

**Reliable and Energy Efficient Scheduling
Protocols for Wireless Body Area Networks
(WBAN)**

Marwa K. S. Salayma

A thesis submitted in partial fulfilment of the requirements of Edinburgh
Napier University, for the award of Doctor of Philosophy

September, 2018

“Wireless Body Area Network, where communication can mean life or death...”

— Marwa Salayma

“If you want to find the secrets of the universe, think in terms of energy, frequency and vibration.”

— Nikola Tesla

“I speak two languages, Body and English.”

— Mae West

“Somewhere in me is a curiosity sensor. I want to know what's over the next hill. You know, people can live longer without food than without information. Without information, you'd go crazy.”

— Arthur C. Clarke

“Life is like riding a bicycle. To keep your balance, you must keep moving.”

— Albert Einstein

To my beloved parents Khalil and Sahar Salayma.

To my beloved sisters Meera, Maram, Enas, Lama, Dana and Zaina.

For their endless love, encouragement and support.

ACKNOWLEDGMENT

Doing the PhD research has been a precious and overwhelming experience. Actually, it has been grappling with both working on the thesis topic itself and writing research papers, presenting talks, participating in international conferences, working in groups or independently, and staying up until the birds start singing. In all cases, I am indebted to all those who made my PhD an unforgettable experience.

Above all else, I would like to thank the one above all of us, the omnipresent God, for answering my prayers and for giving me the strength to plod on despite my constitution wanting to give up and throw in the towel, thank you so much Dear Allah.

This PhD research has been very successful; it yielded several highly prestigious research publications with very good reviews. Those achievements would not have been yielded without the guidance of my director of studies **Prof. Ahmed Al-Dubai**. You have been a steady influence throughout my PhD studies; and have always been patient and encouraging in times of difficulties; you have listened to my ideas and discussions; your technical depth, your ability to select and to approach compelling research problems, and your scientific work inspired me a lot.

Furthermore, I am very grateful to my second supervisor **Dr. Imed Romdhani** for his insightful comments, for his support, and for many motivating discussions. Your professional experience in computer networks, your mathematical understanding and your scientific standards are impressive and many of the achieved results would not have been possible without you. Discussions with you frequently led to key insights and many new research directions.

In addition, I have been very privileged to be guided by my panel chair **Prof Jessie Kennedy**. I learned a lot from you about life and about research, how to tackle new problems and how to develop techniques to solve them. Your attention to detail added a lot to my research, and my work has greatly benefited from your suggestions. You have

been a faithful Panel chair, and reviewer. I admire your ability to balance research interests and personal pursuits.

During my four years of research, I had the pleasure to meet and work with a number of great people who became friends over the four years. In particular, I had the great pleasure of meeting **Dr. Sally Smith**, whose generous support has significantly improved my work and boosted my confidence. Your kind encouragement and motivation supported me a lot. You made me feel as if I were amongst my family. Truly, I was very lucky to meet you and you are my academic role model.

Special thanks to **Dr. Tom Kane, Angus Mackenzie, and June Rapson**. All of you have been an invaluable support day in, day out, during the four years. You have oriented and supported me with promptness and care. Indeed, this thesis would not have been achieved without you all by my side. Your hard work sets an example, and I have greatly enjoyed the opportunity to learn from you and work with you. Above all, you made me feel a friend, which I appreciate from all my heart.

I am also indebted **my friends and to the fellow colleagues in the School of Computing at Edinburgh Napier University** for their assistance and companionships. Working with you has been a real pleasure to me, with heaps of excitement. The fun and the encouraging discussions with you all helped me tremendously.

The School of Computing at Edinburgh Napier University financially (ENU) supported my PhD studies. Hence, I would like to thank ENU for providing resources and funding for my studies throughout my PhD journey.

The very special thanks and my deepest gratitude are to **my parents and my sisters**, who have been extremely understanding and supportive throughout my studies. Thank you for your patience and encouragement for the whole four years. I feel very lucky to have a family that shares my enthusiasm for academic pursuits.

Thanks to all with all my heart!

Marwa Salayma

DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

TABLE OF CONTENTS

ACKNOWLEDGMENT	i
DECLARATION	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	vii
LIST OF TABLES	ix
LIST OF ABBREVIATIONS AND NOTATIONS	x
ABSTRACT	xiv
Chapter 1: Introduction	1
1.1 Introduction	1
1.2 Significance of this research	4
1.3 Thesis statement	8
1.4 Research questions	10
1.5 Research aim and objectives	10
1.6 Thesis contributions	11
1.7 Peer-reviewed publications during the study	12
1.8 Thesis organisation	14
Chapter 2: Literature Review	16
2.1 Introduction	16
2.2 Wireless Sensor Networks (WSN)	17
2.2.1 Wireless Personal Area Network (WPAN)	18
2.2.2 IEEE 802.15.4 standard	19
2.3 Wireless Body Area Networks (WBAN)	22
2.3.1 Characteristics of WBAN	25
2.3.2 Applications of WBAN	28
2.3.3 WBAN communication standards	32
2.3.4 Challenges of WBAN	37
2.4 MAC Protocols for WBAN	44
2.4.1 Static TDMA based MAC scheduling	46
2.4.2 Dynamic TDMA based MAC scheduling	47

2.5	Conclusions	51
Chapter 3:	The Reliable and Energy Efficient Scheduling Algorithms	54
3.1	Introduction	54
3.2	Adaptive Sleep TDMA MAC	55
3.3	Dynamic Scheduling Based on Sleeping Slots (DSBS) MAC	57
3.4	Dynamic Scheduling Based on Buffer (DSBB) MAC	61
3.5	Conclusions	64
Chapter 4:	Validation Methodology	65
4.1	Introduction	65
4.2	Simulation environment	66
4.2.1	Topology and simulation parameters	67
4.2.2	Performance metrics	69
4.3	Performance evaluation in normal situations	70
4.3.1	Scenario 1: The impact of traffic rate	71
4.3.2	Scenario 2: Changing the slot size	75
4.4	Conclusions	79
Chapter 5:	WBAN in Emergency Situations	80
5.1	Introduction	80
5.2	Emergency in WBAN communication	81
5.3	Emergency detection	81
5.4	Emergency in simulation experiments	82
5.4.1	Results of 3.75 ms slot length	84
5.4.2	Results of 1.875 ms slot length	87
5.4.3	Results of 7.5 ms slot length	91
5.5	Conclusions	94
Chapter 6:	A Context-Aware Communication	96
6.1	Introduction	96
6.2	Dynamic Scheduling Based on Context (DSBC) MAC	97
6.3	Simulation setup and evaluation methodology	102
6.3.1	Packets loss rate	102
6.3.2	Latency	104
6.3.3	Energy consumption	108

6.4	Conclusions	110
Chapter 7:	Conclusions and Future Directions	112
7.1	Summary of the work done	112
7.2	Challenging issues and future work	114
	7.2.1 Solutions for the challenging issues	116
	7.2.2 Suggested potential research areas	117
	Bibliography	120
	Appendix: A Typical WBAN Sensor and Wearable Devices	130

LIST OF FIGURES

Figure 2-1: IEEE802.15.4 MAC superframe structure [33].	21
Figure 2-2: Statistics of population aging in developed countries [39].	23
Figure 2-3: Typical WBAN.	24
Figure 2-4: IEEE802.15.6 beacon mode superframe structure.	34
Figure 2-5: WBAN interference [6].	41
Figure 3-1: Adaptive Sleep TDMA MAC.	56
Figure 3-2: Dynamic Scheduling Based on Sleep Slots (DSBS).	60
Figure 3-3: Dynamic Scheduling Based on Buffer information (DSBB).	63
Figure 4-1: The proposed star topology scenario [11].	67
Figure 4-2: Packets loss rate in a normal situation with an increasing CBR(s).	72
Figure 4-3: Latency in a normal situation with an increasing CBR(s).	73
Figure 4-4: Rate of packets received with a delay over 250 ms in a normal situation.	74
Figure 4-5: Total energy consumption for nodes with an increasing CBR(s).	75
Figure 4-6: Packets loss rate for different slot sizes.	76
Figure 4-7: Latency in a normal situation using various slot sizes.	77
Figure 4-8: Rate of packets received with a delay over 250 ms in a normal situation.	78
Figure 4-9: Total energy consumption in a normal situation using various slot sizes.	79
Figure 5-1: Packets loss rate in an emergency for 3.75 ms slot size.	84
Figure 5-2: Latency for nodes in an emergency with 3.75 ms slot size.	85
Figure 5-3: Rate of packets received with a delay over 125 ms for 3.75 ms slot size.	86
Figure 5-4: Total energy consumption for 3.75 ms slot size.	87
Figure 5-5: Packets loss rate in an emergency for 1.875 ms slot size.	88
Figure 5-6: Latency in an emergency for 1.875 ms slot size.	89
Figure 5-7: Rate of packets received with a delay over 125 ms.	89
Figure 5-8: Total energy consumption for 1.875 ms slot size.	90
Figure 5-9: Packets loss rate in an emergency for 7.5 ms slot size.	91
Figure 5-10: Latency in an emergency for 7.5 ms slot size.	92
Figure 5-11: Rate of packets received with a delay over 125 ms for 7.5 ms slot size.	92
Figure 5-12: Total energy consumption for 7.5 ms slot size.	93
Figure 6-1: Dynamic Scheduling Based on Context (DSBC).	101

Figure 6-2: Packets loss rate for nodes in emergencies using 1.875 ms slot size.	103
Figure 6-3: Packets loss rate for nodes in emergencies using 3.75 ms slot size.	104
Figure 6-4: Packets loss rate for nodes in emergencies using 7.5 ms slot size.	104
Figure 6-5: Latency for nodes in emergencies using 1.875 ms slot size.	105
Figure 6-6: Latency for nodes in emergencies using 3.75 ms slot size.	105
Figure 6-7: Latency for nodes in emergencies using 7.5 ms slot size.	106
Figure 6-8: Rate of packets with a delay over 125 ms using 1.875 ms slot size.	107
Figure 6-9: Rate of packets with a delay over 125 ms using 3.75 ms slot size.	107
Figure 6-10: Rate of packets with a delay over 125 ms using 7.5 ms slot size.	107
Figure 6-11: Total energy consumption in emergencies using 1.875 ms slot size.	108
Figure 6-12: Total energy consumption in emergencies using 3.75 ms slot size.	109
Figure 6-13: Total energy consumption in emergencies using 7.5 ms slot size.	110
Figure A-1: A typical WBAN sensor device [78].	130
Figure A-2: Wireless ECG patch, developed at Holst Centre/Imec [79].	131
Figure A-3: ECG sensor developed by Technische Universitaet Berlin [80].	132
Figure A-4: Wireless pulse oximeter developed by CodeBlue [81].	132
Figure A-5: Sensor node of pulse oximeter worn on wrist and finger print [82].	133
Figure A-6: Dual pulse oximeter developed by Technische Universitaet Berlin [80].	134
Figure A-7: EDA developed by Technische Universitaet Berlin [80].	134

LIST OF TABLES

Table 2-1: WBAN devices.	26
Table 2-2: Fields and applications of WBAN.	29
Table 2-3: A comparison between wireless standards that support WBAN.	36
Table 2-4: Heterogeneous requirements for some WBAN applications [47].	44
Table 4-1: Simulation parameters.	68
Table 5-1: Classification of the links' status of the nodes.	83
Table 5-2: Scenarios of the nodes in an emergency.	83

LIST OF ABBREVIATIONS AND NOTATIONS

<u>Abbreviation</u>	<u>Description</u>
aBaseslotDuration	Number of Symbols Comprising a Superframe Slot of Order 0
aBaseSuperframeDuration	Number of Symbols Comprising a Superframe of Order 0
APs	Access Points
aUnitBackoffPeriod	Length of One Backoff Period in Symbols
BCU	Body Control Unit
BER	Bit Error Rate
BI	Beacon Interval
BLE	Bluetooth Low Energy
BO	Beacon Order
BR	Basic Rate
BS	Base Station
C	Capacity of each time slot to hold packets
CA-MAC	Context Aware Medium Access Control
CAP	Contention Access Period
CBR	Constant Bit Rate
CFP	Contention Free Period
CRL	Controller
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
D	Duty Cycle
DSBB	Dynamic Scheduling Based on Buffer
DSBS	Dynamic Scheduling Based on Sleeping Slots
EAP	Exclusive Access Phase
EAP1	Exclusive Access Phase 1
EAP2	Exclusive Access Phase 2
ECG	ElectroCardioGraph
EDR	Enhanced Data Rate
EEG	ElectroEncephaloGraph

E	Extra number of slots the node will acquire in the next TDMA round
E_{idle}	Energy Consumed by a Sensor in Idle Listening
ETDMA	Emergency Time Division Multiple Access
EMG	ElectroMyoGraph
E_{rx}	Energy Consumed in by a Sensor in Receiving a Packet
E_{sleep}	Energy Consumed in by a Sensor in Sleeping
E_{total}	Total Energy Consumption
E_{tx}	Energy Consumed in by a Sensor in Transmitting a Packet
FCC	Federal Communications Commission
FFDs	Full Functional Devices
GHz	Frequency Unit in Gigahertz
GTS	Guaranteed Time Slot
HBC	Human Body Communication
HR	Heart Rate
ID	Identifier
IEEE	Institute of Electrical and Electronic Engineers
IEEE TG4	Institute of Electrical and Electronic Engineers Task Group 4
IEEE TG4j	Institute of Electrical and Electronic Engineers Task Group 4j
IEEE TG6	Institute of Electrical and Electronic Engineers Task Group 6
ISM	Industrial, Scientific and Medical
Kbps	Data Rate Measure in Kilobits Per Second
L	Length of a time slot
LE	Low Energy
m	Distance Length in Metre
MAC	Medium Access Control
MAP	Managed Access Period
Mbps	Data Rate Measure in Megabits Per Second
MBANs	Medical Body Area Networks

MHz	Frequency Unit in Megahertz
MICS	Medical Implant Communication Service
ms	Time Unit in millisecond
mWh	Power Unit in Milliwatt
n	Total Number of TDMA Slots
nJ	Energy consumption unit in Nanojoule
N	Total Number of Nodes in the Network
N_i	Individual Node in the Network
N_r	Number of Remaining Nodes which had a Good Link Status in the Previous TDMA Round
NB	Narrow Band
NTDMA	Normal TDMA
PAN	Personal Area Network
PANc	Personal Area Network Coordinator
PD	Personal Device
PDA	Personal Digital Assistant
PS	Personal Server
p/s	Packets Per Second
QoS	Quality of Service
R	Traffic Rate (CBR) in Normal Situation
RAP1	Random Access Phase 1
RAP2	Random Access Phase 2
RF	Radio Frequency
RFDs	Reduced Functional Devices
S	Original Number of Slots each Node Acquires Once the Network is Established
S_i	Total Number of Time Slots Allocated to Node N _i
s	Time Unit in Second
SAR	Specific Absorption Rate
SD	Superframe Duration
slotsMinValue	Slots Minimum Value
SMS	Short Message Service
SO	Superframe Order

SpO₂	Pulse Oximeter
T	Definition 4 in Section 4.4: The T ime Each Packet Takes From the Moment it is Transmitted until the Node Receives Acknowledgment Frame
T_i	Definition 2 in Section 4.3: The Node's (N _i) Total Channel Access T ime
T	Section 6.4: The Packets Inter-arrival T ime
t_i	T ime Recorded by the Timer for the Sleeping Node (N _i)
TDMA	T ime D ivision M ultiple A ccess
UWB	U ltra W ide B and
WBAN	W ireless B ody A rea N etwork
WLAN	W ireless L ocal A rea N etwork
WPAN	W ireless P ersonal A rea N etwork
WSN	W ireless S ensor N etwork
x	Number of Packets in the Node's Buffer
λ	Traffic Rate (Poisson Traffic) in Emergencies

ABSTRACT

Wireless Body Area Network (WBAN) facilitates efficient and cost-effective e-health care and well-being applications. The WBAN has unique challenges and features compared to other Wireless Sensor Networks (WSN). In addition to battery power consumption, the vulnerability and the unpredicted channel behavior of the Medium Access Control (MAC) layer make channel access a serious problem.

MAC protocols based on Time Division Multiple Access (TDMA) can improve the reliability and efficiency of WBAN. However, conventional static TDMA techniques adopted by IEEE 802.15.4 and IEEE 802.15.6 do not sufficiently consider the channel status or the buffer requirements of the nodes within heterogeneous contexts. Although there are some solutions that have been proposed to alleviate the effect of the deep fade in WBAN channel by adopting dynamic slot allocation, these solutions still suffer from some reliability and energy efficiency issues and they do not avoid channel deep fading.

This thesis presents novel and generic TDMA based techniques to improve WBAN reliability and energy efficiency. The proposed techniques synchronise nodes adaptively whilst tackling their channel and buffer status in normal and emergency contexts. Extensive simulation experiments using various traffic rates and time slot lengths demonstrate that the proposed techniques improve the reliability and the energy efficiency compared to the de-facto standards of WBAN, i.e. the IEEE 802.15.4 and the IEEE 802.15.6. In normal situations, the proposed techniques reduce packet loss up to 61% and 68% compared to the IEEE 802.15.4 and IEEE 802.15.6 respectively. They also reduce energy consumption up to 7.3%. In emergencies, however, the proposed

techniques reduce packets loss up to 63.4% and 90% with respect to their counterparts in IEEE 802.15.4 and 802.15.6. The achieved results confirm the significant enhancements made by the developed scheduling techniques to promote the reliability and energy efficiency of WBAN, opening up promising doors towards new horizons and applications.

