASNs with IoTs which means there will be a huge network of small nodes. In such cases, proper congestion detection and congestion avoidance mechanisms should be used. However, the nodes in WBASNs have fewer

energy resources. Therefore, energy efficient solutions should be adopted for the mechanisms like fault detection and congestion avoidance.

4. Moreover, a new acknowledgement mechanism should be made for health-care MAC protocols, which could increase reliability and consume less energy.
5. The investigations on routing protocols are done by assuming their deployment in indoor hospital environments. An enhancement of routing protocols should also be proposed for outdoor environment that is open environment such as surroundings of the buildings.

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Appendix A: Introduction to Wireless Body Area Sensor Networks (WBASNs)

A.1. Background

WBASN is considered as sub-field of wireless sensor network (WSN). In 1995, Zimmerman first introduced the concept of WBASN where physiological information should be exchanged among devices placed inside or near the human body [17, 18]. He also suggested using the wireless personal area networks (WPANs) for physiological data collection from devices. In their deployed test-bed, communication channel properties, the establishment of the reliable link and network connection of devices to the application was done at the physical layer, data link layer, and network layer respectively. The low carrier frequency is used to minimize the energy consumption. Figure 8-1 explains the setup which consists of WPAN transmitter and receiver and connected to the human body. The current flows with the help of a biological conductor and to prevent shorting "earth ground" is used. The "earth ground" is considered an important aspect of WPAN devices and it is suggested that the best location of these devices are near feet. The term, body area network (BAN)/ WBASNs was used in 2001 and later new communication standards are made for them. Figure 8-1 presents the system diagram of a sensor node.

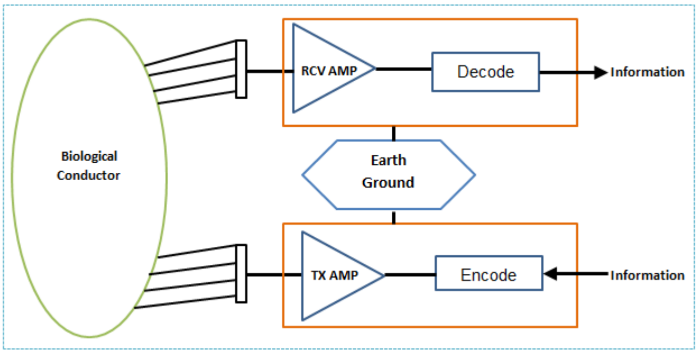

Figure 8-1System diagram of sensor node

A.2. Comparison of WBASN with WSN

WBASN is considered to be a sub-class of WSN. Various communication protocols and mechanisms are developed for WSN but their use in WBASN is not suitable due to the different environment of the human body. There are few common features between them which include network structure, energy efficiency and multi-hop communications [6, 17, 94, 138]. The comparison between WBASN and WSN can be done on the basis of seven aspects i.e., node features, network size, limited resources, accessibility, and mobility.

A.2.1. Node Identification

Node identification refers to the process of assigning a unique identification ID to a node. The IDs have local significance in WSN and WBASN. As in WBASNs, it is expected that a number of a deployed node is less in comparison with WSN where hundreds of nodes are deployed, hence, less number of bits are used to identify the WBASN nodes. Less number of bits as a node identification reduces the processing time which also consumes less energy.

A.2.2. Node size

In WBASNs, smaller size sensor nodes are used, whereas in WSN any size of the node can be used according to the requirement of the scenario. In WBASN, two types of sensor nodes are used i.e., implanted and wearable. The size of implanted nodes is very small. Figure 9 and Figure 8-2 show different implanted and skin sensors nodes. The purpose of figure sensors is to read the text and convert the words into voice signals.

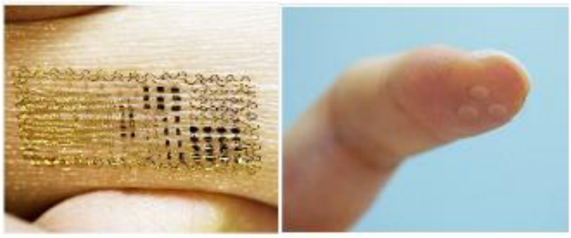

Figure 8-2 Smart skin sensors and Finger implanted sensors [71]

A.2.3. Network Size

Usually, a WBASN consists of a limited number of nodes which vary from 6 to 12, whereas WSN is made of hundreds of nodes. In WBASN, the transmission range is selected according to the height of the human body up to few meters and all the sensor nodes send data to a BAN coordinator (BANC) which transmits the data to the destination. In WSN, the transmission range is high up to 100 meters and a dedicated node cluster-head is used as coordinator. Overall, the network area of WBASN is few meters due to its low transmission range and it requires low transmission power which is not harmful to body tissues. In WSN, the network area is in hundreds of meter due to its high transmission range and requires high power for transmission.

A.2.4. Limited resources

In WBASN, the size of the sensor node is tiny in size and has limited resources in terms of bandwidth, energy source, processing speed and memory, whereas in WSN, due to the bigger size of the nodes, resources are not that much limited as in WBASN.