Chapter 1: Introduction

1.1 Introduction

Wireless Sensor Network (WSN) has revolutionised our daily lives as it pervades most technological applications such as controlling, tracking, monitoring and automation. The communication range of wireless sensor applications varies between tenths of metres to thousands of kilometres and is able to cover continents [1, 2]. The exigency of WSN has been the foundation for developing interconnected and identified devices. Those devices can communicate with each other as well as with the Internet, leading to the paradigm of what is called the Internet of Things (IoT). IoT enables direct access to the surrounding environment, which boosts the productivity and efficiency [3]. It was not long before the IoT revolution shifted its direction to a technology that suited human mobility by devising a technology that can be wearable or even implanted in the human body [4]. This technology has been a key element in e-health to monitor bodies, and enables new applications under the umbrella of different domains, including the medical field, the entertainment and ambient intelligence areas [5, 6, 7, 8, 9, 10]. In essence, this technology is anticipated to provide a breakthrough in the IoT applications, by providing exceptional solutions for taking care of the aging population [4]. This technology forms a special type of WSN, namely, the *Wireless Body Area Network (WBAN)*.

WBAN is usually a small network composed of low-power and low-processing sensors that capture body physiological information and send it wirelessly to a central base station. An example of a typical WBAN sensor along with examples of WBAN physiological sensor devices are provided in the Appendix. WBAN replaces complex and wired healthcare equipment to perform continuous monitoring of vital information without limiting users movements [5, 6, 7, 8, 9, 10]. Nevertheless, the unreliability related problems of this type of network might lead to life-threatening situations. Given that sensors are battery powered and resource-constrained devices, energy depletion can be a serious problem to overcome. In addition, the human body absorbs energy when it is exposed to Radio Frequency (RF) electromagnetic fields leading to a weak signal. In

wireless communications, the reduction in the received signal strength is called signal attenuation [11]. Transmission paths are also affected by the uncontrolled, dynamic nature of the human body movement, because it causes frequent changes in the network topology, which deteriorates the stability of the transmission links, and leads to continuous large attenuation in the transmitted signal. Severe attenuation in the signal pushes the signal below the receiver sensitivity, which is called deep fade in the signal [11, 12]. The dynamic vulnerable medium around the human body causes not only deep fading issue, but also long disconnectivity and the unreachability of the sensor node from the main network [11, 12, 13]. According to an empirical study presented in [11] and conducted on a real WBAN worn by a person doing different daily-activities, it revealed that when a deep fade occurs in the WBAN channel, it lasts for at least 10 ms. However, if nodes are allowed to operate in a timely, scheduled manner, following contention free channel access, such as a Time Division Multiple Access (TDMA) approach, the fading becomes the primary source of unreliability. TDMA based channel access helps in both channel status prediction and energy saving because the scheduled duty cycles at the nodes avoid idle listening and overhearing.

The IEEE 802.15.4 and IEEE 802.15.6 standards are considered as the WBAN de-facto standards. IEEE 802.15.4 supports TDMA channel access by using Guaranteed Time Slots (GTSs) in the Contention Free Period (CFP) [14], while IEEE 802.15.6 provides TDMA mechanisms through the scheduled allocation slots in the contention free access periods [15]. However, TDMA mechanisms adopted by both standards provide static slot allocation, whereby each node in the network is obligated to use the channel in its time slots whether its link encounters deep fading or not. Although there are some efforts proposed in the literature to solve this issue by adopting dynamic slot allocation and considering the channel status, the majority of proposed techniques do not avoid the deep fade when it occurs.

To solve this problem, two novel dynamic TDMA based Medium Access Control (MAC) techniques are proposed in this thesis. The proposed protocols are discussed in three published works in [16, 17, 18]. The first technique is called Dynamic Scheduling Based on Sleeping slots (DSBS), and the second technique is called Dynamic Scheduling Based on Buffer (DSBB). Both DSBS and DSBB avoid the deep fade in the channel by allowing the nodes to sleep dynamically whenever they detect a deep fade in their links. Avoiding

the deep fade in WBAN medium is the first major aim of this thesis. If a node sleeps during its active session when the deep fade occurs, more packets will be saved in its buffer, and hence that node requires more slots in the next TDMA round than other nodes. As a result, proposing dynamic slot allocation scheduling protocols is the second major aim of this thesis. The proposed DSBS and DSBB mainly differ in the dynamic slot allocation to be adopted by the controller of the nodes in the subsequent TDMA round. In DSBS, the controller calculates the number of slots each node has slept during its active session due to deep fade, based on which it assigns that node extra slot in the next superframe. In addition, DSBS is optimised by considering the buffer information of the nodes. The buffer information is encapsulated in the data packet sent by the node. DSBB however, follows an opposite approach, because the controller does not need to perform any calculations related to the link status of the node. Instead it only checks the number of packets in the buffer of each node. This helps to detect whether the node has slept during its active session due to deep fade or not. Accordingly, in both DSBS and DSBB, nodes with more packets in their buffer get extra slots in the subsequent TDMA schedule.

The proposed scheduling techniques are evaluated within the heterogeneous contexts that might occur in WBAN, and their performance is evaluated against the performance of WBAN de-facto standards, i.e. the IEEE 802.15.4 and the IEEE 802.15.6. In essence, this work addresses how further packets loss and energy consumption are decreased in both the normal situations as well as emergencies, while offering all nodes the chance to use the medium regardless of the context. Accessing the medium is only dependent on the nodes' link and buffer status. This is the third major aim of this thesis, and experimental results revealed that the proposed techniques proved to have potential in improving WBAN reliability and energy efficiency in both normal and emergency situations. The proposed protocols are generic TDMA based MAC approaches, which can be applied without the need of substantial amendments on any technology, protocol or standard that adopts the TDMA based MAC mechanism.

This chapter introduced the main topic of this thesis. Next, it explains the reasons for choosing the area of WBAN as the topic of this thesis in general and the reliability in the WBAN medium in particular, and highlights the barriers to achieving a reliable and energy efficient WBAN. The third section details precisely the challenge that the research will address '*Reliable and Energy Efficient scheduling for Wireless Body Area Networks*',

thus reinforcing its novel contribution. Accordingly, the main research aim emerged after identifying the thesis problem, along with the objectives to achieve this aim are outlined in the fourth section. The fifth section summarises the thesis contributions, which is followed by a list of peer-reviewed publications for the thesis achievements, and which are presented in the sixth section. Finally, the structure of the thesis is provided in the seventh section.

1.2 Significance of this research

Developed countries, such as the United Kingdom, are characterised by an increased aging population. This adds a pressure on hospitals and the healthcare systems, which is accompanied by a massive increase in healthcare costs [5, 6]. Therefore, there is a need for an affordable technology that enables online monitoring and which harnesses the cheap existing technologies. Such technology should be proactive by adopting RF wireless communications and sensor devices. This provided the motivation for the evolution of WBAN technology [5, 6]. WBAN comprises a number of heterogeneous micro-electro-mechanical systems that send physiological information via Wireless Local Area Network (WLAN) to a medical centre (Appendix). WBAN has been a key element in e-health to monitor bodies as it enables online monitoring without limiting the human movements. Adopting WBAN not only reduces the overload on hospitals as well as healthcare costs, but also improves life expectancy, because it enables early detection of chronic diseases [5, 6]. This technology allows new applications under the umbrella of different domains, including the medical field, the entertainment and ambient intelligence areas [5, 6]. Although WBAN provides a solution for the reactive and unaffordable current healthcare systems, it suffers from several critical challenges, such as reliability and power consumption. Due to its timeliness, the criticality of its applications as well as its challenging issues, WBAN is chosen as the topic of this thesis.

- Reliability and deep fading in WBAN

Two components of a sensing device, the wireless transceiver and a sensing unit, normally interact directly with the environment, which is prone to various physiological, chemical, and physical defects [19]. Even if the hardware is of a good status, the communication between sensor devices can be influenced by several factors, e.g. interference, obstacles, weather conditions and signal strength [19]. Additionally, the human body absorbs signal

energy when it is exposed RF electromagnetic; this energy absorption adversely affects the propagation paths [7]. Transmission paths are also affected by reflection, diffraction, and the shadowing that occurs because of rapid body movement, body structure and posture. Body motion also causes a frequent change in network topology [20]. Those factors break the communication path between the sensor devices and their controller, leading to links failure. These conditions adversely affect the reliability and performance of WBAN, which is characterised by the criticality of the data the nodes should sense. Some of the data might be critical to human life; thus, any loss of data could be fatal. Nevertheless, WBAN will not be sufficiently adopted unless it proves its reliability, especially in emergency situations. An emergency in WBAN is an abnormal monitoring context, which is decided by diagnoses performed by the controller through data processing, and predefined by doctors. An example of emergency in WBAN is when a patient under monitoring falls down, which leads to an increase in their heart rate (more than 200 hard rate).

To meet the aim of achieving a reliable healthcare system, the reliability and Quality of Service (QoS) of WBAN ought to be preserved within a desirable percentage while maintaining maximum transmission power below a required level [21]. Due to its criticality, reliability is chosen as the major challenge that this thesis aims to tackle.

WBAN reliability faces different and unique challenges compared to other wireless networks. For example, the probability of link failures occurring in WBAN medium is higher than in WSN. Link failure weakens the signal, and in wireless systems the reduction in the received signal strength is called signal attenuation. Due to the uncontrolled and frequent body movements, WBAN is prone to continuous and large attenuation in the signal, which eventually falls below receiver sensitivity and therefore, the signal may not be received at all. This phenomenon is called the deep fade and it is one of the primary reasons that degrades WBAN reliability [11, 12, 13]. Although fading occurs in all wireless communication networks, it is more problematic in WBAN, due to its unpredictability, its frequent occurrences, and its long duration. Deep fade is the main reason for the severe packets loss in WBAN medium, and it is noted that packets retransmission is no longer a solution for WBAN. This is because if deep fade occurs, it persists for at least 10 ms, hence, performing packets re-transmission is useless, which is also at the expense of the energy consumption [11, 12, 13]. Ongoing research efforts are

focused on various technical issues in WBAN, such as lowering power consumption, the design of tiny sensor devices to be inserted in, on, and around the human body, the design of an optimal network topology to achieve the highest network performance, proposing portable and convenient communication protocols, coexistence with other network technologies, infrastructure, the heterogeneous applications of WBAN and so forth [6, 8, 9, 10, 22]. Nevertheless, few have addressed the anomalous behaviour of WBAN medium due to the deep fade phenomena. For those reasons, deep fade is chosen as the main gap that this thesis aims to tackle so to achieve a reliable WBAN.

- **Constrained resources (battery and buffer)**

Any proposed solution to achieve a reliable WBAN should be energy efficient. This is because WBAN sensors are tiny resource constrained devices (Appendix) that are battery powered with small batteries, which makes energy depletion a serious problem. For example, some sensor such as the pacemaker should operate for at least five years [8]. Therefore, any solution to mitigate the effect of deep fade in WBAN medium ought to be energy efficient. Another example of a constrained resource in WBAN devices is the nodes' buffer [11]. The size of the buffer is limited, and when it gets overloaded with data packets, this increases packets loss, and hence reduces WBAN reliability. Therefore, not only the limited power consumption should be considered, but also the size limited packets storage resources.

- **Heterogeneity of devices, contexts and applications**

Medical sensors might be introduced under various situations; such as normal situations and emergency situations. Emergency is a variation in the behavior of the current context in a way that could lead to life threatening situations. Emergency could occur when a patient with a life threatening disease suddenly falls down, or his ambient environment encountered an unpredictable extreme high or low temperature, pressure, oxygenation, humidity, and so on. For example: temperature readings might be higher or lower than the average normal temperature, which could be life, threatening. Consequently, WBAN has two levels of variation in the reliability requirements of its sensors: amongst heterogeneous sensors and within the same sensor, as it might run in different situations [5, 23]. Therefore, in addition to energy efficiency, any proposed solution to alleviate the

effect of deep fade in WBAN should prove its resilience within the heterogeneous contexts that might occur in WBAN.

- **The Medium Access Control (MAC) layer**

Unlike WSN, WBAN is considered a short range wireless network, due to its short area communication space and the limitations on the number of nodes where there is no need for multi hopping; thus, WBAN often follows a star topology [13]. At the same time, this very short range network suffers from a very vulnerable medium. Nevertheless, sensors are ought to send their data packets successfully especially in the context of an emergency. For these reasons, the majority - if not all- the WBAN challenges are confined with the reliability of the MAC layer. Therefore, the proposed solution of this thesis is targeted towards the MAC layer of the software layer stack.

- **Why TDMA based MAC?**

Usually, any MAC protocol follows one of three approaches, either contention based access, contention free access or hybrid access of both. In fact, contention based techniques are not recommended for WBAN channel access. This is because a contention based MAC leads to collision, which is very severe in WBAN medical applications, due to the correlation in the physiological data [24]. For example, in an emergency, a group of sensors might be involved in transmission, leading to a collision and consequently packet loss even if every component of WBAN is working properly, which could be fatal. Not only contention based access causes packets loss, but also dissipates energy due to packets re-transmission, idle listening and overhearing. Contention free based MAC access, such as the TDMA based techniques are more reliable and energy efficient for WBAN, because they avoid the drawbacks of the contention based. Moreover, the traffic of medical applications in a normal situation is usually periodic, which makes TDMA approaches more suitable for WBAN than other channel mechanisms because the nodes are duty cycled in accessing the medium [24]. Besides, the major goal of this thesis is to achieve a reliable WBAN, and hence the proposed solutions in this thesis adopt a TDMA MAC based approach for WBAN channel access.

- **The problem of the traditional TDMA scheduling**

While it is true that TDMA based MAC approaches provide a reliable and energy efficient WBAN, the traditional static TDMA scheduling techniques cannot tolerate the unpredictability and the long duration of the deep fade phenomenon in WBAN. In fact, to alleviate the effect of the deep fade, the TDMA slot allocation should not be static, it should be adaptive according to the channel status. For example, sensor nodes can be prohibited from using the medium whenever the deep fade occurs, or otherwise packet loss persists and a reliable WBAN would not be achieved, which will also dissipate energy.

This discussion provided motivation to propose dynamic TDMA based MAC scheduling approaches for WBAN that tolerate the deep fade phenomenon in WBAN medium, in order to boost WBAN reliability. The solution should be energy efficient, and should prove its resilience within the heterogeneous contexts of WBAN.

1.3 Thesis statement

Due to the sensitivity of the data carried and handled by WBAN, achieving a reliable WBAN is crucial. Reliability is a very critical challenge in emergencies, because any packet loss could be fatal. One of the main reasons that degrades WBAN reliability is the channel deep fade phenomenon. The occurrence of the deep fade is frequent, unpredictable and if it occurs it lasts for a long time. Deep fade is the primary reason for an increased packets loss in WBAN. Packets' loss is followed by failed packets re-transmissions due to the long duration of the deep fade. This not only degrades WBAN reliability but also severely dissipates energy. TDMA mechanisms adopted by WBAN de-facto standards are not able to provide a reliable and energy efficient channel access for WBAN as they provide static slot allocation. Static slot allocation has two major drawbacks. First, each node in the network has to use the channel in its time slots whether its link encounters deep fading or not. Second, each node is allocated the same number of slots in each TDMA round regardless of its needs. For those reasons, if a node loses data packets during its time slots due to deep fade, performing re-transmission will be useless because the deep fade of the links, usually persists for a long period of time.

Based on the extensive literature review related to the deep fade phenomenon in WBAN, it is found that in many solutions, there is a trend to adopt dynamic slot allocation mechanisms to tolerate the deep fade phenomenon. Those efforts vary between re-ordering the nodes in the schedule when the deep fade occurs [25, 26, 27], delaying the channel access when the deep fade is detected [27, 28], and even consider hybrid channel access so to distribute the effect of the deep fade between sensors [28, 29]. However, none of those techniques consider the unpredictability and the frequent occurrences of the deep fade in WBAN medium, and avoid its effect accordingly. Moreover, current TDMA approaches do not justify the distribution, and the length of the TDMA time slots, especially in normal situations. Regarding emergencies however, the vast majority of literature work proposes to allocate nodes in emergency more slots than other nodes, i.e., proposes to schedule the nodes according to their traffic context [26, 28, 29]. This is problematic if the deep fade phenomenon is considered. This is because in emergency context, using the medium for longer time severely increases the loss of the very sensitive data and dissipates more energy. Additionally, some-if not all- nodes in normal situations are prohibited from accessing the medium in order to give their time slots to the nodes in emergencies. Besides their failure to tackle the deep fade phenomenon, all the new proposed techniques require complex amendments to the superframe structure of WBAN de-facto standards. Moreover, nodes rely heavily on the controller to manage channel access schedule as these TDMA techniques are fully centralised. However, if the TDMA approach is adopted by WBAN MAC, then it is possible to manage packets loss in WBAN by avoiding the channel deep fade when it occurs. This can be achieved by allowing the nodes to switch off their transceiver whenever they fail to receive acknowledgment frame from the controller. Data packets that arrive during the sleeping phase of the nodes will be saved in the buffer. Accordingly, in the next TDMA round, time slots can be allocated to nodes dynamically based on their reliability requirements, which is based on both their links and buffers status. This presents the bottom line of the proposed solution for the presented limitations of the current WBAN TDMA mechanisms.

1.4 Research questions

According to the presented problem statement, which is emerged from the extensive literature review related to the thesis problem, the following research questions arose:

1. Is it possible to avoid the deep fade in WBAN medium, without re-ordering the nodes, delaying their medium access or considering hybrid channel access?
2. Can the nodes decide their links' status without relying on the controller?
3. How the nodes can access the medium according to their needs, in both normal situation and in emergencies, while considering the deep fade in WBAN medium?
4. Is there a way to guarantee all the nodes to have a reliable and energy efficient access to WBAN medium in both normal situation and emergencies?
5. Is it possible to satisfy the QoS in emergencies without increasing energy consumption?
6. Is it possible to propose a generic channel access mechanism for WBAN that does not require substantial amendments to the superframe structure of the WBAN de-facto standards?
7. To what extent considering context awareness in scheduling the nodes in WBAN, improves WBAN reliability and energy efficiency?

1.5 Research aim and objectives

Based on the extensive literature review related to the thesis problem, and the research questions that have been emerged, this thesis aims to propose novel generic, adaptive, reliable and energy-efficient MAC channel-access mechanisms for WBAN. The protocols should be able to avoid, mitigate and cope with the effect of fading, for the aim of achieving the highest possible level of reliability, without increasing energy consumption. The proposed scheduling techniques must cope with the heterogeneous contexts of WBAN. The new protocols should solve technical difficulties by providing techniques that are generic enough, so that amendments to the superframe structures of the IEEE 802.15.4 and IEEE 802.15.6 standards are not required. The protocols should perform under pre-defined evaluation metrics that concern reliability, including packet loss and rapid response, while also considering energy-efficiency. The proposed MAC protocols will be compared with the performance of the MAC protocols adopted by IEEE 802.15.4 and IEEE 802.15.6.

The following objectives have to be achieved:

- A critical analysis of various WBAN challenges and critical issues that render the requirements for adopting a reliable WBAN as highly important.
- An exploration of the principles used by wireless standards such as IEEE 802.15.4, IEEE802.15.6 to achieve reliable and energy efficient WBAN.
- An analysis of other MAC protocols proposed to achieve a reliable and energy efficient WBAN.
- A review of existing methodologies that tackle the phenomenon of the channel deep fade in WBAN. This requires a thorough review of TDMA based MAC protocols that tackle the realistic behavior of WBAM medium.
- New algorithms, presenting new solutions to overcome the limitations and the drawbacks of the existing works. This involves designing, implementing and validating the performance of the proposed algorithms.
- Suggestions for future work to fill in the remaining gaps regarding the traditional static and dynamic TDMA approaches for WBAN will be proposed, along with a suggestion for other interesting research areas, where the proposed protocols can be adopted.

1.6 Thesis contributions

To the best of our knowledge, the literature has not reported so far any MAC protocol that avoids the deep fade phenomenon in WBAN medium, and reduces the nodes energy consumption in both normal and emergency situations, while offering all nodes the chance to use the medium regardless of the context, and without making any amendments to the current WBAN de-facto standards. To fill in this gap, this thesis makes six-fold contributions:

1. Develop a technique that avoids channel deep fade, which is explained in Section 3.2.

2. Introduce an adaptive scheduling technique that dynamically allocates the nodes time slots by analysing their channel status, and which is optimised by including the buffer status. This technique is presented in Section 3.3.
3. Propose another dynamic scheduling technique, which assigns time slots to nodes according to their buffer status only as it reflects their links' status. This technique is presented in Section 3.4.
4. Evaluate the performance of the proposed techniques in both normal and emergency situations, which are discussed in Chapter 4 and Chapter 5 respectively.
5. Propose a third technique, which investigates whether considering context awareness in WBAN scheduling improves WBAN reliability and energy efficiency. This technique is illustrated in Chapter 6.
6. Develop an approach to parametrise the length of the TDMA schedule through choosing a suitable slot size. This approach is presented in the validation methodology of the proposed protocols in both the normal situation and the emergencies, which are presented in Section 4.3.2 and Section 5.4 respectively.

1.7 Peer-reviewed publications during the study

During the process of conducting this thesis, several publications have been yielded, wherein each publication marks the achievement of some objectives of the overall aim of the thesis. The most recent publication presents all the thesis contributions in an article submitted to **IEEE Transactions on Green Communications and Networking** [18]. This IEEE journal article highlights the performance of the proposed protocols in the heterogeneous context of WBAN. This IEEE journal article is an extended version to a previous paper presented at **IEEE International Conference on Communications (ICC'17)**, which is one of the two flagship IEEE conferences in the field of communications, and at which some major telecommunications discoveries have been announced. The IEEE ICC'17 paper summarises the main achievements of the thesis which are the proposed dynamic reliable and energy efficient TDMA scheduling approaches for WBAN [17]. The preliminary results of the proposed protocols are also published and were presented at the **19th Conference of Open Innovations Association (FRUCT)** [16]. Publications regarding WBAN started by a comprehensive **ACM survey** that covers the concept of

WBAN technology, its challenges, applications, and standards [5]. The aforementioned achievements preceded by two publications (one of which is **a book chapter published by Springer International Publishing**), which focus on improving the energy efficiency of IEEE 802.15.4 for WSN [30, 31]. The details of the publications achieved throughout the PhD period are as follows:

- M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, “Reliability and energy efficiency enhancement for emergency-aware wireless body area networks (wban),” **IEEE Transactions on Green Communications and Networking**, pp. 1–1, February 2018.
- M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, “New dynamic, reliable and energy efficient scheduling for wireless body area networks (wban),” proceeding in **2017 IEEE International Conference on Communications (ICC), May 2017**, pp. 1–6.
- M. Salayma, A. Al-Dubai, and I. Romdhani, “Reliability and energy efficiency enhancement in wireless body area networks for e-health,” proceeding in **19th Conference of Open Innovations Association (FRUCT), Nov 2016**, pp. 203–211.
- M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, “Wireless body area network (wban): A survey on reliability, fault tolerance, and technologies coexistence,” **ACM Computing Surveys**, vol. 50, no. 1, pp. 3:1–3:38, **Mar. 2017**.
- M. Salayma, A. Al-Dubai, I. Romdhani, and M. B. Yassein, “BARBEI: A New Adaptive Battery Aware and Reliable Beacon Enabled Technique for IEEE 802.15.4 MAC,” book chapter in *Advances in Network Systems. Advances in Intelligent Systems and Computing*, M. Grzenda, A. Awad, J. Furtak, J. Legierski, Eds. Cham: **Springer International Publishing, 2017**, pp. 317–335.
- M. Salayma, A. Al-Dubai, and I. Romdhani, “Battery aware beacon enabled IEEE 802.15.4: An adaptive and cross-layer approach,” proceeding in **Federated Conference on Computer Science and Information Systems (FedCSIS), Sep 2015**. IEEEXplore, Conference Proceedings, pp. 1267–1272.

1.8 Thesis organisation

- **Introduction** - This chapter introduces the topic of the thesis. It has also presented the motivation behind tackling this research. Thesis statement, a list of the emerged research questions, and the aim and objectives of the research were identified. Moreover, it provided an abstract view of the thesis contributions.
- **Literature Review** – The concepts of WSN, and WBAN in general are provided. Thereafter, WBAN is discussed in details by introducing its applications and its unique characteristics. The latest trends in wireless communication to adopt such networks are introduced. The theoretical concept behind WBAN challenges is provided, which highlights the challenge of reliability and the phenomenon of channel deep fade in WBAN in particular. In order to provide justification for the novelty of this research, an in-depth review of the existing TDMA based approaches, which tackle the deep fade phenomenon as an attempt to provide both reliable and energy efficient WBAN is discussed.
- **The Reliable and Energy Efficient Scheduling Algorithms** – According to the emerged research questions, and the identified thesis problem, this chapter presents the proposed approach, which aims to provide a reasonable and favorable answers to the presented research questions. The proposed approach addresses the limitations found in the literature by achieving a reliable and energy efficient WBAN. The proposed approach involves two novel and dynamic scheduling techniques, which are discussed separately in details in this chapter.
- **Validation Methodology** – This chapter highlights the methodology that will be followed to evaluate the proposed approach. The simulation setup, the topology and the evaluation metrics are also introduced. It explains the scenarios adopted for evaluating the performance of the proposed techniques in the context of the normal situation. It also provides an illustration of the justifications, for the experimental results achieved.
- **WBAN in Emergency Situations** – This chapter identifies the context of emergencies, and illustrates the approach to handle emergencies in simulations. It explains the methodology and the scenarios for evaluating the performance of the

proposed techniques in the context of an emergency. It also provides an illustration of the justifications, for the experimental results achieved.

- **Context-Aware Communication** –This chapter investigates whether considering heterogeneous traffic contexts in scheduling the nodes is beneficial for WBAN especially in emergencies. The chapter proposes and validates a third context aware technique that is integrated into the solutions proposed in Chapter 3. It explains the scenarios adopted for evaluating the performance of the proposed technique, and provides justifications for the experimental results achieved.
- **Conclusions and Future Directions** – The final chapter concludes the thesis and highlights thesis limitations. Furthermore, the chapter provides the future work to further enhance the proposed solutions. Besides WBAN, the chapter opens new interesting and emerging research areas where the proposed protocols can be deployed as a promising future direction.

Chapter 2: Literature Review

2.1 Introduction

The first decades of the last century heralded a revolution in wired communication: they brought about an almost magical technological evolution especially sensing data and communications. It did not take long for people to realise however that this technology was inefficient, especially when it came to wiring costs, mobility and independent connections. Such inefficiencies have been the key driving forces towards the evolution of wireless technology [1]. Wireless communication has revolutionised our daily lives as it pervades most technological applications such as controlling, tracking, monitoring and automation [2]. The communication range of such applications varies between tenths of metres to thousands of kilometres and is able to cover continents. Most wired sensors were replaced with wireless ones, thus forming a wireless network of sensors characteristic of the WSN era and beyond under the umbrella of the Internet of Things (IoT) paradigm. IoT enables direct access to the surrounding environment, which boosts the productivity and efficiency [3]. It was not long before the IoT revolution shifted its direction to a technology that suited human mobility by devising a technology that can be wearable or even implanted in the human body [4]. This technology is characterised by low cost, energy constrained, tiny, heterogeneous sensor nodes that form a special type of WSN, namely, the WBAN [5, 6]. Examples of WBAN sensor devices are provided in the Appendix.

A WBAN comprises sensors that capture physiological information and send it to a central base station through wireless communication. WBAN replaces complex and wired healthcare equipment as it is able to continuously monitor the body's vital statistics without limiting an individual's movements [5, 6]. WBAN sensor devices are supposed to provide real time feedback without causing any discomfort, thereby providing a greater deal of flexibility and mobility to the user. More importantly, the data provided by WBAN gives doctors a better view of a patient's situation as this data is gathered during a patient's normal activities in a natural environment [32]. The criticality of WBAN applications, the dynamic environment within which they operate (limited to the human body), the

vulnerability of WBAN medium, its frequent and dynamic topology and the heterogeneity of the deployed sensor devices confirm that WBAN has special characteristics that impose key challenges in designing an efficient and resilient WBAN. For instance, a WBAN has to be reliable as any abnormality could be life threatening for the person dependent on this technology.

This chapter discusses the theory behind the main topics covered in this thesis and presents the key relevant background information to the subject. The second section presents a general overview of WSN, and covers the background of the Personal Area Networks (PANs). WBAN concept is introduced in the third section, which provides a review of key characteristics and applications facilitated by this networking technology. The third section then explores a wide variety of communication standards and methods deployed in this technology. Additionally, the third section investigates the reliability challenge in WBAN, and places a substantial emphasis on the other challenging issues pertaining to the heterogeneity of WBAN devices and power consumption along with some suggested trends in these aspects. The fourth section reviews literature work that tackles the reliability challenge of WBAN from MAC layer perspective. It highlights the TDMA based scheduling techniques proposed for WBAN along with their drawbacks. This chapter is summarised in the fifth section.

2.2 Wireless Sensor Networks (WSN)

As its name indicates, a Wireless Sensor Network (WSN) is a network constructed from sensing devices that communicate with each other and with the surrounding world via a wireless communication medium [1, 2]. Sensing devices, which are usually referred to as sensor nodes or motes, convert the actual world into a virtual one by detecting, gathering, processing and emitting the sensed data to a central station usually referred to as a Base Station (BS) or sink node [1, 2]. This opens the door to a limitless number of wireless applications including monitoring, such as industrial and health monitoring applications, and tracking of people, animals and vehicles [1]. It is therefore not surprising that WSN has attracted interest the world over. The characteristics of such applications impose design constraints on sensor nodes in order to enable them to achieve intended goals. Sensor nodes are typically cheap, light, multitasking, battery powered devices [1, 2]. Sensor nodes may be scattered across areas ranging from a tenth of a meter to thousands of kilometers where they cannot be easily recharged, so it made sense to make them

battery operated to enable them to be used for long term monitoring that lasts for months or even years [1].

The battery is one of four basic components that make up the sensor node. These tiny devices comprise a sensing component which is responsible for sensing the target environment, a microcontroller which resembles the device brain through which all processes, including communication and signal processing, are controlled and the transceiver which is responsible for the transmission and reception of wireless signals when it is switched on (when there is no activity in the medium it stays idle or goes into sleep mode). Sleep mode helps promote the sensor node lifetime, which is controlled by the battery unit which in turn controls the lifetime of the WSN as a whole [1]. The appendix provides examples for WSN biosignals devices, which are used for healthcare purposes.

Technological and economic constraints imposed on the design of sensor components, especially on the battery unit, led to an increased number of researchers focusing on the design of the WSN's energy efficient algorithms and standards, one of which is the IEEE 802.15.4 standard discussed in Section 2.2.2.

2.2.1 Wireless Personal Area Network (WPAN)

The term Wireless Sensory Network calls to mind hundreds or thousands of sensor nodes scattered across large scale areas. This is not always the case as applications which operate within a very small range area (less than 10m), which is typically referred to as Personal Area Network (PAN), are very common. Bluetooth technology is one example of a wireless technology that supports PAN and commonly used in our personal life [33]. Bluetooth has decreased in popularity because it has failed in the automated multi-hopping arena [33]. WSN technology has led to many other applications helping to make our lives easier. However, these applications need special attention especially when it comes to energy consumption. On the one hand, the current WSN technology research areas are rich in algorithms and protocols that purport to achieve efficient energy consumption; on the other hand, other technological applications continue to be developed which have their own characteristics and thus demand special attention and monitoring [33]. For example, multi-media based applications are high speed constrained applications that require complex processing capabilities with very high QoS, which often

need to work in wide range areas, which will affect power consumption and peripherals' size, complexity and cost [33]. The protocols designed for such applications need to provide features to also suit home and industrial automated applications which transfer simple information at low data rate with ultra-low power consumption within very short range areas.

Clearly, none of the existing protocols can meet the requirement to be energy efficient while still being robust enough to be able to tackle critical situations and utilise the medium efficiently. The core problem is that the existing protocols are specific to the applications they are proposed for, and might not be able to meet the requirements of other applications [33]. Therefore, in order to overcome this problem there is the need to adopt a reliable and globally applicable standard, such as the proposed IEEE 802.15.4 standard. The IEEE 802.15.4 standard is discussed in the following subsection.

2.2.2 IEEE 802.15.4 standard

As stated above, most wired sensors are now being replaced with wireless ones, thus marking the emerging era of WSN. WSN consists of sensing devices that can communicate with each other and with the surrounding environment via a wireless communication medium [34]. A huge number of sensor nodes are often scattered in unreachable areas and WSN is often battery powered and cannot be easily recharged. Thus, energy conservation is one of the main concerns in the area of WSN. Many studies that focus on designing WSN energy efficient algorithms and standards based on IEEE 802.15.4 have emerged recently [34]. The IEEE 802.15.4 standard has been proposed by the IEEE 802.15 Task Group 4 (IEEE 802.15 TG4) to support the physical and MAC layers of the layer stack of the ZigBee technology. IEEE 802.15.4 MAC supports two types of devices, namely, Full Functional Devices (FFDs) and Reduced Functional Devices (RFDs). FFDs act as regular coordinators and/or as sink nodes. If both features are used, the node is typically referred to as a Personal Area Network Coordinator (PANc). In contrast, RFDs act as ordinary end devices [14, 30, 31, 33, 34, 35, 36]. Despite these differences, both FFDs and RFDs communicate with each other, forming two types of topologies, star and peer to peer topologies. Peer to peer topology is further classified into cluster tree and mesh topologies. All of the supported topologies must have one PANc. In a star topology, all network nodes can only communicate with the PANc in

their active period. In mesh network topology, all devices can talk to each other directly to broadcast messages [37].

The IEEE 802.15.4 standard adopts three different RF bands that work through different data rates distributed all over the world. The most popular RF is the 2.4 GHz. Choosing to operate through the 2.4 GHz band is reasonable because it is capable of operating without a license across the globe while offering the highest data rate out of the 16 operating channels. This RF also demands less power resources because the transceiver does not need to work for long periods due to the high data rate it offers [14, 30, 31, 33, 34, 35, 36].

The IEEE 802.15.4 MAC layer operates both in beacon enabled or beaconless modes. In the beacon enabled mode, the FFD broadcasts regular beacon frames that synchronise nodes when they need to access the channel [14]. The time between two successive beacons is referred to as the Beacon Interval (BI), which is virtually divided into 16 equally sized slots. The BI duration is specified by the Beacon Order (BO) parameter according to the following formula [14, 30, 31, 33, 34, 35, 36]:

$$BI = aBaseSuperframeDuration \times 2^{BO} \quad (1)$$

Nodes can use the channel during the whole BI period or can sleep through some time portions depending on the Superframe Order (SO) parameter. This parameter decides the Superframe Duration (SD) active session according to the following formula [14, 30, 31, 33, 34, 35, 36]:

$$SD = aBaseSuperframeDuration \times 2^{SO} \quad (2)$$

where $0 \leq SO \leq BO \leq 14$, The $aBaseSuperframeDuration$ value depends on the slot duration according to the following formula:

$$aBaseSuperframeDuration = aBaseslotDuration \times total\ slots \quad (3)$$

All these concepts can be grouped under one concept: the Duty Cycle (D). This is the percentage of time the node is awake within the time period between two successive beacons. D is mathematically expressed as [14, 30, 31, 33, 34, 35, 36]:

$$D = \frac{SD}{BI} \quad (4)$$

When a node needs to access the medium, it has to locate the beginning of the next time slot in order to compete for the channel based on the Carrier Sense Multiple Access/Collision Avoidance algorithm (CSMA/CA). This time portion is referred to as the Contention Access Period (CAP) [38]. Furthermore, the standard gives PANc the authority to assign a number of slots to some nodes exclusively. During these slots these nodes have sole use of the channel, which is why such slots are referred to as Guaranteed Time Slots (GTS). The optional period, which includes those slots is referred to as the Contention Free period (CFP) and includes seven GTS(s), which are preserved optionally after CAP. The CFP along with the GTS(s) resemble a TDMA based MAC mechanism. CAP and the optional CFP together are referred to as the Active Period as this is the time during which nodes can be active and use the medium. Its duration is often referred to as the SD [14, 30, 31, 33, 34, 35, 36]. The standard deals with time in terms of the backoff period unit which, in the beacon enabled mode, is aligned between the slot boundaries and is indicated by aUnitBackoffPeriod, which equals 20 symbols or 0.32 ms. The lengths of the periods discussed are assigned through the beacon frame, which is transmitted in the first time slot (slot 0) [14, 30, 31, 33, 34, 35, 36]. IEEE 802.15.4 superframe structure is depicted in Figure 2-1.