A.2.5. Mobility

In WBASN, as the network is deployed on the human body so the internal and external body mobility creates complexity. Hence, the protocols need to support the mobility in WBASNs. In WSN, usually, the network structure is static.

A.2.6. Accessibility

In WSN, due to reasonable size and deployment environment, it is easy to access the node, whereas in WBASN as the node size is tiny so it is difficult to access a node. Sometime to access the implanted node a surgical operation is required.

A.3. WBASN components

The WBASN's node structure contains various modules including an energy source, processor, memory, transceiver, sensor, actuators and operating system [73, 139, 140]. Figure 8-3 shows the structure of the WBASN's node.

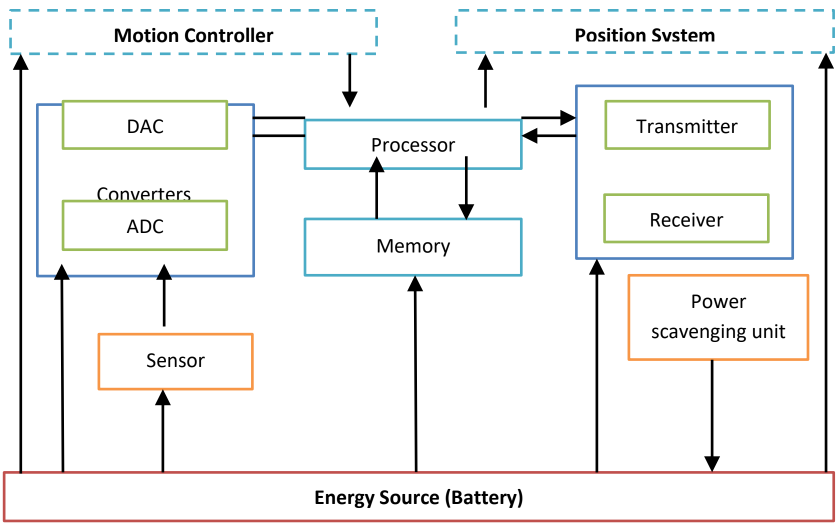

Figure 8-9 Structure of a WBAN node

A.3.1. Energy source

In the WBASNs, small battery sizes limit the energy source and it allows very low power levels due to increasing the lifetime of the sensor node.

A.3.2. Processor

The function of the processor is to manage all the computation activities. Various companies' makes processors for WBASNs, in this context, MSP430 from Texas Instrument (TI) is a popular example which is considered as world's Ultra-low power with 16-bit microcontroller platform. The speed of this processor varies from 8 MHz to 15 MHz.

A.3.3. Memory

Memory capacities vary in WBASN e.g., a node with MSP430 contains up to 64KB RAM with up to maximum 512KB flash memory.

A.3.4. Transceiver

The transceiver is a component which can transmit and receive the data. Usually, WBASN consists of the CC2420 chip which is useful for low power data communications.

A.3.5. Sensors

Generally, the sensing module contains various sensor nodes which use to monitor physiological parameters of the human body.

A.3.6. Actuators

Actuators take the action against the data received from sensors e.g., on receiving some critical data regarding diabetes, the actuator can inject insulin.

A.3.7. Operating system

TinyOS is a popular open source operating system used in WBASN. As TinyOS's design supports the low-power communications, therefore it is suitable for WBASN's devices.

A.4. WBASN Topologies

The network topologies describe the data communication structure among the network's nodes. In WBASN different types of topologies are used including peer-to-peer (P2P), mesh, cluster tree, hybrid, and star. According to the requirement of application, a topology is selected. These requirements include scalability, robustness, energy, reliability, latency, and mobility. According to IEEE 802.15.4 standard, functionality-wise sensor nodes are divided into two types i.e., full function sensor nodes (FFSNs) and reduced function sensor nodes (RFSNs). FFSNs are capable of routing functions, whereas RFSNs can only do peer to peer communication. Usually, RFSNs are deployed where energy is a critical issue. The advantages and disadvantages of these topologies are discussed below [1, 62, 113].

A.4.1. Star Topology

In a star topology, a central coordinator controls the communication of the network as shown in Figure 8-4. The coordinator is a FFSN device and all the communication among node is only possible through the coordinator. The advantages of the star topology include simple deployment, fewer energy requirements, and limited latency etc. The disadvantages are single point failure, low scalability and high energy requirement of the coordinator etc.

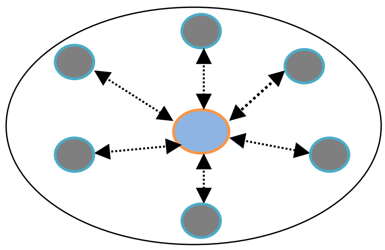

Figure 8-4 Star topology

A.4.2. Mesh Topology

All the nodes in mesh topology are FFSNs and capable of routing operations. As mesh topology provides multiple paths to the nodes as shown in Figure 8-5, so in case of a node failure, nodes can continue the communication process.

The mesh topology is scalable, fault tolerance and provides a balanced energy usage, but it provides higher delays and low throughput.