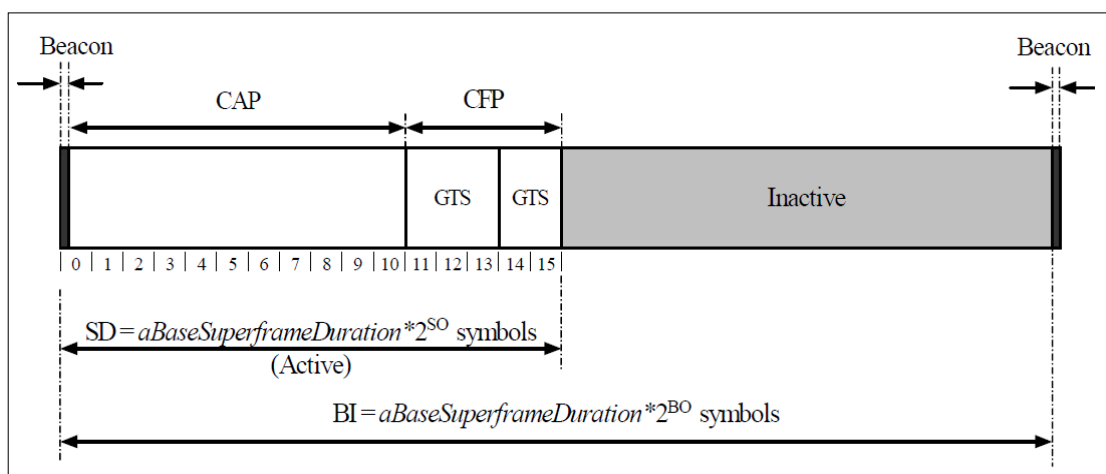


Figure 2-1: IEEE802.15.4 MAC superframe structure [33].

BO and SO values control the performance of beacon enabled IEEE802.15.4. Small BO values lead to frequent beacon frames and consequently increase beacon overheads, which, in turn, drains more power in a shorter period of time. Small SO values, on the other hand, decrease the nodes' active time while increasing the sleep time period. However, while small SO values might save energy, they increase delay and adversely affect throughput. This is because nodes which do not have enough time to send their data frames during the current Superframe, will defer their activity to the next Superframe and therefore attempt to send their data packets in one go causing a collision. Clearly, this situation becomes worse as the number of nodes increases [34]. Beacon overhead, collision and packet retransmission are all causes of early battery charge depletion.

It is worth mentioning that each IEEE 802.15.4/ZigBee node has two addresses, the 64 bit MAC unique address and the 16 bit PAN local address (nodes in different PANs may have the same network addresses). Thus, the IEEE 802.15.4/ZigBee network can support up to 2^{64} nodes globally, while each single PAN can support up to 2^{16} nodes. However, PANc can accommodate up to two to eight active nodes at the same time as the basic network building block is the piconet. In a piconet, the point to point communication is between two nodes: one master node and one slave node. The point to multiple (single cell) communication is between two and eight nodes: one master node and two or more slaves. The multicell communication is between two or more piconets [33, 34].

2.3 Wireless Body Area Networks (WBAN)

Our world is facing a rapid growth in population which is accompanied with an increase in the average lifetime expectancy of individuals, especially in the developed countries, leading to an increasing number of people who are over 65 years old [39]. Given the population chart shown in Figure 2-2, 23.6% of the United Kingdom's population is expected to be over 65 by 2050. Figure 2-2 reveals that not only the United Kingdom is characterised with population aging, but the majority of the developed countries lead this phenomenon. The ratio of people of age 16-64 to those who are over 65 will be 2.5:1 in the United Kingdom [39].

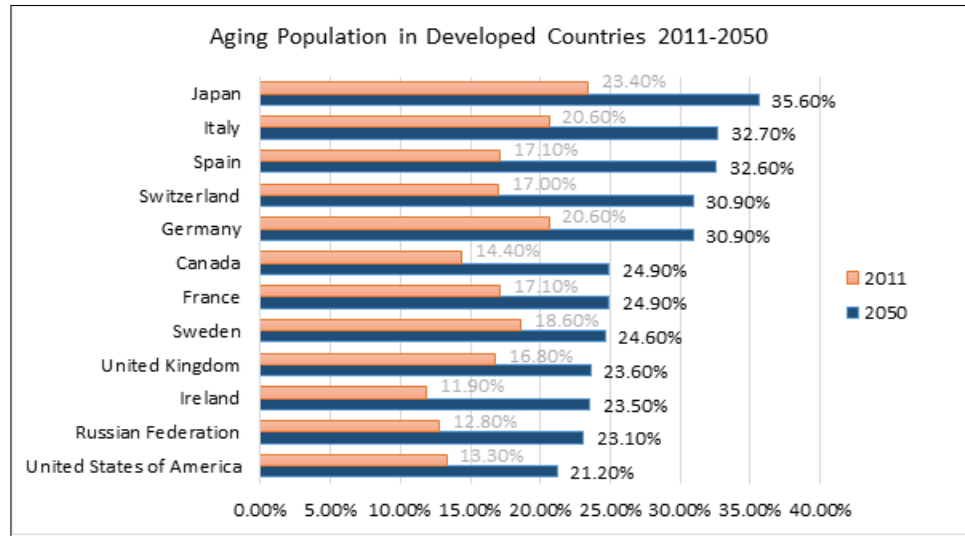


Figure 2-2: Statistics of population aging in developed countries [39].

Unfortunately, chronic and fatal diseases such as cancer, cardiovascular and asthma disease are often diagnosed too late. Consequently, this increases the death rate of individuals who are diagnosed with such diseases [5, 6]. Early detection would mitigate the impact of such diseases and increase the sufferers' life expectancy. Furthermore, traditional monitoring systems do not provide a complete picture of a patient's status as the bodily functions are monitored too infrequently. The lack of early detection and effective monitoring of diseases affect increases health care cost and adds a huge load to health care systems with limited financial resources [5, 6]. This calls for more affordable and scalable systems that are able to move current health care in the direction of early disease diagnosis and proactive wellness management [5, 6].

Wireless technologies, including WSN and WPAN, nanotechnologies and the Internet provide the means through which economical solutions could be found for health care systems. Such technologies suggest the idea of using tiny, smart, low-power, micro sensors and actuators to sample physiological data and then forward it to a remote server through wireless communication (Appendix) [40]. While WPAN devices operate within very small range area (less than 10m), the communication range of WBAN devices would be narrower than that of WPAN as they are limited to the human body area where they could be worn or implanted [41]. A comparison between WBAN and other wireless technologies, such as WPAN and WLAN in terms of data rate, frequency, coverage,

topology and power requirements can be found in [6]. Actually, WBAN is considered to be the next generation of WPAN. A typical WBAN is shown in Figure 2-3.

Though WBAN comprises the typical characteristics of both WSN and WPAN, it also has its own characteristics and thus its own requirements [40]. WBAN saves lives by allowing early detection of abnormal situations through wearable and implanted monitoring devices. It allows continuous and real time monitoring with no human or mechanical intervention, which improves the quality of the achieved results. Moreover, WBAN offers patients the ability to carry out their normal activities without interruption while their vital signals are monitored, as they are no longer required to stay in hospital or stick to a medical service. The adoption of WBAN should reduce health care costs, by lessening the need for expensive in-hospital monitoring [5, 6]. Such benefits have motivated practitioners in other fields, such as sports, the military and the entertainment field to adopt it in their systems [41]. WBAN however has special requirements which reflect the challenges it confronts. The following subsection discusses the WBAN requirements, characteristics and the main WBAN devices which are due to its special nature. The classification of the various applications that can be facilitated by WBAN is presented in the third part of this section, followed by the four popular standards proposed for WBAN, and finally the most important WBAN challenges featured in the literature to its special nature.

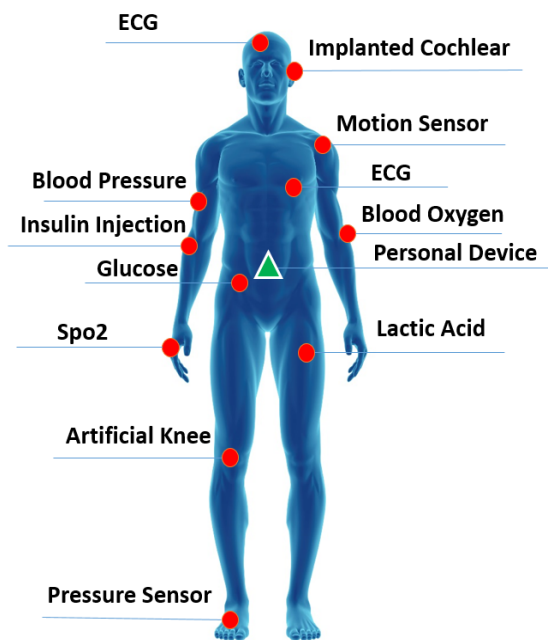


Figure 2-3: Typical WBAN.

2.3.1 Characteristics of WBAN

WBAN sensor devices are used to sense and communicate vital signals. They allow continual monitoring of an individual's physiological parameters and are able to provide real time feedback without causing any discomfort, thereby providing greater mobility and flexibility to the user [32]. More importantly, the data provided by WBAN gives doctors a clearer view of a patient's status as this data is gathered during a patient's normal activities in a natural environment. WBAN devices are characterised by their heterogeneity [42]. In other words, they vary in their capabilities, tasks, sizes, sampling rates, required resources and levels of intelligence. The criticality of WBAN applications, the dynamic environment within which they operate (which is limited to the human body) and the heterogeneity of the sensor devices they employ, mean WBAN has special characteristics, which are presented below.

A. Types of devices

As the name indicates, WBAN comprises tiny devices with communication capabilities (Appendix). Based on their functions and roles, these devices are divided into three classes. This section presents a brief taxonomy of WBAN devices according to their functionality. This taxonomy is summarised in Table 2-1.

- **Wireless sensor node:** A sensor node samples physiological attributes, communicates this information and provides a response to the information through wireless communication. It comprises four components: transceiver, battery, microprocessor and the sensor component. WBAN sensor nodes provide wireless monitoring for anybody, anywhere and anytime. Nodes can be physiological sensors, ambient sensors or bio kinetic sensors [43]. Sensor nodes are classified according to their position on the body, as follows:
 - **Wearable sensors:** These devices are added to clothes or placed on the body to gather vital signs, such as the Peripheral Oxygen (SpO_2) that measures the oxygen saturation level in the human blood which coincides with the cardiac cycle. The Electrocardiogram (ECG) sensor that investigates the heart function by sampling the heart muscle propagation electric waveform with respect to time (Appendix). The Electromyography (EMG) sensor that detects brain electrical activity and the motion

detection sensors that combine both accelerometer and a gyroscope to monitor and analyse a person's movements [44, 45].

- **Implantable sensors:** These devices are injected under the skin or in the blood stream [46]. In Parkinson's disease, for example, these sensors are used to send electrical impulses to the brain through neural simulators. Other applications for implantable sensors can be found in [46, 47].
- **Actuators:** Actuators are used to administer medicine to a patient. The required drug is administered directly in a predefined manner when a sensor detects an abnormality or when it is triggered by an external source, according to the doctor's decision. Similar to a sensor node, an actuator consists of a transceiver, battery, memory and the actuator hardware that holds and manages the drug. The drugs could be used to control blood pressure, the body's temperature and to treat many other illnesses. The actuator is activated upon receiving data from the sensors [6, 22].

Table 2-1: WBAN devices.

WBAN devices	Functionality	Examples	
Sensor node	Samples and communicates physiological attributes and provides a response to the information through wireless communication for anybody, anywhere and anytime.	Wearable: added to clothes or placed on the body to collect vital signs.	Peripheral Oxygen (Spo2), Electrocardiogram (ECG), Electromyography (EEG).
		Implantable: injected under the skin or in the blood stream.	In Parkinson's disease, sensors send electrical impulses to the brain through neural simulators
Actuators	Administer medicine to a patient when a sensor detects an abnormality according to the doctor's decision.	control blood pressure, the body's temperature and to treat many other illnesses	
Personal Device (PD)	Set up communication between a cellular phone sensors, actuators wirelessly.	Can be a specialised dedicated unit, such as a smart phone	

- **Wireless Personal Device (PD):** This device can also be called a Body Control Unit (BCU), body gateway or a sink. It is the central unit that is responsible for establishing communication between sensors, actuators and a cellular phone in a wireless fashion. PD can be a specialised dedicated unit, a Personal Digital Assistant (PDA) or a smart phone. A personal cellular phone, for example, can be used to transmit the information to and from the human body to the external world. This device is usually more resource rich than the sensor nodes and actuators. Its main components are: a transceiver; a rich power source; a large processor; and a large memory [6, 22].

B. Network architecture

The WBAN architecture can be either of the two kinds described below:

- **Flat architecture:** Comprises a PD that collects data and sends it to a remote application that is running on a PDA for example [6].
- **Multitier architecture:** Comprises a set of nodes that collect wide physiological information in the first tier, send the collected data to a gateway on the second tier, which in its turn acts as an interface between the first tier and a server at the third tier [6]. Thus, WBAN architecture can be separated into three different tiers:
 - **Tier-1 (Intra-WBAN communication):** Sensor nodes send body signals to a Personal Server (PS), in Tier-1. The processed data is then transmitted to an access point in Tier-2 [6].
 - **Tier-2 (Inter-WBAN communication):** This tier presents the communication between the PS and one or more Access Points (APs). Tier-2 communication aims to interconnect WBAN with various networks and communication technologies, such as cellular networks and the Internet [6].
 - **Tier-3 (Beyond-WBAN communication):** This tier is needed in metropolitan areas. A bridge is needed to connect Tier-3 with Tier- 2. A PDA can be used as a gateway for this purpose. The design of this tier is application-specific. For example, a database is considered a crucial part of Tier- 3 for medical applications as it includes the medical history and profiles of the patient. This enables access to the necessary information of a patient and the notification of an emergency through the Internet or a Short Message Service (SMS) [6].

C. Communication range and topology

WBAN is considered to be a short range network due to its space limitation. As is stated in [8], the WBAN communication range should be limited to few meters (three to six meters). Hence, it is not convenient to follow topologies other than a simple star topology. Due to limitations in the nature of WBAN in terms of short space, network architecture, transmission techniques and communication protocols, the numbers of nodes in a WBAN is limited. According to [48] a typical WBAN comprises a set of nodes which ranges from a few devices (actuators or sensors) that communicate with a portable handset to hundreds of devices that communicate with Internet through a gateway. However, the majority of the work in literature that is geared towards WBAN support up to 6 nodes, not only due to the short range of communication over the human body, but also human beings in general do not tend to wear more than that [11, 12, 13, 25, 26, 27, 28, 29]. However, as stated in [7], each WBAN is allowed to have one hub and, due to limitations in the transmission strategy, a hub can support up to 64 nodes. It is stated in [6] that each person can have 2-4 hubs coexisting per m^2 , thus within a six m^3 , each network can support up to 256 nodes. [32] specify that a one second superframe is split into 50 ms nonoverlapping time slots allowing 20 nodes to be supported orthogonally. As can be seen, there is no general agreement on the maximum number of devices that can be supported by a WBAN as the devices' interaction with the environment and other networks is still a challenging issue, yet generally the number of devices in WBAN is limited and much smaller than the number of devices in WSN.

2.3.2 Applications of WBAN

WBAN applications span from the health care and entertainment fields to sport and the military among others. According to [48], WBAN applications are categorised as either medical or non-medical. This section classifies WBAN applications according to their target domain of application. Each application is further classified into medical, non-medical, implanted, and wearable. WBAN fields of applications are summarised in Table 2-2, which also gives some examples for each WBAN field.

Table 2-2: Fields and applications of WBAN.

WBAN fields	Applications types		Examples of applications
Healthcare	Medical	Wearable	ECG, EEG, Electromyography (EMG), SpO ₂ , temperature, blood pressure, drugs delivery
		Implant	Diabetes control
	Non-medical	Motion detection	
		Secure authentication	
Military and defence	Medical wearable	Asses soldier fatigue, detect life threatening situations	
	Non-medical wearable	Fire detection, poisonous gas	
Sports	Medical wearable	Heartbeat, temperature, blood pressure, motion sensor	
Entertainment	Non-medical wearable	Real time streaming: Video streaming by camera, audio streaming by headsets	
		Consumer electronics: MP3 player, microphone, camera	
		Gaming purposes, virtual reality, ambient, intelligence areas, personal item tracking and social networking	

Healthcare: This is one of the most promising fields for WBAN. Implanted and wearable sensors are used to collect biomedical signals remotely and continually [5, 8, 49]. This continual monitoring allows a proactive fatal and anomalies detection which is vital for diagnosing heart and brain activities. Actuators help in automatic drug delivery. Some applications such as cochlear implants, hearing aids and artificial retinas help enhance the life style of human beings [22, 50]. Additionally, given that medical accidents can and do happen, WBAN applications can help to reduce them and increase public safety by using profiles of previous medical accidents to alert medical personnel before similar accidents occur [8, 22, 49]. Consequently, WBAN is expected to improve the management of illnesses and reaction to crisis, which will increase the efficiency of health care systems [15]. WBAN health care applications can be further classified as follows:

- **Medical applications:** WBAN medical applications enable the continual monitoring of physiological parameters such as the heartbeat, the body temperature and blood pressure. The data collected can be sent through a cell phone, which acts as a gateway, to a remote location such as an emergency centre so that the relevant action can be taken [5, 22, 43]. WBAN is considered key to the early detection and treatment of

patients with serious cases such as diabetes and hypertension [6, 22]. Medical applications of WBAN can be further divided according to the position of the medical sensors as follows:

- **Wearable applications:** Medical wearable healthcare applications include temperature monitoring, blood pressure monitoring, glucose level monitoring, ECG, EEG, Electromyography (EMG), SpO₂, drugs delivery (Appendix). Other applications can be found in [6].
- **Implant applications:** These applications comprise nodes implanted either under the skin or in the stream of the blood such as in diabetes control systems, cardiovascular diseases and cancer detection [6, 49].
- **Non-medical applications:** These applications are considered to fall within the wearable sensor class of applications and include two applications which are [6]:
 - **Motion detection:** This application is used to detect, capture, recognise and identify body gestures and motions and send alerts to the owner of the application. For example, fear increases heartbeat, which leads to sweating and other symptoms. Thus, emotional status can be measured and monitored anywhere and anytime by detecting emotion-related physiological signals as is done by the EMG, ECG, EEG [6].
 - **Secure authentication:** This is a very promising WBAN application as it is the core of both multi-modal biometrics and electroencephalography. This application harnesses physiological and behavioural human body biometrics such as fingerprints and facial patterns [6, 22].

Sports: Sport activities and fitness can be improved by keeping a log of vital physiological data such as heart beat, temperature and blood pressure. The data can be used to avoid sport accidents and injuries and to plan for future training [8, 22, 49]. According to [6] WBAN sport applications are considered to be medical wearable applications. Such applications enhance professional and amateur sport training especially for athletes. For example, they provide the necessary information to enable the training schedules of professional athletes to be adapted to make them more effective [6].

Entertainment: Entertainment is also a promising field for WBAN. The film industry for example benefits from motion capturing and post production mechanisms to produce movies in which actors perform the objects roles [8]. Using the on body accelerometers and gyroscopes for capturing motions facilitates the possibility of tracking the different positions of body parts. According to [6], WBAN entertainment applications are considered to be wearable non-medical applications. WBAN can be used in three types of entertainment applications, presented below:

- **Real time streaming:** This includes video streaming such as capturing a video clip by a camera, as well as audio streaming such as voice communication for headsets that are used for listening to explanations, illustrations and multicasting (for example, conference calls) [6].
- **Consumer electronics:** These applications include appliances/devices such as microphones, MP3-players, cameras and other advanced human-computer interfaces such as neural interfaces [8, 49].
- **Gaming:** This includes virtual reality, ambient intelligence areas, personal item tracking and social networking [49].

Military and defence: WBAN provides new capabilities to improve the performance of individual and teams of soldiers in military situations. To avoid threats at an individual tier, a group of sensors sample important information on the surrounding emerging actions and environment. At the team level, the taken information enables the commander to coordinate team tasks efficiently. Inter-WBAN communications and security play a key role in preventing critical data from being hacked by enemies [8]. WBAN applications can be considered as either medical wearable or non-medical wearable as follows:

- **Medical military WBAN applications:** These types of applications are used to assess soldier fatigue and battle readiness and for safeguarding uniformed personnel. For example, sensors surrounding soldiers, firefighters or police officers can foresee a life-threatening situation by monitoring the level of air toxins [6].
- **Non-medical military WBAN applications:** Such applications involve off-body sensors (on buildings) that are used for emergencies. Such sensors are capable of, for example, detecting a fire in the home or a poisonous gas and must directly send this

information to on and in body devices to notify the wearer of the emergency situation [6].

2.3.3 WBAN communication standards

As it is stated in Section 2.2.1, there are several reasons behind the motivation of wireless communities to standardise their technologies. Standardisation allows interoperability which enables wide use of the products since manufacturers depend on common fixed specifications in developing their products [8]. Additionally, customers need not depend on a certain vendor. This saves the costs for both the vendors and customers [8]. Due to the quite large number of available standards, it is necessary to identify the best solution depending on the application requirements. In this regard, the wireless communication community has proposed several technologies to support WBAN in addition to the IEEE 802.15.4, namely IEEE 802.15.6, IEEE 802.15.4a, IEEE 802.15.4j and Bluetooth Low Energy (BLE). These standards are presented in more details in the following subsections.

A. IEEE 802.15.6 standard

The existing standards (e.g. IEEE 802.15.4) do not meet the regulations of medical communication as they fail to support the needs of applications in terms of key issues such as reliability, low power, the variety of traffic flows and coexistence [8]. The IEEE 802.15 Task Group 6 (IEEE 802.15 TG6) has proposed a communication standard that is geared toward applications in the vicinity of, or inside, the body, such as in medical, sports and military applications [15]. The first draft of the standard was published in 2010 and the final draft was released in 2012. It supports low cost, low complexity, very short range, and highly reliable and ultra-low power wireless communication. It aims to support an array of applications with a range of requirements such as data rates and channel bandwidths [6, 8, 15]. To support various applications, the standard offers three bandwidths defined in three different physical layers: Narrow Band (NB), Human Body Communication (HBC) and Ultra Wide Band (UWB). These physical layers share only one MAC layer. The supported data rate ranges between 75.9 Kbps in NB and 15.6 Mbps in HBC [6, 8, 15]. As the range, it is limited to 3m for in-body communication and has to be at least 3 m for body-to-body communication patterns. The standard allows star and 2-hops tree topologies [6]. IEEE 802.15 TG6 provides two classifications for devices, according to their position in the body: implanted nodes, body surface nodes and external

nodes, and according to their functionality: coordinator relays and end nodes. More detail about this classification is provided in [15].

IEEE 802.15.6 MAC layer:

The IEEE TG6 proposes only one shared MAC to manage the channel access above the three physical layers. It combines both contention and contention-less access techniques to support the variety of data flows that might occur in WBAN, such as burst, continuous and periodic traffic. The coordinator splits the time axis or the channel into a successive number of superframes. The coordinator bounds the length of superframes through beacon frames that are sent in fixed length beacon periods [5, 8, 15] . To access the channel, the coordinator chooses one of three access modes; these are illustrated below:

- **Beacon mode with beacon superframe periods:** Here, the coordinator sends successive beacon frames to specify the beginning and the end of the Superframe, which is referred to as the beacon period. The Superframe structure of this mode is presented in Figure 2-4 and comprises the Exclusive Access Phase 1 (EAP1), a Random Access Phase 1 (RAP1), a Type I/II phase, an Exclusive Access Phase 2 (EAP2), a Random Access Phase 2 (RAP2), a Type I/II phase, and a CAP. The Type I/II phase is sometimes referred to as Managed Access Period (MAP). Table 2-3 provides more details about the MAC access mechanisms that are offered by this access mode. The coordinator uses the beacon frame to specify the duration of each access phase in the Superframe structure according to the application requirement. The controller can also deactivate those periods by setting the duration to zero. The Exclusive Access Phase (EAP) is only used for emergency situations and offers the channel exclusively to the high priority data traffic, whereas RAP1 and RAP2 and CAP are used for normal traffic. Type I/II phases are used to schedule uplink, bi-link and downlink allocation intervals and for polling nodes for resource allocation. In CAP, RAPs and EAPs, nodes compete for the channel access following either the slotted Aloha or CSMA/CA [5, 8, 15].

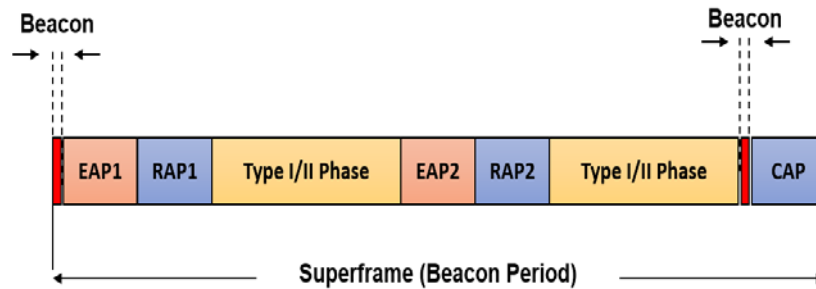


Figure 2-4: IEEE802.15.6 beacon mode superframe structure.

- **Non-beacon mode with superframes:** No beacon frame is used in this access mode, and the superframe may only comprise either Type I phase or Type II phase as explained in [5, 8, 15].
- **Non-beacon mode without superframes:** A coordinator follows an unscheduled allocation using unscheduled Type II poll allocation. Thus, each node specifies its time schedule in a distributive manner considering either EAP1 or RAP1 as access phases, during which it competes for channel access following CSMA/CA [5, 8, 15].

From this brief description, it can be seen that these diverse channel access mechanisms offer the flexibility to support a variety of WBAN applications. However, the parametrisation of the IEEE 802.15.6 Superframe and the selection of the optimal solution is not an easy task and requires further study.

B. IEEE 802.15.4a

This is a WPAN standard but with an amendment to the physical layer of the legacy IEEE 802.15.4 to cater for the continuous monitoring needed in health care applications [51]. The physical layer of the IEEE 802.15.4a supports UWB signals to provide very low power consumption for health care applications due to the Federal Communications Commission (FCC) rules. The IEEE 802.15.4a power consumption is much lower than Bluetooth and ZigBee. This standard also supports a wide range of data rates to allow sufficient transmission of medical signals, such as ECG and EMG. Data rate values vary between 125 kbps and 50 Mbps with the compulsory rate being 850 kbps, which is three times the 250 kbps data rate supported by IEEE 802.15.4. Thus, the amendment to the physical layer aims to achieve a very low power consumption while supporting high precision rate [51]. The MAC structure of IEEE 802.15.4a is identical to that of IEEE 802.15.4. IEEE 802.15.4a MAC supports a Superframe structure with both CAP and GTS

enabled to allow a high QoS for applications that require continuous monitoring such as ECG. While the CSMA/CA is the mandatory mechanism used for the channel access in the CAP of the legacy IEEE 802.15.4, it is not convenient to adopt such a mechanism for healthcare applications, as sensing the carriers of the UWB signals is very sophisticated. Instead IEEE 802.15.4a adopted ALOHA and slotted ALOHA protocols as its channel access mechanism, while CSMA/CA is assigned as optional [51].

C. IEEE 802.15.4j

A new amendment to the physical/MAC layers of the IEEE 802.15.4 is now taking place by the IEEE 802.15 Task Group 4j (IEEE 802.15 TG4j). The objective of this amendment is to develop a technology, which is the IEEE 802.15.4j that supports the Medical Body Area Networks applications (MBANs). FCC allows MBAN users to operate within 2360–2400 MHz spectrum on a secondary basis. The goal of IEEE 802.15.4j is to cope with the rules of this MBAN spectrum. At the physical layer, IEEE 802.15.4j provides channel schemes that allow coexistence between MBAN devices and other technologies that can operate within WBAN band. For more information about the MBAN channelisation scheme refer to [52]. IEEE 802.15.4j also provides power friendly techniques at the MAC level for WBAN implementation. A case in point is that the IEEE 802.15.4j provides a novel channel switching command that allows the MBAN coordinator to abandon a portion of the spectrum dynamically to protect its primary devices. This command defines a time stamp that assigns the time unit at which the MBAN coordinator should switch to a channel. This channel switching mechanism allows to support different WBAN priorities and channelises devices according to their priorities, which will improve reliability as it avoids collision [52].

In IEEE 802.15.4, the GTS allocation is static and once the sensor is granted GTS(s), it maintains the same number of GTS(s) in the subsequent superframes following the same order forming a static synchronisation. IEEE 802.15.4j however, provides an extension to the IEEE 802.15.4 original superframe structure by supporting a multi-periodic GTS(s). In this scheme, the coordinator grants GTS(s) to its devices every M superframes, where $M=2^N$ and N is the GTS period exponent, which can have values from 1 to 8. This scheme is useful for devices that send periodic streams such as heart rate traffic. In those applications, devices need to sleep most of the time as they work in low duty cycles. Accordingly, adopting multi-GTS(s) scheme will help in saving power as it allows

devices to sleep most of the time. Moreover, IEEE 802.15.4j defines other novel schemes that help in saving power such as association proxy and coordinator switching [52].

A comparison between the WBAN MAC mechanisms adopted by the IEEE 802.15.4, IEEE 802.15.6, IEEE 802.15.4a, and IEEE 802.15.4j is presented in Table 2-3.

Table 2-3: A comparison between wireless standards that support WBAN.

Standard /Criteria	IEEE 802.15.4	IEEE 802.15.4a	IEEE 802.15.4j	IEEE 802.15.6
Network type	WPAN	UWB WBAN	MBAN	WBAN: NB, UWB and HBC.
MAC modes	Beacon/Non-Beacon mode with/without superframe.	Superframe Beacon mode enabled.	Superframe Beacon mode enabled.	Superframe with beacon mode. Superframes with non-beacon mode. Non-beacon mode without superframe.
Access mechanisms	Random access with contention in CAP. Scheduled access without contention in CFP.	Random access, contention based in CAP. Scheduled access, contention free in CFP.	Random access with contention in CAP. Scheduled access, contention free in CFP.	Contention based random access: EAP1,RAP1,EAP2,RAP2,CAP. Connection oriented contention-free in TypeI/II.
Contention access resource allocation procedure	Slotted and un-slotted CSMA/CA in beacon mode and in non-beacon mode, in CAP.	slotted or unslotted Aloha (CSMA is optional in CAP).	Slotted CSMA/CA in CAP.	CSMA/CA / a slotted Aloha in EAP1,RAP1,EAP2,RAP2,CAP.
Contention free access resource allocation procedure	Schedule access by allocating static GTS Allocation persists in the upcoming superframes. (1-periodic in CFP)	Schedule access by allocating static GTS Allocation persists in the upcoming superframes. (1-periodic in CFP)	a multi-periodic scheduled access by allocating static GTS. (m-periodic in CFP)	Two access modes: 1-Schedules the allocation of slots : one / multiple upcoming superframes. (single-periodic or m-periodic allocations) 2-In unscheduled access: unscheduled polling/posting
Specific Access for prioritised (emergency) traffic	No	No	No	Yes exclusive access in EAP1,EAP2.

D. Bluetooth Low Energy (BLE)

Bluetooth is a popular and widespread short range communication technology which is used to connect personal, portable and fixed devices replacing wired communication [8]. It is used for several applications that run on tiny button cell battery powered WSN. Because of its low price, low power and robustness, it is considered as the best choice for short range networks that support the star topology. It is also considered as a good choice for WBAN. Bluetooth based technology devices can be configured to either a Basic Rate (BR) with an optional Enhanced Data Rate (EDR) or Bluetooth Low Energy (BLE). BLE is an ultra-low power consumption configuration of Bluetooth technology. It supports 1 Mbps data rate. As with the legacy Bluetooth, only star topologies are possible. BLE adopts 40 channels of 2.45 GHz Industrial, Scientific and Medical (ISM) band, each 2 MHz wide [8]. BLE defines two implementation modes: a single-mode, which targets applications that require very low power consumption and very small devices and the dual-mode, which is an extension to the legacy Bluetooth technology and targets mobile phones and personal computers. Recently, devices come with dual mode Bluetooth RF. Some medical monitoring devices, such as heart rate belts, are equipped with only BLE. The basic limitation of BLE technology is its communication range, as it does not support multi-hop communication [8]. The survey [8] provides a detailed evaluation comparison between IEEE 802.15.4, IEEE 802.15.6 and BLE for WBAN, in terms of packet loss rate, average delay and the throughput.

2.3.4 Challenges of WBAN

As WBAN is a special type of WSN, it inherits many of its challenges. However, several new challenges characterise WBAN and a number of problems require better solutions. A survey of the differences between WBAN and WSN is given in [40]. Practical adoption of WBAN could not be achieved without tackling the various technical, ethical and social challenges this type of networks faces. The main objective is to achieve a reliable network with minimum delay and maximum throughput while considering power consumption by reducing unnecessary communication such as a control frame overhead, idle listening and frame collisions. User requirements such as privacy, safety, ease of use, security and compatibility are also of great importance. The most challenging issues concerning WBAN are detailed in this section. This thesis will put a great deal of emphasis on the reliability challenge, which is discussed in the following subsection.

A. Reliability

WBAN demands a high degree of reliability as it directly affects the quality of patient monitoring [22, 41]. Undetected life-threatening situations can lead to fatality [22]. The main requirement is that the monitored data is received correctly by the health care professionals. Thus, reliability is a crucial issue in WBAN. Reliability can be considered either end-to-end or on a per link base [22, 53]. Examples of reliability include guaranteed, in-order and in time data delivery [22]. In order to achieve a reliable network, there are three basic characteristics that any network technologies, programmed services and protocols need to address: fault tolerance, QoS and security [53]. Designing protocols for unforeseen problems is an essential element of WBAN design because it is necessary that the WBAN work continuously for users who rely on it. This requires that the WBAN design and architecture be fault tolerant. A network is called fault tolerant if it is able to control the influence of the failure limiting it from effecting the rest of the components [53]. It is also built in a way that enables quick recovery when such a failure occurs. The survey in [5] provides a comprehensive study for fault tolerance challenge in WBAN and proposes solutions that could fill in the gaps found in the literature.