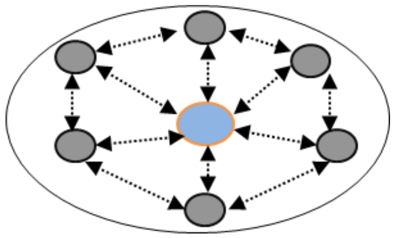

Figure 8-10 Mesh topology

A.4.3. Cluster Tree Topology

Cluster tree topology is composed of multiple star topologies as shown in Figure 8-6. The nodes of one-star topology are capable of communication with the nodes of other star topology only through the coordinator of their topology. The cluster tree topology provides high scalability but provides less bandwidth with higher delays.

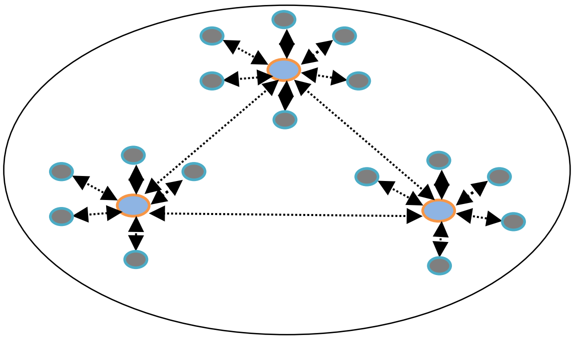

Figure 8-6 Cluster tree topology

A.4.4. Hybrid Topology

A hybrid topology is composed of mesh and star topologies as shown in Figure 8-7. Although hybrid topology provides high scalability with reliable data communication, its deployment is complex with higher delay and high power consumption.

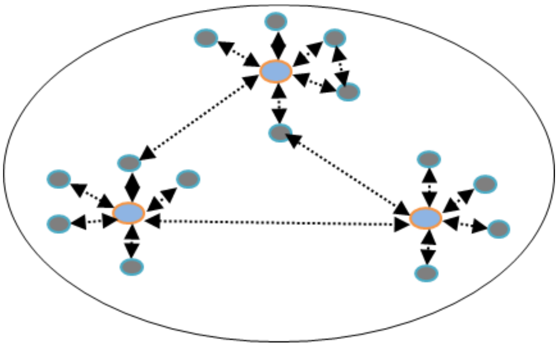

Figure 8-7 Hybrid topology

A.5. WBAN Requirements

WBASNs face various challenges due to diverse nature of applications and these requirements are different from other wireless network technologies. Table 8-1 describes these requirements in detail [141, 142].

Table 8-1 Requirement analysis of WBASN

Parameters	Requirements	Range
Lifetime	Long for wearable sensors and ultra-long for implanted sensors	One week-month for wearable and 8-5 years for implanted
Covered Area	Inside and around the body	1-5 meters
Data Rate	Application dependent	1Kbps-10Mbps
Setup Time	Fast	From 1-30 seconds maximum, Application dependent
Security	Simple and light mechanisms required	Authentication, Privacy, Confidentiality
Customization	Configurable sensor nodes	Remotely accessible and adaptive
Fault Management	Detection mechanisms for the case of the node failure	Self-configuring and self-healing
Quality of Service	Application dependent	An efficient combined set of delay, reliability, priority, throughput, and energy
Power and Energy	Efficient energy and power mechanisms	0.1 mW for standby mode and 30 mW for fully active nodes, hardware dependent
Medium Access Control	Controllable, Scalable and reliable	Power controls during listening, wakeup and sleeping states
Frequency Bands	Medical bands and compatible with human tissues	UWB, ISM, and WMTS etc.

A.6. Power Consumption

The miniature sized batteries are engaged in a WBASN node which does not contain a higher level of power. For efficient utilization of this limited resource, new energy efficient communication protocols are used at MAC and network layer. These protocols reduce the power consumption by introducing duty-cycle mechanisms. Table 8-2 describes the power consumption comparison of WBASN with other existing wireless technologies.

Table 8-2 Power consumption comparison among technologies

Standard	**Provided data rate**	**Power requirement**	**Battery lifetime**
WiFi	100 Mbps	100 mW - 1000 mW	Hours - days
Bluetooth	1Mbps - 10 Mbps	4 mW - 100 mW	Days - weeks
Wibree	600 Kbps maximum	2 mW - 10 mW	Weeks - months
ZigBee	250 Kbps	3 mW - 10 mW	Weeks - months
802.15.4	250 Kbps maximum	3 mW - 10 mW	Weeks - months
802.15.6	1Kbps - 10 Mbps	0.1mW – 2mW	Months - years

A.7. WBASN in healthcare

Healthcare is becoming a challenge as the population of expected patients that need remote monitoring will reach 761millions in 2025 [1, 16, 17]. Also, the patients with the number of elderly and chronic diseases have increased, so there is a need to provide quality of life in terms of healthcare. Patient's data monitoring is one of the important application in healthcare. Further, continuous monitoring of the patient in indoor and outdoor environment proved to be very useful for doctors to extract useful information for treatment and care. Hence, WBASNs can be used for the remote healthcare and monitoring for various environments like hospitals, ambulatory, emergencies and elderly care centers etc.