WBAN medical applications create higher expectations for the quality of the delivered services as for such applications any constant breaks, pauses, delays or packet loss could be fatal especially in emergency situations. Therefore, quality of service or QoS is also an ever-increasing requirement of WBAN. QoS could be achieved through well-designed WBAN protocols that can prioritise network traffic. QoS also means that all packets arrive on time and in their correct order [45, 53]. This requires strategies that avoid or could manage traffic congestion. Network channel bandwidth is the capacity of the network to carry data during a specific time [53]. Network bandwidth is measured according to the number of bits that can be transmitted in a single second. Channel congestion occurs when more than one source is trying to use the channel simultaneously and channel bandwidth usage exceeds its availability. In this case, the network has more bits to transmit than what the bandwidth of the communications channel can deliver [53]. In most cases, when the volume of packets is greater than what can be transported across the network, then packets are queued and wait for the channel to become available. The more the packets are queued, the sooner the memory will be filled up which will increase the number of the dropped packets. Packets are queued and wait in a buffer. When the buffer is overloaded, this is called buffer overflow [50]. Such issues should be considered

when tackling the reliability in WBAN, so to meet user expectations, especially in emergencies. The third requirement that should be addressed to achieve a reliable WBAN is Security. Security is of primary importance, especially in medical and military applications and it should be addressed in terms of privacy and confidentiality. Security is fully addressed in [6, 9, 53].

Despite that there are solutions to achieve a fault tolerant and secure that provides QoS in WSN, achieving a reliable WBAN remains an important challenge. The primary factor that hinders achieving a reliable WBAN is the vulnerability of WBAN channel due to its unique characteristics. The realistic behaviour of WBAN channel is rarely considered in literature, which when it does it considers an ideal characteristics of WBAN channel inherited from WSN medium. Additionally, WBAN medium can be easily interfered by other RFs that operate within the same channel bandwidth. Understanding the uniqueness of the characteristic of WBAN medium is of high importance and is presented below.

- **Unique characteristics of WBAN channel**

Generally, attenuation is a term used in wireless communication to refer to the reduction in the received signal strength, whether its analog or digital signal. This is why attenuation is usually measured in decibels or dBs. Sometimes attenuation refers to the loss in the received signal. Typically, in wireless networks, which is of longer transmission paths compared to WBAN, the wireless signal is attenuated due to the long distance between the source and the destination. However, in WBAN, the signal power is attenuated due to other factors and mainly due to human body nature and its dynamic movement [12].

The variation in the signal attenuation due to multiple parameters is called fading. Those parameters include the RF, time, geographical position, and other variables. The fade length is expressed in average outage duration [11]. In wireless communications, fading could occur due to the weather (due to rain), multipath propagation, or due to shadowing. Shadowing is the fluctuation in the received signal power due to obstacles in the propagation path of the signal. In WBAN the shadowing, occur due to rapid body movement, body size and posture [6, 7, 12, 20]. Uncontrolled and dynamic nature of body movements causes frequent change in network topology, which is a very complicated issue, as nodes might move with regard to each other due to the correlation between some moving parts of the body [6, 7, 20]. Moreover, the human body absorbs energy when it

is exposed to RF electromagnetic waves that heat the surrounding tissues [6, 7]. The rate at which the human body absorbs RF energy, which is defined as the Specific Absorption Rate (SAR), should comply with the FCC regulations, to allow the approval of new WBANs, i.e. short-range, low-energy wireless networks capable of connecting medical devices [7]. Besides tissue heating, signal energy absorption deteriorates the propagation paths in WBAN.

Those reasons deteriorate the stability of the transmission links and causes large and continuous attenuation in WBAN signal. This severe attenuation pushes the signal energy below the level required to achieve a reliable WBAN communication. This level is called receiver sensitivity and it is very limited in WBAN due to its resource constrained and tiny nodes, which are accompanied by very small antenna [12]. When the signal falls below required reliable communication level, this is called deep fade. In other words, deep fades are the fades that bring the signal below radio sensitivity [11, 12]. Continuous period of deep fade or continuous period of attenuation below sensitivity is called outage [12].

The strength of the received signal in WBAN is used as an indication of the WBAN channel status. The work in [11] and [12] analysed WBAN channel characteristics by conducting an empirical study on a real WBAN worn by a person doing different daily indoor and outdoor activities. Results revealed that WBAN channel has a slow changing behavior. In particular, it is found that at any short period, the channel gain is correlated. However, the aggregation of all those short periods results in an independent signal. This indicates that the WBAN channel can be in a good status for a long time, yet also means that channel status can be bad for long time too. The poor status of WBAN medium is primarily due to the shadowing, which attenuates the signal strength continuously and causes deep fade in the signal.

The occurrence of the deep fade in WBAN medium is frequent, unpredictable and when it happens, it persists for a long time. In essence, the empirical study in [11] and [12] revealed that when a deep fade occurs in the WBAN channel, it lasts for at least 10 ms. Deep fade in WBAN medium not only cause packets loss but also long disconnectivity and unreachability of the sensor node from the main network. The study in [13] shows statistics about the duration of the deep fade for each node's link and how frequent the signal falls below receiver sensitivity for that link. The slow changing behaviour of

WBAN medium helps in predicting the channel status of WBAN in the upcoming periods. For instance, adopting appropriate MAC protocols that consider the long durations of the deep fade in WBAN channel could boost WBAN reliability.

- **Interference and coexistence**

There are many causes of interference in WBAN. Interference occurs when several people wearing WBAN devices exist in each other's range; this causes off-body interference. Off-body interference may also occur in cases of collision from external sensors [6, 54]. On-body interference occurs between on-body devices deployed in one WBAN. The coexistence issues become more prominent with higher WBAN density [54]. Due to the unpredictability of body movements, it is very easy for multiple WBAN to move in and out of the range of each other's [6]. Figure 2-5 shows the types of interference that might occur in WBAN and when multiple WBAN coexist in the same location. Typically, WBAN operates within a free licensed ISM band that is 2.45 GHz. This band is shared amongst other radio technologies such as Wi-Fi, Bluetooth, IEEE 802.15.4/ZigBee and other technologies [8]. Techniques to minimise and avoid interference should be addressed because of the strict requirements of WBAN in terms of reliability especially in emergency events. This could be achieved by assessing the performance of WBAN in terms of packet loss rate and delay in the existence of interfering technologies [8].

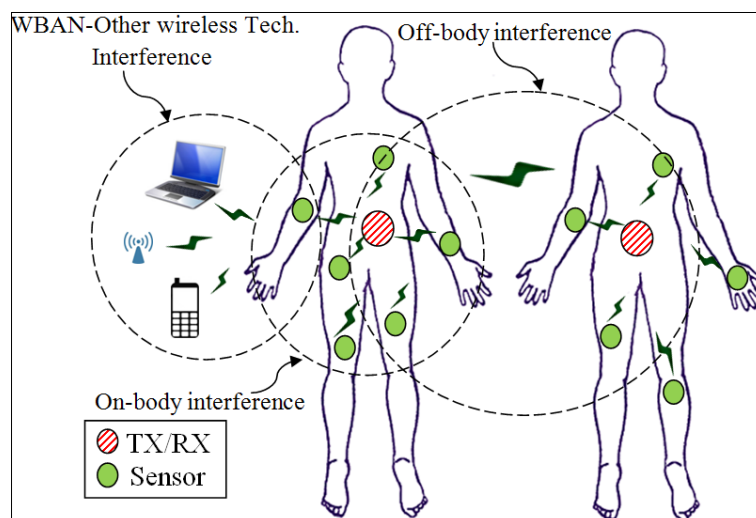


Figure 2-5: WBAN interference [6].

The long duration of the deep fade in WBAN medium as well as the interference and coexistence issues lead to severe channel impairments. This affects sensor channel allocation strategies and even the common mechanisms mentioned in the literature to mitigate interference might not be sufficient [7, 20]. Channel impairments increase Bit Error Rate (BER) and cause unreliable data transmission as critical data might not be sent in real time and the doctor might mistakenly diagnose the patient, which could be fatal [6]. Moreover, the packet loss increases data retransmission, which increases power consumption. Power consumption is the second challenge in WBAN and it is discussed in the following subsection.

B. Constrained resources

WBAN has fewer and smaller nodes with smaller components compared to the other WSN. Devices in WBAN are generally battery powered which adds more constraints on power consumption in communication [23]. The power required by nodes in WBAN varies according to the application type. All implanted nodes are required to operate for multiple years. Pacemakers, for example, need to operate for at least five years [8]. Therefore, the transmitting power must be as low as possible, for which it is essential to design ultra-low power radio transceivers. WBAN protocols have to be able to minimise power consumption without sacrificing reliability. A common technique is to allow devices to sleep for most of the time and thus lower the duty cycle [8]. However, balancing between power consumption and average end-to-end delay should be considered [8]. The first point to consider when choosing a wireless technology for WBAN is the power usage [6]. WBAN peak power demands in idle mode vary between 0.001 mW and 0.1 mW and requires up to 30 mW in active mode [6]. Wireless technologies focus on minimising the average current drawn from the battery by duty cycling the active and sleep periods of radio. Further improvements are necessary to reduce the drawn peak current in sensing technologies, radio hardware and integrated circuits [6]. The issue of minimising interference and increasing WBAN lifetime by adopting transmit power control requires further attention. A discussion on meeting this challenge can be found in [7]. Some studies reviewed in the literature focus on scavenging energy from body heat or motion [8]. Power consumption challenge is deeply discussed in [6, 8].

Besides the small power sources, WBAN devices have small buffer sizes, which adds constrained on the storage of the arrived packets. In emergencies, the traffic increases which adds burden on the limited sized buffer, and hence buffer will be quickly overloaded, and packets will be dropped from the buffer, which is another factor for packets loss in WBAN. Buffer overflow can be handled by proposing MAC techniques that consider buffer information. For example, nodes with more packets in their buffer require to access the medium as soon as possible.

C. Heterogeneous devices and applications

Since sensors in WBAN capture different kinds of data, reliability is a key issue. For instance, sensors vary in their sensed traffic rate as this depends on the type of application and data to be sent [23]. Bit rate values vary between less than 1 Kbps to 10 Mbps [8]. Inherently, some sensors sense more critical data than others. For example, heart rate related data is more critical than motion detection data and hence should be served first under the condition of lack of shared resources [23]. Moreover, the same sensor might be in different states that vary in their criticality. Hence, the reliability grade may change dynamically at runtime [23]. For example, the human temperature might be normal and require a normal level of reliability, but when the temperature suddenly goes over or under the natural limit, the reliability requirement becomes much more rigorous. As a consequence, WBAN needs to dynamically guarantee reliability for the sensor nodes. Assuring a dynamic level of reliability for different sensors is a challenge of great importance. Table 2-4 shows bit rate and some QoS requirements for a number of WBAN applications.

Another important challenge is the antenna design in terms of height, size and material shape. These factors, as well as sensor limitations and breakdowns change the network operational conditions, which consequently leads to incomplete and erroneous sensor data [7]. Due to these challenges, the design of these networks requires the definition of new protocols with respect to those used in general purpose WSN.

Table 2-4: Heterogeneous requirements for some WBAN applications [47].

Application	Bit Rate	Delay	Bit Error Rate (BER)
Deep brain simulation	< 320 kbps	< 250 ms	< 10^{-10}
Drug delivery	< 16 kbps	< 250 ms	< 10^{-10}
Capsule endoscope	1 Mbps	< 250 ms	< 10^{-10}
ECG	192 kbps	< 250 ms	< 10^{-10}
EEG	86.4 kbps	< 250 ms	< 10^{-10}
EMG	320 kbps	< 250 ms	< 10^{-10}
Glucose level monitor	< 1 kbps	< 250 ms	< 10^{-10}
Audio streaming	1 Mbps	< 20 ms	< 10^{-5}
Video streaming	< 10 Mbps	< 100 ms	< 10^{-3}
Voice	50 -10 Mbps	< 100 ms	< 10^{-3}

2.4 MAC Protocols for WBAN

Unlike WSN, WBAN is considered a short range communication network due to the short communication space and the limitations on the number of nodes where there is no need for multi hopping; and therefore, WBAN often follows a star topology [13]. At the same time, this very short range and scale network suffers from a very vulnerable medium due to the deep fade phenomenon. However, nodes still need to access the medium successfully, and their data packets must be received in a reasonable time, in the same order and in the same way when sent without the lowest percentage of packet loss. For those reasons, the majority - if not all- the WBAN challenges are confined with the reliability of the MAC layer, for which proposing MAC techniques present a number of unique gaps, and makes designing reliable and energy efficient WBAN a challenge. These observations provided motivation to tackle WBAN from MAC layer perspective.

Generally MAC protocols are grouped into two categories: **contention based access and contention free access** [24]. In contention based access, nodes compete in accessing the medium, which leads to channel congestion and packets collision. As it is stated in Section 2.3.5, channel congestion leads to a buffer overflow, which increases packets loss [53]. A collision is very likely to occur in WBAN because physiological data is correlated. For example, in an emergency, a group of sensors might be involved in transmission, leading to collision and consequently packet loss, which could be fatal even if every

component of WBAN is working properly [28, 29]. Besides packets loss, collision dissipates energy due to packets re-transmission. Additionally, contention based MAC requires nodes to stay idle, and research in this arena revealed that idle listening consumes as much energy as transmitting. During idle listening, it is highly likely that some nodes receive data packets that are not designated to them. This phenomenon is called overhearing which is another factor for energy dissipation. Channel congestion, packets collision, idle listening, overhearing and energy dissipation are reasons for why the contention based MAC protocols are not recommended for WBAN channel access [24].

The study in [24] reveals that the contention free based access MAC protocols achieve a more reliable and energy efficient WBAN than the contention based protocols. TDMA based MAC is one of the typical contention free access mechanisms that is widely used in literature to achieve a reliable and energy efficient wireless networks. By following TDMA based MAC, nodes are scheduled in accessing the medium. Each node uses the channel at a specific time slot and sleeps at other nodes' time slots. Consequently, this strategy avoids the major drawbacks of the contention based MAC algorithms, which are the collision, idle listening and overhearing. Moreover, the normal traffic of WBAN medical applications is usually periodic, and TDMA approaches are very suitable for this kind of traffic because the nodes are duty cycled to use access the medium. It could be argued that the complexity of scheduling is one of the major drawbacks of the TDMA based algorithms for a scalable network [24]. However, since WBAN is a short range and non-scalable network, the complexity of scheduling is not an issue.

TDMA based MAC protocols can help in anticipating the status of WBAN channel. This is because, if nodes can operate in a timely, scheduled manner following a TDMA approach, then nodes can realise that the reason behind losing packets is the deep fade in their links with the controller. Other reasons, such as packets collisions, would be unlikely because the nodes follow contention free channel access mechanism. Additionally, since deep fade persists for a long time, then TDMA based techniques could help in anticipating the channel status in the upcoming periods. Due to those reasons, this work adopts the TDMA based MAC for WBAN channel access.

Although the study in [24] surveys multiple contention and contention-free based MAC protocols [55, 56, 57, 58, 59, 60], and recommends TDMA based MAC techniques for WBAN channel access, it discusses the presented literature work from energy efficiency

perspective only. The vast majority of the work proposed in the literature, consider the ideal behavior of the channel status in WBAN. Nevertheless, WBAN cannot be studied in isolation with the realistic characteristics of its channel status, which involve the deep fade phenomenon. Tolerating the deep fade phenomenon in WBAN medium is crucial, and to date the work described in the literature remains limited.

The following subsection discusses the drawbacks of the traditional static TDMA approaches adopted by WBAN de-facto standards, and discusses why their adopted TDMA based techniques fail to provide a reliable and energy efficient WBAN. Next, Section 2.4.2 highlights the main dynamic TDMA based MAC approaches proposed in the literature to overcome the limitations of the two standards by tackling the deep fade phenomenon in WBAN medium, those solutions are classified into four categories.

2.4.1 Static TDMA based MAC scheduling

As it is stated in Section 2.3.4, the IEEE 802.15.4 and IEEE 802.15.6 standards are considered as the WBAN de-facto standards. IEEE 802.15.4 supports TDMA channel access by using GTS(s) in the CFP [14], while IEEE 802.15.6 provides TDMA mechanisms through the scheduled allocation slots in the contention free access periods [15]. Section 2.2.2 and Section 2.3.4 discusses the principles of the superframe structures of those standards in more details. Although the two standards support TDMA based channel access in the contention free period of their superframe, their mechanisms do not provide enough reliability and energy consumption efficiency. This is because TDMA mechanisms adopted by the standards provide static slot allocation. Static TDMA scheduling has two drawbacks. First, each node in the network is obligated to use the channel in its time slots whether its link suffers from deep fade at a given time or not. Second, each node is allocated the same number of slots in each TDMA round regardless of its needs. For those reasons, if a node loses packets during its time slots due to deep fade, performing re-transmission will be useless because the deep fade of the links persists for a long time. In addition, offering the node, the same number of time slots in each round is not useful, and there is a need to propose solutions that help in parametrising the TDMA schedule and the select the optimal number of time slots according to nodes' requirements in each round. Although the IEEE 802.15.4j supports a multi-periodic GTS(s) to solve the problem of the static GTS allocation provided by the legacy IEEE 802.15.4 standard [52], the major goal of IEEE 802.15.4j amendment is to reduce the

energy consumption of medical devices of periodic traffic, and it does not consider the channel status in WBAN. In fact, to alleviate the effect of the deep fade, the TDMA slot allocation should be dynamic according to the channel status.

2.4.2 Dynamic TDMA based MAC scheduling

There are several MAC schemes that attempt to tackle reliability in WBANs by proposing dynamic scheduling techniques. Those solutions vary between tolerating the deep fade of the medium by reordering the nodes in the schedule, delaying the channel access period, or by exploiting both the contention and contention free access mechanisms in a hybrid manner. Some of the proposed techniques consider the heterogeneity of the traffic context in WBAN, while others do not. Those solutions are presented in the following subsection.