A.7.1. Patient monitoring for chronic diseases

For a chronic disease patient, the formal procedure of routine visits is required to monitor the progress, development of complications or relapse of the disease. The questions like what, how and when to monitor are really crucial for disease treatment. In this context, various biosensors can be used for monitoring the patient's physiological conditions which gets relevant information on a regular basis. Table 8-3 provides some examples of such diseases.

Table 8- 3 Diseases with monitoring sensors

Diseases	**Physiological parameters**	**Biomedical sensor type**
Cancer	Body fat sensor, Weight loss inication sensor	Implantable/Wearable
Hypertension	BP	Implantable/Wearable
Heart Disease	ECG, BP, heart rate	Implantable/Wearable
Asthma	Respiration and oxygen saturation	Implantable/Wearable
Diabetes	Visual impairment	Wearable
Rheumatoid Arthritis	Joint stiffness	Wearable
Renal Failure	Urine output	Implantable
Vascular Diseases	blood pressure and peripheral perfusion	Implantable/Wearable
Infectious Diseases	Temperature	Wearable
Stroke	Activity recognition, Impaired speech, memory etc.	Implantable/Wearable

A.7.2. Elderly patient monitoring

The fast growth in the elderly population will produce a considerable shortage of healthcare experts in the near future. WBASN delivers a highly cost-effective solution to monitor the physiological parameters of the elderly persons by the seamless integration of their daily routine activities. Moreover, the physician can monitor the health conditions of an elderly person remotely with the courtesy of WBASNs. Figure 8-8 presents WBASNs.

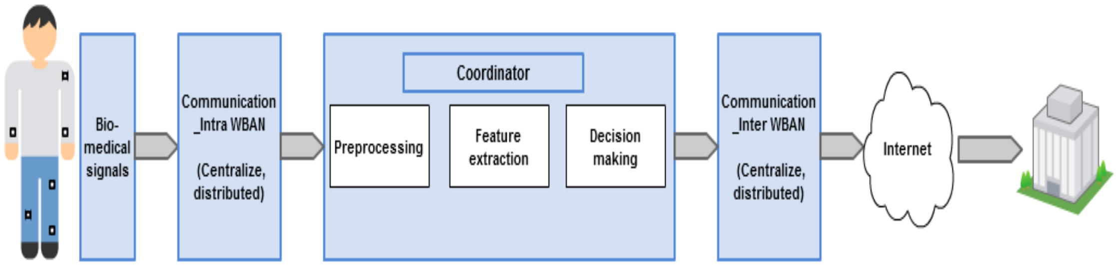

Figure 8-8 Elderly patients monitoring

A.7.3. Hospital patient monitoring

In the hospital environment as shown in Figure 8-9, several levels of patient monitoring services are required as different patients required different monitoring services e.g., a patient in Intensive Care Unit (ICU) requires high prioritized periodic data services with limited delay and high throughput than the patient in a normal ward. Usually, a patient is equipped with multiple sensors that measure vital signals like heart activity, muscle movements, blood pressure, body oxygen level and brain stimulation via integrated sensors i.e., ECG, BP monitor, EMG, pulse oximeter and EEG etc.

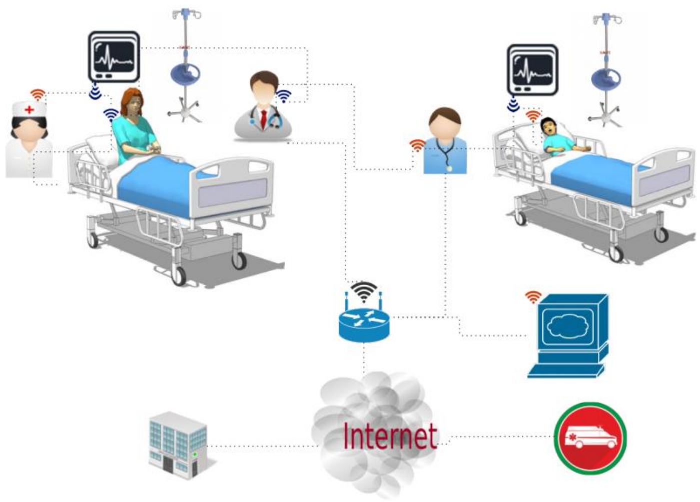

Figure 8-9 Hospital scenario for patient monitoring

A.8. WBASNs Projects

Many institutions and universities executed WBASN projects for healthcare domain. Table 8-4 describes the list of popular projects.