A. Reordering nodes in the schedule

Tselishchev et al. in [25] proposed to change dynamically the order of nodes in the TDMA schedule according to the deep fading in the channel to minimise its effect. In [25], the hub observes the performance of nodes' links on the previous superframe and schedules nodes on the upcoming superframe accordingly. Those nodes whose links are observed good in the previous superframe are synchronised before the nodes of bad links. Yet, the order of nodes with good links in accessing the channel is flipped according to when their links status was observed. The advantage of flipping the order of the nodes in the TDMA schedule is to harness the good status of the link as fast as possible before it goes to a bad state. Liu et al. in [26] followed the same approach proposed by Tselishchev et al. in [25] and [27], and suggested to re-order the nodes in the next TDMA schedule when the deep fading occurs in the current one. However, changing the nodes order assures a slight reduction in packet loss rate over the static scheduling algorithm only. This is because the hub assumes that the deep fading of the links always occurs at the beginning of the active sessions of the node. In fact, the occurrence of the deep fade of the links is unpredictable. Deep fade might occur during the node's active period or at the end of the node's session as well, which means that the flipping technique might not contribute to any improvement and it might make things rather worse.

B. Delaying channel access

Tselishchev et al. in [27] tried to improve their solution in [25] by suggesting that packet retransmission should be delayed to the subsequent superframes because direct packet retransmission is useless, and at the expense of energy consumption. Tselishchev et al. also suggested a number of allocation slots larger than the number of nodes in the network, and thus having extra slots dedicated for packets retransmission. Extra slots are adaptively allocated anywhere in the superframe according to the energy budget of the nodes. Rezvani and Ghorashi in [28] also adopted a similar strategy and suggested delaying the transmission of nodes in normal situations to the end of the superframe structure when deep fade occurs. However, this does not guarantee successful packets delivery, due to the unpredictability of the occurrences of the deep fade of the links, which is at the expense of power consumption.

C. Hybrid channel access

Other solutions suggested that the effect of the deep fade in the channel could be distributed by allowing nodes to contend in accessing the channel. Liu et al. in [29] suggested that the effect of the deep fade could be mitigated by adopting a hybrid superframe structure that involves both contention and contention free channel access techniques. The superframe based MAC protocol proposed in [29] is called Context Aware MAC (CA-MAC). CA-MAC inherits the basics of the IEEE 802.15.4 beacon enabled superframe structure, and comprises three parts: the beacon frame, the contention based period which's duration changes dynamically according to the level of fading in the channel, and the third part is the contention free period which follows the TDMA mechanism. Scheduled-based slots are allocated adaptively for nodes based on traffic intensity. To relax the effect of the channel deep fade, Liu et al. in [29] estimate the channel status in the current TDMA round. Accordingly, if the channel suffers from deep fade, nodes are allowed to contend in accessing the medium in the next superframe structure, so that the deep fade of the channel is distributed between nodes. Although their solution considered the collision that could occur in the contention based period, they did not consider the energy consumption. Moreover, distributing the effect of the deep fade between the nodes does not offer a good solution as the node that transmits during the contention access period might have a poor link, which is also at the expense of power consumption.

Rezvani, and Ghorashi in [28] suggested adopting contention access approach for non-medical traffic and for medical data in emergencies (the proposed superframe in [28] is also based on the IEEE 802.15.4 superframe structure). However, due to the availability of contention-random based access period, collision, idle listening and overhearing are likely to occur between nodes. This increases packet loss and dissipates energy. Moreover, the node which accesses the medium in the contention based access could have a poor link status as well. As a result, packets will not only be lost due to the deep fade in the channel, but also due to collisions.

D. Heterogeneous traffic consideration

In their proposed work in [28], Rezvani, and Ghorashi handled three types of traffic: the normal medical traffic, the emergency medical traffic, and the non-medical traffic. The separation between the non-medical, normal medical, and emergency medical traffic is adaptive, according to channel condition and the user's medical situation. As mentioned previously, the proposed superframe structure comprises contention and contention free channel access mechanisms. Nodes with non-medical traffic contend in accessing the medium in CAP, whereas the nodes with normal medical traffic access the medium in the Normal TDMA period (NTDMA). The hub specifies a time slot to check for an emergency. During this time slot, the hub examines the channel to check if it is busy or not, if it is busy then it decides there is an emergency. Nodes in emergencies follow two mechanisms, they first try to compete in accessing the medium with the non-medical traffic in CAP, and if their transmission attempts fail, they are given extra slots to use the medium in the Emergency TDMA period (ETDMA). Although Rezvani and Ghorashi considered that using CAP for emergencies is not reliable due to collision with the non-medical traffic, offering more time to the nodes in an emergency will not solve the problem either and could be even worse. This is because, a longer time in accessing medium exposes the nodes to longer deep fade durations, which lead to an increase of loss of sensitive data and severely consumes energy. In addition, due to the channel deep fade, an emergency could not be detected in the first place. Moreover, the proposed technique requires a very sophisticated superframe structure while nodes in an emergency might wait for multiple superframes, which increases packet delays. The authors claimed a guarantee of less than one second for emergency transmission, however, as stated in [5] the delay requirements in emergencies should be less than 125 ms.

Liu et al. considered emergencies in their two proposed works in [26] and [29], and proposed a technique that changes nodes' transmission duration according to their monitoring context, i.e. nodes in emergencies are given more slots than other nodes, due to their increased traffic load. In [26] Liu et al. proposed a constraint, which suggests that the transmitted information in an emergency should be larger than the minimum throughput. Minimum throughput is correlated with the sampling rates that is decided by doctors according to the medical scenario. This constraint is achieved by offering nodes in emergency more slots than other nodes. In their next work in [29], Liu et al. adopted a similar approach, but without providing a reliability constraint or slot allocation procedure. When the master node detects an emergency, it offers those nodes that are related to the monitoring context more slots than other nodes. However, as WBAN is composed of a very vulnerable medium, offering emergency nodes extra slots could not be beneficial at all. This is because if a node is in an emergency situation and has a poor link status, and has been allowed to access the valuable medium for longer time periods, then more sensitive information will be lost, which adversely reduces WBAN reliability. Moreover, according to their performance evaluation, accessing the channel for a longer time in emergencies consumes more energy. In addition, the extra slots offered to the nodes in emergencies are taken from the rest of the nodes, and thus, in emergency situations, not all the nodes in the network will have the chance to use the medium.

To conclude, in normal situations, all previously discussed techniques allocate a static number of time slots to nodes and do not justify the allocation criteria for the slots, or the slot length used for such allocation. It is important to justify the parametrisation of the slot length, as it is the basic building block of the TDMA schedule. In addition, their implementation requires complex amendments to IEEE 802.15.4 and IEEE 802.15.6 superframe structures. Moreover, nodes rely heavily on the controller to manage the channel access schedule as these TDMA techniques are fully centralised. The drawbacks of the dynamic TDMA based MAC protocols that tackle deep fade in WBAN medium are summarised in the following points:

1. None of the proposed techniques consider the unpredictability of the occurrence of the deep fade phenomenon. Therefore, none of them can avoid the effects of the deep fade.
2. Neither time slot allocation nor the slot durations are justified in normal situations.

3. The vast majority of the proposed techniques tend to offer nodes in emergency more slots than other nodes, which is very problematic in the occurrence of the deep fade, because it severely increases the loss of the sensitive data and dissipates more energy.
4. All proposed techniques, which consider emergencies suffer from a dramatic increase in energy consumption due to the high load of traffic.
5. The extra slots offered to nodes in emergency are usually taken from other nodes, therefore some nodes will be prohibited from accessing the medium. Accordingly, not all nodes have the chance to use the medium when an emergency occurs.
6. In all the proposed techniques, only the controller decides the status of the links of the nodes, which makes the proposed approaches fully centralised.
7. All proposed techniques are based on the superframe structure of the IEEE 802.15.4 and the IEEE 802.15.6, thus they are not generic and require complex amendments to the superframe structures of the standards.

Indeed, the long duration of the deep fade could be harnessed in two ways: by adopting TDMA based MAC approach, a node has a sole use of the medium at a certain time slot. Accordingly, the node itself can realise that the reason behind losing its packets is the deep fade in the link between itself and the controller. In addition, when a node is in deep fading, it can realise that this phenomenon might last for a long time and therefore performing re-transmission is useless. In other words, the node predicts its link status in the upcoming time-periods in the channel. Following this prediction, the node can take direct action whenever it detects that its link is poor during its time slots without relying on the controller. This idea is the entrance point to the proposed techniques, presented in Chapter 3, which also provides an answer to the first two research questions presented above.

2.5 Conclusions

This chapter has provided the background to the topics that are covered in this thesis. First the chapter presented an overview of WSN and WPAN. Next, the chapter investigated WBAN in details. A description of WBAN was provided along with a justification of why this technology has potential in various applications. The features and requirements that

characterise WBAN and differentiate it from WSN were also presented. A number of communication standards that support WBAN are highlighted. It has been shown that several key challenges need to be solved to design a WBAN, which meet the applications' and the user's needs. One of the challenges is achieving a reliable WBAN with very high QoS, especially in the medical applications. Appropriate scheduling, duty cycling and interference-avoidance methods should be implemented at MAC and physical layers to reduce BER and packet loss [6]. Other essential parameters to consider including the end-to-end delay and the capability to provide a fast reliable reaction in emergency situations [23, 28, 29]. The QoS requirements of WBAN applications must be met without degrading performance or increasing network complexity [21]. The limited energy resources in WBAN call for energy efficient channel access mechanisms in terms acknowledgement, retransmission, along secure correction and error detection strategies [6, 8]. Besides power resources, other resource constraints should be considered, such as the buffer which is of a limited size due to the tiny WBAN devices.

To meet these challenges, the design of WBAN requires the definition of new protocols other than those proposed for WSN. In essence, a special attention should be made to the MAC layer, because WBAN often adopts a star topology, all the challenges revolve around the channel access, at the same time WBAN should guarantee a successful packets transmission especially in emergencies, despite the vulnerability of WBAN, which suffers from the phenomenon of the deep fade. Deep fade in WBAN channel is a unique phenomenon that distinguishes WBAN from other networks. Deep fade represents a serious challenge that degrades WBAN reliability, because its occurrence is frequent, unpredictable, and when it occurs, it persists for long time, which increases packets loss and degrades energy consumption. Ongoing research efforts are focused on various technical issues in WBAN, such as lowering power consumption, proposing portable and convenient communication protocols, coexistence with other network technologies, infrastructure, the heterogeneous applications of WBAN and so forth [6, 8, 9, 10, 22, 23]. Nevertheless, few have addressed the anomalous behaviour of WBAN medium due to the deep fade phenomena. For those reasons, deep fade is chosen as the main gap that this thesis aims to tackle to design reliable WBAN solutions. In depth review of the literature work that tackles the issue of reliability and channel deep fade in WBAN, their limitations and drawbacks are presented in Section 2.4.

Literature work suggests that TDMA based MAC techniques are more reliable and energy efficient than other medium access techniques. However, static TDMA techniques adopted by the standards are not suitable for WBAN channel access, because they do not avoid the channel deep fade when it occurs, which increases packets loss and dissipates energy. To solve the drawbacks of static TDMA techniques, several approaches are proposed in literature to alleviate the effect of deep fade by adopting dynamic TDMA based MAC techniques. Those approaches are classified in Section 2.4 into four categories. None of the proposed techniques avoids the challenge of the deep fade in WBAN medium, because the occurrence of the deep fade is unpredictable. Moreover, considering the deep fade in the WBAN channel should not be isolated from the other challenges of WBAN, which are energy consumption and the heterogeneity of its applications. Hence, other ways should be proposed, which avoid the deep fade in the WBAN channel, and prove its resilience in the various contexts and without increasing energy consumption. This thesis addresses these issues by proposing a novel and dynamic TDMA based scheduling protocols that provide reliable and energy efficient WBAN. The proposed protocols avoid the channel deep fade and tolerate the heterogeneity of the traffic. Those protocols are discussed in the Chapter 3.

Chapter 3: The Reliable and Energy Efficient Scheduling Algorithms

3.1 Introduction

As it is discussed in Section 2.4, none of the proposed TDMA techniques avoids the deep fade in WBAN medium. This is very problematic especially in emergency situations. The vast majority of the work in literature do not justify the distribution of the time slots between nodes or the slot duration, and those who do, they do not consider the channel deep fade in the slot allocation strategy. Literature work that consider channel status in WBAN are not generic and require sophisticated amendments to the superframe structures of the IEEE 802.15.4 and IEEE 802.15.6 standards.

This chapter presents the proposed solution to solve the discussed drawbacks of the TDMA techniques proposed in the literature. The proposed solution comprises three TDMA based MAC algorithms, which are generic enough to be adopted by any protocol, standard or communication technology that provides TDMA based capabilities. The proposed solution emphasises that the phenomenon of the deep fade in the medium should be strictly avoided, and the time slot allocation should be dynamic while considering the channel status, the node's buffer requirements, and energy efficiency. The first part of the solution is presented in the second section of this chapter and is called Adaptive Sleep MAC. It enables the nodes to avoid the deep fade in the medium by allowing them to sleep dynamically whenever they detect a deep fade in their links. In order to achieve fairness in utilising the medium, and to avoid buffer overflow, two novel dynamic slot allocation techniques are proposed.

The first technique is called Dynamic Scheduling Based on Sleeping slots (DSBS) and is presented in the third section of this chapter, and the second technique is called Dynamic Scheduling Based on Buffer (DSBB) and is presented in the fourth section of this chapter. Both DSBS and DSBB uses the Adaptive Sleep MAC. Besides, both DSBS and DSBB schedules the nodes dynamically, yet they differ in their slot allocation strategy. In DSBS,

the controller calculates the duration the node spent in avoiding the medium due to the occurrence of a deep fade in the node's link. According to the estimated time, the controller offers the nodes that didn't have the chance to use the medium in the previous TDMA round, more slots than other nodes. In DSBB however, the controller follows an opposite approach, as it calculates the number of packets that are saved in each node's buffer, which reflects whether the node avoided using the medium in the previous round or not. Consequently, both DSBS and DSBB validate each other, as in both of them, nodes with more packets in their buffer get extra slots in the subsequent TDMA schedule. This chapter is summarised in the fourth section.

3.2 Adaptive Sleep TDMA MAC

This solution provides an answer to the first two research questions presented in Section 1.4. After a successful association with the controller, nodes send TDMA slot request frames to ask the controller to assign them a number of TDMA slots. The initial number of TDMA slots to be requested is one of the configuration parameters of the network, and it should be parametrised once the network is established. In order to achieve the highest level of reliability, the TDMA schedule has to be configured in a way that all the slots in the TDMA are occupied by the nodes leaving no availability for extra free time slots. In addition, at the beginning of the network operations, the slots of the TDMA schedule should be distributed equally between the nodes. After receiving the TDMA slots request, the controller records the number of slots requested by each node in a control frame that specifies the TDMA schedule. This control frame manages the network and specifies the parameters values of the TDMA schedule. The control frame is similar to the beacon frame adopted by the IEEE 802.15.4 and the IEEE 802.15.6 standards. Using this frame, nodes are scheduled to access the channel when the controller receives the TDMA slot request. If the request has been accepted first, the associated node will use the channel before others. Besides, the controller offers each node a number of time slots equal to the number of requested slots. The controller advertises the schedule using the control frame. Therefore, a node will wake up during its allocated time slots and try to transmit its packets. The node should receive an acknowledgment from the controller after every successful packet transmission. If the node fails to receive an acknowledgment frame, then the node assumes that its link suffers from a deep fade, and thus will not perform packet re-transmission. In addition, the node will shut down its transceiver and continue

sleeping until the TDMA current round finishes. Other nodes will continue to use the channel according to the schedule. The pseudocode of Adaptive Sleep TDMA MAC is depicted in Figure 3-1.

```

Input: A number of nodes  $N$ , TDMA schedule of  $n$  slots, each  $N_i \in N$  is assigned equal number
of slots  $S$ , where  $S = n/N$ , and each  $N_i$  has a buffer  $B_i$ .
Output: Adaptive Sleep TDMA MAC

//the following is performed by each node  $N_i$  once its active time starts (allocated time slots)
1  FOR each  $N_i \in N$  do the following
2      WHILE TDMA round
3          IF  $N_i(S_i)$ . start = true
4              WHILE  $N_i(S_i)$  //during the node's active session
5                   $N_i$ .set(state)  $\leftarrow$  Active;
6                  IF  $N_i(B_i.numOfPkt) = 0$ 
7                       $N_i$ .set (state)  $\leftarrow$  idle; //no packets in  $N_i$  buffer
8                  END IF
9                  ELSE
10                      $N_i(Data\_Packet.bufferField) \leftarrow B_i.numOfPkt$ ;
11                      $N_i.send(Data\_Packet)$ ;  $N_i.wait(Ack)$ ;
12                     IF  $Ack(Timer.timeout)$  //because of deep fade
13                          $N_i.set(state) \leftarrow sleep$ ;
14                     END IF
15                 END ELSE
16             END WHILE
17         END IF
18     END WHILE
19 END FOR

```

Figure 3-1: Adaptive Sleep TDMA MAC

3.3 Dynamic Scheduling Based on Sleeping Slots (DSBS) MAC

Allowing the nodes to sleep during their active period leads to unfairness in utilising the medium, hence it will increase the number of packets in the node's buffer. At very high traffic rates, this will cause a buffer overflow. As a result, if the packets are not lost due to deep fade, they are more likely going to be lost due to buffer overflow. Moreover, sleeping during active session increases packet delay. Therefore, optimised solutions are required to solve the delay, unfairness and buffer overflow issues without increasing the size of the buffer. Optimised solutions can be achieved by dynamically allocating the resources according to nodes' requirements. Consequently, the proposed DSBS technique is based on the sleeping duration of the nodes. For example, extra slots can be allocated to the nodes that have more packets in their buffers. Typically, nodes which have slept during their active period in the previous round would logically have more packets in their buffer compared to others (assuming nodes transmit identical amount of traffic rates).