Table 8-4 WBASN's healthcare projects

Projects	Institution	Application	Communication Scope	Sensors
LiveNet [143]	MIT	Epilepsy seizures detection	Wire, wireless 2.4 GHz radio	ECG, BP, EMG, SaO2
AMON [144]	EU IST FP5 Program	Cardiac and respiratory	GSM-based	ECG, BP, SaO2
WEALTHY [68]	EU IST FP5 Program	Rehabilitation for elderly people through monitoring	Bluetooth, GPRS	ECG, EMG respiratory, activity and temperature sensors
LifeGuard [145]	Stanford University, NASA	Monitoring in space and terrestrial	Serial cables, Bluetooth	ECG, BP, SaO2
MagIC [146]	University of Milan, Italy	Cardiology, Respiratory and motion signal	Bluetooth	ECG, respiratory and temperature sensors
CodeBlue [147]	Harvard University	Activity monitoring system	ZigBee	ECG, SaO2 and activity recognition (motion sensors)
Body area networks [148]	Valencia, Spain and Malta Universities	Recognition of physiological state (stress and fatigue)	WiFi, ZigBee, and GPRS	ECG, BP and respiratory
Human++ [149]	IMEC	Wearable sensor system for health monitoring	ZibBee	ECG, EEG, EMG
HealthGear [150]	Microsoft	Detection of sleep apnea events	Bluetooth	ECG, SaO2
Personal Health Monitor [151]	University of Technology Sydney, Australia	Heart-attacks	Bluetooth, GPRS	ECG, BP and Activity sensors
Mobi-Health [152]	University of Geneva	Ambulatory Patient Monitoring	ZigBee, Bluetooth, GPRS	ECG, BP
CareNet [153]	Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering	Remote Health monitoring	ZigBee	Gyroscope, Accelerometer
ASNET [154]	King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia	Remote Health monitoring	WiFi, Ethernet	BP and temperature sensors
WiMoCA [155]	University of Bologna, Italy	Sports /Gesture detection system	Bluetooth	Accelerometer
UbiMon [156]	University of University of South Florida	Health Care	ZigBee, WiFi, GPRS	ECG, SaO2

A.9. WBASN global connectivity

WBASNs are capable of creating interaction with the Internet and other existing wireless technologies including ZigBee, Bluetooth, wireless local area networks (WLAN) and cellular network etc. There are various ways to connect WBASNs with the Internet; usually, it connects with the help of ambient sensors. Figure 8-10 shows the example of WBASN global connectivity.

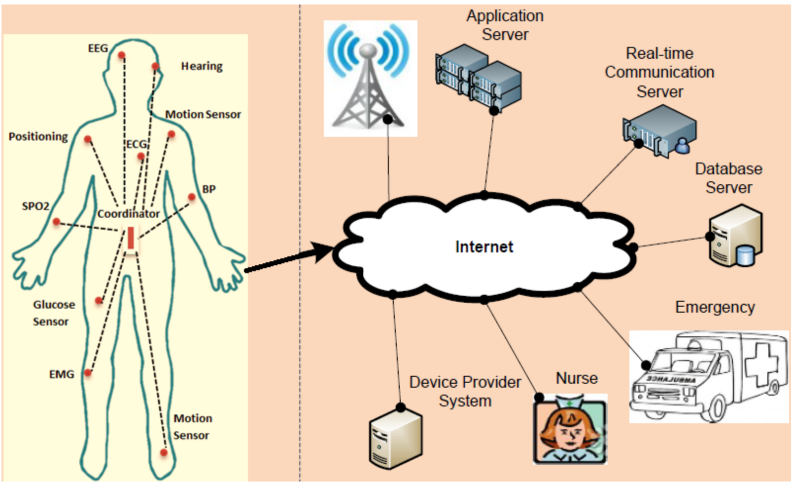

Figure 8-10 WBASN global connectivity

The standard like IPv6 over low power wireless personal area networks (6LoWPAN) help to connect them directly to the Internet. The concept of 6LoWPAN follows the idea that Internet Protocol can be applied even to the small low-power devices which have limited processing capabilities and make them part of IoTs. The 6LoWPAN is a working group of IETF and defines encapsulation and header compression mechanisms that allow IPv6 packets to interact with IEEE 802.15.4 standard. The focuses of IP networking for low-power radio communication are those applications that require wireless internet connectivity at lower data rates. The “Thread” is the consortium for 50 companies that make protocol running over 6LoWPAN.

Appendix B: Transmission of IPv6 Packets over Wireless Body Area Networks (WBANs)

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Transmission of IPv6 Packets over Wireless Body Area Networks (WBANs)
draft-sajjad-6lo-wban-01

Abstract

Wireless Body Area Networks (WBANs) intend to facilitate use cases related to medical field. IEEE 802.15.6 defines PHY and MAC layer and is designed to deal with better penetration through the human tissue without creating any damage to human tissues with the approved MICS (Medical Implant Communication Service) band by USA Federal Communications Commission (FCC). Devices of WBANs conform to this IEEE standard.

This specification defines details to enable transmission of IPv6 packets, a method of forming link-local and statelessly autoconfigured IPv6 addresses on WBANs.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

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This Internet-Draft will expire on May 3, 2018.

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1. Introduction

Wireless Body Area Networks (WBANs) are comprised of devices that conform to the [IEEE802.15.6], the standard by the IEEE. IEEE 802.15.6 provides a specification for the MAC layer to access the channel. The coordinator divides the channel into superframe time structures to

allocate resources [SURVEY-WBAN] [MAC-WBAN]. Superframes are bounded by equal length beacons through the coordinator. Usually, beacons are sent at beacon periods except for inactive superframes or limited by regulation.

Task group for 802.15.6 was established by IEEE in November 2007 for standardization of WBANs and it was approved in 2012. This standard works in and around the human body and focuses on operating at lower frequencies and short range. The focus of this document is to design a communication standard for MAC and physical layer to support different applications, namely, medical and no-medical applications.

Medical applications refer to a collection of vital information in real time (monitoring) for diagnoses and treatment of various diseases with help of different sensors (accelerometer, temperature, BP and EMG etc.). It defines a MAC layer that can operate with three different PHY layers i.e. human body communication (HBC), ultra-wideband (UWB) and Narrowband (NB). IEEE 802.15.6 provides specification for MAC layer to access the channel. The coordinator divides the channel into superframe time structures to allocate resources. Superframes are bounded by equal length beacons through coordinator. The purpose of the draft is to highlight the need of IEEE 802.15.6 for WBASNs and it's integration issues while connecting it with IPv6 network. The use cases are provided to elaborate the scenarios with implantable and wearable biomedical sensors. 6lowpan provides IPv6 connectivity for IEEE 802.15.4; however, it does not work with IEEE 802.15.6 due to the difference in frame format in terms of size and composition.

1.1. Frame Format and Addressing Modes

Figure 1 shows the general MAC frame format consisting of a 56-bit header, variable length frame body, and 18-bit frame check Sequence (FCS). The maximum length of the frame body is 255 octets. The MAC header further consists of 32-bit frame control, 8-bit recipient Identification (ID), 8-bit sender ID, and 8-bit WBAN ID fields. The frame control field carries control information including the type of frame, that is, beacon, acknowledgement, or other control frames. The recipient and sender ID fields contain the address information of the recipient and the sender of the data frame, respectively. The WBAN ID contains information on the WBAN in which the transmission is active. The first 8-bit field in the MAC frame body carries message freshness information required for nonce construction and replay detection. The frame payload field carries data frames and the last 32-bit Message Integrity Code (MIC) carries information about the authenticity and integrity of the frame. The IEEE 802.15.6 standard supports two kinds of addresses:

1. 8-bit short address, which is the sender ID. This address is located in the MAC header used for communication.

2. 48-bit EUI-48 address, which is used for the association process. For some certain frame types, e.g. Security Association frames, this MAC address exists inside the MAC payload, for the node joining process.

```
                   Octets      7          0-255           2
                         +--------+-----------------+--------+
                         |  MAC   |  MAC frame body |        |
                         | header |Variable length: |   FCS  |
                         |        |  0-255 bytes    |        |
                         +--------+-----------------+--------+
                         <--MHR--><--------X--------><---FTR-->
                          /       \
                         /         \
                        /           \
        +---------+------------+-------------+--------------+
        |  Frame  | Recipient  |   Sender    |      Ban     |
        | control |     ID     |     ID      |       ID     |
        +---------+------------+-------------+--------------+
 Octets <---4----><-----1-----><------1-----><-------1------>
```

Figure 1: The general MAC frame format of IEEE 802.15.6

1.2. Why 6lo is required for IEEE 802.15.6

Based on the characteristics defined in the overview section, the following sections elaborate on the main problems with IP for WBANs.

The requirement for IPv6 connectivity within WBANs is driven by the following:

o The number of devices in WBANs makes network auto configuration and statelessness highly desirable. And for this, IPv6 has (default auto-configuration as a) ready solutions.

o A large number of devices poses the need for a large address space, moreover a WBAN may consist of 256 nodes maximum and IPv6 is helpful to solve this address space limitation.

o Given the limited packet size of WBANs, the IPv6 address format allows subsuming of IEEE 802.15.6 addresses if so desired. Applications within WBANs are expected to originate small packets. Adding all layers for IP connectivity should still allow transmission in one frame, without incurring excessive fragmentation and reassembly. Furthermore, protocols must be

designed or chosen so that the individual "control/protocol packets" fit within a single 802.15.6 frame. Along these lines, IPv6's requirement of sub-IP reassembly may pose challenges for low-end WBANs healthcare devices that do not have enough RAM or storage for a 1280-octet packet [RFC2460].

o Simple interconnectivity to other IP networks including the Internet.

o However, given the limited packet size, headers for IPv6 and layers above must be compressed whenever possible.

2. Conventions and Terminology

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Topology and Scope of Communication

This is a standard for short-range, wireless communication in the vicinity of, or inside, a human body (but not limited to humans). It uses existing industrial scientific medical (ISM) bands as well as frequency bands approved by national medical and/or regulatory authorities. Support for quality of service (QoS), extremely low power, and data rates from 10Kbps to 10 Mbps is required while simultaneously complying with strict non-interference guidelines where needed. Table 1 shows a comparison of WBAN and other available technologies in terms of data rate and power consumption.

Standard	Provided data rate	Power requirement	Battery lifetime
802.11 ac (WiFi)	700 Mbps	100 mW - 1000 mW	Hours - days
Bluetooth	1Mbps - 10 Mbps	4 mW - 100 mW	Days - weeks
Wibree	600 Kbps maximum	2 mW - 10 mW	Weeks - months
ZigBee	250 Kbps	3 mW - 10 mW	Weeks - months
802.15.4	250 Kbps maximum	3 mW - 10 mW	Weeks - months
802.15.6	1Kbps - 10 Mbps	0.1 mW - 2 mW	Months - years

Table 1: Comparison of WBAN

Data rates, typically up to 10Mbps, can be offered to satisfy an evolutionary set of entertainment and healthcare services. Current personal area networks (PANs) do not meet the medical (proximity to human tissue) and relevant communication regulations for some application environments. They also do not support the combination of reliability, QoS, low power, data rate, and non-interference required to broadly address the breadth of body area network (BAN) applications.

The IEEE 802.15.6 working group has considered WBANs to operate in either a one-hop or two-hop star topology with the node in the centre of the star being placed on a location like a waist. Two feasible types of data transmission exist in the one-hop star topology: transmission from the device to the coordinator and transmission from the coordinator to the device. The communication methods that exist in the star topology are beacon mode and non-beacon mode. In a two-hop start WBAN, a relay-capable node may be used to exchange data frames between a node and the hub.

4. Protocol Stack

The IPv6 over IEEE 802.15.6 protocol stack is presented in Figure 2. It contains six elements from bottom to top including IEEE 802.15.6 PHY layer, IEEE 802.15.6 MAC layer, Adaptation layer for IPv6 over

IEEE 802.15.6, IPv6 layer, TCP/UDP layer, and Application layer. The adaptation layer supports the mechanisms like stateless address auto-configuration, header compression and fragmentation and reassembly.

```
+----------------------------------------+
|           Application Layer            |
+----------------------------------------+
|                TCP/UDP                 |
+----------------------------------------+
|                                        |
|                 IPv6                   |
|                                        |
+----------------------------------------+
| Adaptation layer for IPv6 over 802.15.6|
+----------------------------------------+
|               MAC Layer                |
|             (IEEE 802.15.6)            |
```

```
                  +----------------------------------------+
                  |               PHY Layer                |
                  |            (IEEE 802.15.6)             |
                  +----------------------------------------+
```

Figure 2: Protocol stack for IPv6 over IEEE 802.15.4

5. Maximum Transmission Unit (MTU)

The IPv6 packets have the MTU of 1280 octects and its expects from every link layer to send data by following this MTU or greater. Thus maximum Transmission Unit (MTU) of MAC layer describes the implementation of fragmentation and reassembly mechanism for the adaption IPv6 layer over IEEE 802.15.6.

The IEEE 802.15.6 has the MTU of 256 octects, if we consider the link layer security overhead (16 octects for AES-128) leaves 240 octects which is not sufficient to complete an IPv6 packet. Therefore, an adaption layer below IP layer is required to manage fragmentation and reassembly issues.

6. Specification of IPv6 over WBAN

Due to stringent QoS requirements in WBAN, a 6lo adaption layer is needed to support the transmission of IPv6 packets.6 LoWPAN standards [RFC4944], [RFC6775] and [RFC6282] provides useful information including link-local IPv6 address, stateless address auto-configuration, unicast and multicast address mapping, header compression and fragmentation and reassembly. These standards are referred in the specifications of 6lo adaptation layer which is illustrated in the following subsections:

6.1. Stateless Address Autoconfiguration

An IEEE 802.15.6 device performs stateless address autoconfiguration to obtain an IPv6 Interface Identifier(IID). The IPv6 EUI-64 format address is obtained through the EUI-48 bit MAC address of IEEE 802.15.6 node. The 64-bit IID SHALL be derived by utilizing 8-bit node address and 8-bit BAN ID (part of MAC header) as follows:

ID: 0xYY00:00FF:FE00:00XX

Where YY is the BAN ID, XX is the node address. As this generated IID is not globally unique, the "Universal/Local" (U/L) bit (7th bit) SHALL be set to zero.

6.2. IPv6 Link-Local Address

The IPv6 link-local address [RFC4291] for an IEEE 802.15.6 interface is generated by appending the interface identifier to the prefix FE80::/64.

```
    10 bits          54 bits                    64 bits
      +----------+-----------------------+----------------------------+
      |1111111010|        (zeros)        |    Interface Identifier    |
      +----------+-----------------------+----------------------------+
```

Figure 3: IPv6 Link-Local Address in IEEE 802.15.6

6.3. Unicast and Multicast Address Mapping

The address resolution procedure for mapping IPv6 unicast addresses into IEEE 802.15.6 link-layer addresses follows the general description in section 7.2 of [RFC4861], unless otherwise specified. Multicast address mapping is not supported in IEEE 802.15.6.

6.4. Header Compression

The IEEE 802.15.6 PHY layer supports a maximum PSDU (PHY Service Data Unit) of 256 octets. Because of the limited PHY payload, header compression at 6lo adaptation layer is of great importance and MUST be applied. The compression of IPv6 datagrams within IEEE 802.15.6 frames refers to [RFC6282], which updates [RFC4944].Multiple headers compression stacks are defined in RFC6282 which specifies the fragmentation methods for IPv6 datagrams on top of IEEE 802.15.4;however, for IEEE 802.15.6, a LoWPAN encapsulated LoWPAN_HC1 the compressed IPv6 datagram can be used as IEEE 802.15.6 does not require mesh header due to IEEE 802.15.6 communication scope. Moreover, static header compression techniques of [RFC7400] can also, be used as header compression.

6.5. Fragmentation and Reassembly

IEEE 802.15.6 provides Fragmentation and reassembly (FAR) for a payload of 256 bytes. FAR as defined in [RFC4944], which specifies the fragmentation methods for IPv6 datagrams on top of IEEE 802.15.4 MUST be adapted to work with IEEE 802.15.6. All headers MUST be compressed according to [RFC4944] encoding formats, but the default MTU of IEEE 802.15.6 is 256 bytes which MUST be considered.

7. IANA Considerations

[TBD]

8. Security and Privacy Considerations

IPv6 over WBAN's applications often require confidentiality and integrity protection. This can be provided at the application, transport, network, and/or at the link. IEEE 802.15.6 considers the security as a key requirement for healthcare applications and defines a complete framework. This framework defines three levels of security which can be used according to requirements. Overall, it covers privacy, confidentiality, encryption, and authentication.AES-64 is preferred for encryption due to its efficiency.

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Appendix A. Patient monitoring use case - Spoke Hub

Refer the following diagram:


```
                            ########
                          # @ EEG    #
                        ##   |      @ # Hearing
                        #    |      | #
                         #   |      |#
                          #  |     #|
                    #####    |      |## ###
                 #           |      |   @   ## Motion Sensor
     Positioning#  @         |      /  /     #
               #    \        |ECG /  /       #
               #     \       |  @ | /         #
              #         \    | / / /           #
             #      ##    \   |/ //      ##       #
             #      ##     \  ||//       ##       #
            #      # #     \ ||||      # #  @    # BP
           #       # #      \||||      # # /     ##
           #      ## #       ||||      # #/       ##
      SPO2# @     ##  #   Coordinator   # /##      #
         #   \  ##  ##        +-+        /  ##      ##
        #     ------+--------| |-------/ #   #      #
     ##      ##      #        +-+        ##     #    ##
   ##      ##      #         //\         #       #      ##
###       #        #        //  \        #       ##         ###
  ##      #        #       //    \       #       #      ## ##
  #      #        #       //      \      #        #      #
 ###   # #        #      //  ##    \     #        #     ###
   #  ###         #     //   # #     \    #         # #  ###
   ###            #    //   # #     |    #          # ###
                  #   //     # ##    |    #
   Glucose Sensor # @ /     #  #    |   #
                  ##  |     ##  #    |   #
                   # /      #   #    |   #
                   #/     #      #  |   #
               Emg#@      #      #  |   #
                  #      #         ## |   #
                  ##              # |   #
                   #    #         # |   #
                   #    #          #\   #
                  #     #          # |   #
                  #     #          # @   # Motion Sensor
                   ##  #            ## ##
                     ##               #
```

Figure 4: Patient monitoring use case - Spoke Hub

Appendix B. Patient monitoring use case - Connected

Refer following diagram:

```
                                 ########
                              #   @ EEG    #
                             ##   |\-----@ # Hearing
                             #     |      \#
                               #   |     # |
                               #    |   ##  |Motion Sensor
                       #######      |     ##|####
                      #              |       |   ##
          Positioning#   @            |      @    #
                    #    /\        ECG|       \   #
                    #   /  \----------@        \   #
                   #   /                        |  #
                  #  /   ##                 ##   |  #
                 # /    # #                 # #  @   # BP
                #/     ## #                 # ##  |   ##
           SPO2# @    ##  #                 #  ## |    #
             #    \ #    #                   #   #|     #
          ##     ## \    #                   ##   | #    ##
       ##      #      \ #                     #  |    #      ## ##
      ###   # #        # \        ##          #  |     #     ###
        #  ###         #   \      # #          # |       # #  ###
        ###            #   |     # #          # |        # ###
                       #   |     # ##         # |
        Glucose Sensor #   @     #  #        #  |
                        # /     #    #       # /
                        #|    ##      #      #/
                        #/     #      #      #|
                    Emg#@      #      #      #|
                       #  \    #      #      #|
                       #    \  #      #      #|
                       #     \#       ##     #|
                       ##     \        #     #|
                        #     #\       #     #|
                        #    #  \      #     #|
                        #    #    \    #     #|
                        #    #     \   ##    #/
                        #    #       \ ##    /
                        #    #        \ ##  /#
                       ##    #          \  |  #
                       #     #          # \/  #
                        #    #           # @ # Motion Sensor
```

#

Figure 5: Patient monitoring use case - Connected

Appendix C. Changes

Compared with version-00, this updated draft is no longer all informative. Two main changes have been made as below:

1. Introduction part of 802.15.6 is simplified and more focused on the features that relate to the 6lo-WBAN adaptation layer, e.g. MAC frame format including MAC address and MTU, topology and the scope of communication, and why the 6lo-WBAN adaptation layer is needed.

2. The 6lo-WBAN adaptation layer is specified in this draft titled as "Specification of IPv6 over WBAN" that lists the main features needs to be added in the 6lo adaptation layer including the formation of IID, IPv6 link-local address, unicast address mapping, header compression, and fragmentation and reassembly. These parts have never been mentioned in other documents related to WBAN, and in this version, we provide a guidance for such IPv6 enabled WBAN implementations.

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