At its basic level, in this step, traffic prioritisation is not considered. Since all the time slots in the TDMA schedule are occupied and as the number of time slots in any TDMA schedule is finite and limited, the only possible way to give nodes extra slots is to borrow these slots from other nodes whose links have not suffered from fading in the current round. This is to relax the constraint on their buffer and to meet at the same time the delay requirement, which is 250 ms at maximum for normal traffic [5]. Each node should be allocated a number of slots equal to the number of slots it slept during the previous round. By recording the time at which the node slept, and when the node's active session ends, the controller can decide for how long the node has slept during its active time slots and allocates a number of slots accordingly. The DSBS pseudocode is depicted in Figure 3-2. To have a better description of the DSBS, the following definitions are provided.

Definition 1: Let N and n be the total number of nodes in the network and the total number of the TDMA schedule slots respectively, $\forall Ni \in N \leftarrow S$ slots is assigned to Ni once the network is established, where $S = n/N$.

Definition 2: Given a slot length L , the node's total channel access time is denoted as T_i , where $T_i = S_i \times L$.

Definition 3: Let the time recorded by the timer for a node be t_i , then the number of slots the node has slept will be $E = t_i/L$, where $E \leq S$. Accordingly, as long as there are enough slots in the schedule, the controller (CRL) assigns N_i extra slots E . Therefore, in the next round, N_i will be assigned a total number of slots $S_i = S + E$ slots. Note that if $E \leq 1$ then there is no need for the controller to offer N_i any extra slots in the next round and there will be no change in the TDMA original schedule. Thus, at any round, $1 \leq E \leq S$, and more than one node could sleep during its active session due to the deep fade in the channel.

DSBS works as follows: During the TDMA round, the controller should expect to receive packets from the nodes according to the TDMA initial schedule. If the controller does not receive what it expects from a certain node at a certain time, it switches on directly a clock timer and keeps it activated until the end of the active time duration of that node. This timer will record how long that node is sleeping. Therefore, during any TDMA round, if at least one node sleeps during its active period, the CRL creates a list and saves the identifiers (IDs) of nodes with bad links along with the calculated number of slots they slept. The ID of a node is the node's index in the network. The nodes in the list can acquire an extra number of slots E as long as there are enough slots to distribute. The group of nodes that are not included in the list is denoted as N_r . N_r refers to the remaining nodes which had a good link status in the previous TDMA round, and therefore do not require extra slots for the next round. Accordingly, a minimum number of slots that each $N_i \in N_r$ can acquire should be defined. This threshold is denoted as **slotsMinValue**. If the number of the remaining slots in the schedule is not enough to be distributed over N_r , then the extra slots for the nodes in the list should be decremented until there are enough slots to distribute over the nodes that are not in the list. This is to avoid any $N_i \in N_r$ from acquiring a number of slots less than **slotsMinValue**. However, in some conditions, the opposite case might occur, i.e., after allocating the nodes in the list extra slots, and allocating **slotsMinValue** each node in the set N_r , a number of remaining slots in the schedule might still be available. In this case, those remaining slots will be allocated to the nodes that buffered more packets.

To achieve fairness between nodes, a new field is added to the node's data packet to carry its current buffer load. Besides calculating the sleeping time of the node in the current round, CRL sorts nodes according to the value of their buffer field, which is

added to the node's last received data packet. Accordingly, in the next round, after assigning extra slots to nodes with bad links, the remaining number of slots are assured to be distributed equally over the N_r , whereby each $N_i \in N_r$ is assigned **slotsMinValue**, then any extra slots will be granted to nodes according to the number of packets in their buffer. Using this approach, the slot allocation will consider a node's communication requirements and avoids fading in the channel. It is worth mentioning here that this technique should take place just in case at least one node had a bad link during the previous TDMA round. Otherwise no change should take place on the next schedule and nodes should be re-allocated a number of time slots S equivalent to the number they requested when the WBAN was established. Accordingly, DSBS provides an answer to the third research question presented in Section 1.4, because it allows the nodes to access WBAN medium according to their needs, which depend on their link's status and buffer load. In the sequel, two examples are presented implementing DSBS.

Example 1: Assume that the total number of nodes in the network is $N = 5$. If the total number of the TDMA schedule is $n = 15$ time slots, then each node in the network N_i should be assigned $S_i = 3$ slots. If the slot length $L = 3$ ms, then for each $N_i \in N$, the node's total channel access time $T_i = 9$ ms. Let's assume N_3 slept during its active session for $t_3 = 6$ ms, then the number of slots N_3 has slept is two slots, which also means that the number of extra slots the node should acquire is $E = 2$. Accordingly, the CRL creates a list $L = N_3, 2$. Therefore, in the next round, N_3 will be assigned a total number of slots $S_i = 5$ slots (three original slots + two extra slots). The rest of the nodes in $N_r = N_1, N_2, N_4, N_5$ will be offered the **slotsMinValue**. If **slotsMinValue** is set to two for example, then the overall number of the allocated slots will be 13 slots. The remaining unassigned two slots will be offered to those nodes with the highest number of packets in their buffer.

Example 2: Now, assume that there is another node recorded in the list L , which requires extra slots, $L = N_3, 2, N_4, 3$. This means that in the next round, N_3 should be assigned a total number of slots $S_3 = 5$ slots, N_4 should be assigned a total number of slots $S_4 = 6$ slots. As the total number of slots in the TDMA schedule $n = 15$, then there is not enough time slots to distribute over $N_r = N_1, N_3, N_5$. Because according to this calculation, the overall number of slots that should be allocated to the nodes in both lists L then N_r will be 17, whereas the total number of slots of the TDMA schedule is

15. In this case, the number of slots for N_4 should be decremented to five, and N_3 should be allocated just four slots. Consequently, there will be enough time slots to distribute over $N_r = N_1, N_3, N_5$ as each $N_i \in N_r$ will be allocated the **slotsMinValue**.

```

Input: 1 controller CRL, a number of nodes N, TDMA schedule of n slots, each  $N_i \in N$  is assigned
equal number of slots S, where  $S = n/N$ , the minimum number of slots  $N_i$  can acquire is
slotsMinValue and each  $N_i$  has a buffer  $B_i$ .
Output: Dynamic slot allocation TDMA schedule

1 // the following is performed by the controller CRL during the active time of each node  $N_i$ 
2
3 FOR each  $N_i \in N$  do the following
4     WHILE TDMA round
5         IF  $N_i(S_i).start = true$ 
6             WHILE  $N_i(S_i)$ 
7                 IF NOT (CRL.received( $N_i(Data\_Packet)$ ))
8                     CRL.create(list); CRL(list[item])  $\leftarrow N_i(ID)$ ;
9                     CRL(timer.start)  $\leftarrow local\_time$ ; //switch on timer
10                END IF
11            END WHILE
12            CRL(timer.end)  $\leftarrow local\_time$ ;  $ti \leftarrow timer.end - timer.start$ ;
13             $E \leftarrow ti / slotSize$ ; CRL(list[ $N_i(ID)$ ])  $\leftarrow E$ ; //calculate num of extra slots
14        END IF
15    END WHILE
16 END FOR
17
18 // the following is performed by the controller CRL, to prepare the new time schedule
19
20 IF NOT (list = NULL)
21     Sort (N, Data_Packet.bufferField); //sort nodes according to buffer load
22      $NR \leftarrow N - list.length$ ; //remaining nodes, which had good links in previous round
23     FOR each  $N_i \in list$  do the following //list of nodes of bad links, slept during previous round
24         IF  $N_i(E) < 1$  //if  $N_i$  slept less than one slot
25             CRL.allocate( $N_i$ )  $\leftarrow S$ ; //Ni offered only original num of slots
26         END IF
27         ELSE
28              $S_i \leftarrow S + E$ ; //offer Ni extra slots E
29             WHILE  $(n - (S_i \times list.length) / NR) < slotsMinValue$ 
30                  $S_i \leftarrow S_i - 1$ ; //no enough slots
31             END WHILE
32             CRL.allocate( $N_i$ )  $\leftarrow S_i$ ;  $n \leftarrow n - S_i$ ; list  $\leftarrow list - N_i$ ;
33         END ELSE
34     END FOR
35     FOR each  $N_i \in NR$  do the following //the remaining nodes not in the list (of good links)
36         IF  $(n/NR \geq slotsMinValue) \text{ AND } (n \text{ MOD } NR) > 0$ 
37              $S_i \leftarrow (n/NR) + 1$ ; CRL.allocate( $N_i$ )  $\leftarrow S_i$ ;  $n \leftarrow n - S_i$ ;  $NR \leftarrow NR - 1$ ;
38         END IF
39         ELSE // no enough slots remains, offer nodes slotsMinValue
40              $S_i \leftarrow n / NR$ ; CRL.allocate( $N_i$ )  $\leftarrow S_i$ ;  $n \leftarrow n - S_i$ ;  $NR \leftarrow NR - 1$ ;
41         END ELSE
42     END FOR
43 END IF
44 ELSE // if no node slept during the previous TDMA round, i.e. deep fade didn't occur
45     FOR each  $N_i \in N$  do the following
46         CRL.allocate( $N_i$ )  $\leftarrow S$ ; //nodes offered only original num of slots
47     END FOR
48 END ELSE
49 CRL.send(CRLframe); CRL.delete(list); //send the new TDMA schedule and delete the list

```

Figure 3-2: Dynamic Scheduling Based on Sleep Slots (DSBS).

3.4 Dynamic Scheduling Based on Buffer (DSBB) MAC

This section provides another solution for the third research question presented in Section 1.4. When the node sleeps during its active period, the packets during this time will be stored in its buffer. Assuming a basic scenario where nodes send packets at Constant Bit Rate (CBR) with the same packet arrival rate, then the number of packets in the node buffer could help to estimate the sleep duration. Therefore, in the second technique, the nodes are offered extra time slots based only on the number of packets in their buffer. Nodes with the highest number of buffered packets will be allocated more slots in the next round. The following definitions are proposed to help in the description of the proposed approach.

Definition 4: Let T be the time each packet takes from the moment it is transmitted by the node until it receives the acknowledgment frame and let L be the slot length, then the capacity of each time slot to hold packets is given by $C = L/T$. Accordingly, if one slot can occupy C packets, then two slots can occupy $2C$ packets, and three slots can occupy $3C$ packets, and so on.

Definition 5: Let x be the number of packets in the buffer, and C the number of packets that can be carried by a time slot (or the capacity of a time slot), then the extra slots E allocated to nodes according to the number of packets carried in their buffer can be calculated as follows:

$$E = \begin{cases} 1 & \text{if } (1 \leq x \leq C) \\ \lfloor \frac{x}{C} \rfloor + 1 & \text{if } (x \bmod C > 0) \\ \frac{x}{C} & \text{Otherwise} \end{cases} \quad (5)$$

The pseudocode of DSBB is depicted in Figure 3-3. Similar to DSBS technique, nodes can be allocated extra slots according to the number of packets in their buffer, as long as there are enough slots remaining to cover all nodes. When there are not enough slots in the schedule to offer nodes extra slots, then each $N_i \in N_r$ acquires **slotsMinValue**. However, if all the nodes have been allocated the required slots, the remaining slots in the schedule will be eventually granted to those nodes that carry more packets in their buffer. Example 3 depicts a scenario of DSBB. Accordingly,

DSBB allows the nodes to access WBAN medium according to their needs, which depend on their link's status and buffer load.

Example 3: If we assume that $T = 1$ ms and the slot length $L = 3$ ms, then the capacity of each time slot to hold packets $C = 3/1 = 3$ packets. As each node is originally allocated $S = 3$ slots, then the three slots can hold nine packets. Assume that in the current TDMA round, N_3 sends its data packet to the *CRL* and the buffer field of N_3 is $x_3 = 6$ packets, then the number of the extra slots that should be offered to N_3 for the next TDMA schedule, is $E = 2$ slots. So in total $S_3 = 5$ slots. The procedure of distributing the slots over the remaining nodes is identical to the one presented in Example 1 in Section 3.3.


```

Input: 1 controller CRL, a number of nodes N, TDMA schedule of n slots of capacity C
Data_Packets, each  $N_i \in N$  is assigned equal number of slots S, where  $S = n/N$ , the minimum
number of slots  $N_i$  can acquire is slotsMinValue and each  $N_i$  has a buffer Bi.
Output: Dynamic slot allocation TDMA schedule

1 // the following is performed by the controller CRL, to prepare the new time schedule
2
3 IF NOT (list = NULL)
4     Sort (N, Data_Packet.bufferField); //sort nodes according to buffer load
5     NR  $\leftarrow$  N - list.length; //remaining nodes which had good links in previous round
6     FOR each  $N_i \in$  list do the following //list of nodes of bad links, slept during previous round
7         i  $\leftarrow$  1;
8         //calculate extra slots according to buffer load & slot size
9         WHILE (n / NR  $\geq$  slotsMinValue) //enough slots remain
10            IF i  $\leq$  list [Ni(Data_Packet.bufferField)] AND
11                list [Ni(Data_Packet.bufferField)]  $\leq$  i $\times$ C
12                Si  $\leftarrow$  S + i;
13            END IF
14            ELSE IF i $\times$ C  $\leq$  list[Ni(Data_Packet.bufferField)] AND
15                list[Ni(Data_Packet.bufferField)]  $\leq$  (i+1) $\times$ C
16                Si  $\leftarrow$  S + i;
17            END ELSE IF
18            CRL.allocate(Ni)  $\leftarrow$  Si ; n  $\leftarrow$  n - Si; list  $\leftarrow$  list - Ni;
19        END WHILE
20    END FOR
21    FOR each  $N_i \in$  NR do the following //the remaining nodes not in the list (of good links)
22        IF (n / NR  $\geq$  slotsMinValue) AND (n MOD NR) > 0
23            Si  $\leftarrow$  (n / NR) + 1; CRL.allocate(Ni)  $\leftarrow$  Si ; n  $\leftarrow$  n - Si; NR  $\leftarrow$  NR-1;
24        END IF
25        ELSE // no enough slots remains, offer nodes slotsMinValue
26            Si  $\leftarrow$  n / NR; CRL.allocate(Ni)  $\leftarrow$  Si; n  $\leftarrow$  n - Si; NR  $\leftarrow$  NR-1;
27        END ELSE
28    END FOR
29 END IF
30 ELSE // if no node slept during the previous TDMA round, i.e. deep fade didn't occur
31     FOR each  $N_i \in$  N do the following
32         CRL.allocate(Ni)  $\leftarrow$  S; //nodes offered only original num of slots
33     END FOR
34 END ELSE
35 CRL.send(CRLframe); CRL.delete(list); //send the new TDMA schedule and delete the list

```

Figure 3-3: Dynamic Scheduling Based on Buffer information (DSBB).

3.5 Conclusions

This chapter introduced the proposed techniques to achieve a reliable and energy efficient WBAN. The proposed protocols enables the network sensors to avoid the deep fade without relying on the controller, by allowing them to switch off their transceivers when their links encounter deep fade in the medium. This provides an answer to the first two research questions presented in Section 1.4. The proposed algorithms exploit the deep fade in the nodes' links and use it as a criterion to dynamically allocate slots to nodes. The proposed protocols differ in their dynamic slot allocation approach. The first scheduling technique is called DSBS. DSBS distributes the time slots over nodes based on the time duration they slept on their previous TDMA round. Besides, DSBS is optimised by considering the number of packets in the nodes' buffer. The second scheduling technique is called DSBB. DSBB distributes the time slots over nodes based only on the number of packets in their buffer, which reflects whether the node has slept in the previous TDMA round due to deep fade or not. Consequently, the proposed techniques avoid deep fade in the medium and distribute the time slots over nodes according to their reliability requirements, which is related to their links' status and the number of packets in their buffer. The proposed protocols provide two alternative solutions for the third research question presented in Section 1.4. The proposed techniques are generic and they do not require substantial amendments to the IEEE 802.15.4 and IEEE 802.15.6 superframe structures. Only one extra buffer field is added to the data packet format. This provides a solution for the sixth research question presented in Section 1.4. Therefore, the proposed techniques can be adopted by any technique, technology or standards that adopts TDMA based MAC.

The proposed protocols should be tested for their ability to achieve a reliable and energy efficient WBAN and in various contexts. In Chapter 4 and Chapter 5, the performance of the proposed protocols is evaluated in the context of a normal situation and emergencies respectively.

Chapter 4: Validation Methodology

4.1 Introduction

This chapter discusses the methodology adopted in evaluating the performance of the proposed protocols. In general terms, the wireless communication community utilises three approaches to evaluate the performance of wireless protocols; these are: mathematical analysis; simulation analysis; and test-bed evaluation. Test-bed evaluation provides the most accurate results, but rather is very expensive [61]. Both mathematical and simulation methods are effective and can be complementary, however, this work will tackle the latter for several reasons. On the one hand, the research community recommends the use of simulation methods when evaluating wireless network protocols, because they readily allow for reproducible environmental conditions. On the other hand, the complexity of each layer of the network stack on its own discourages the system mathematical evaluation, and the layering interactions multiply the complexity of the analytical analysis [61]. More importantly, the majority of the literature work, which related to this study target the WBAN de-facto standard [25, 26, 27, 28, 29], and the proposed techniques are evaluated using simulation, and since the performance of the proposed technique will be compared with the performance of WBAN standards, a similar method will be employed.

The second section presents general information concerning the simulation tool that will be used. In addition, it discusses the simulation setup, the adopted WBAN topology, and the performance metrics based on which the protocols are evaluated. The third section evaluates the performance of the protocols in the context of the normal situation and it considers two scenarios: the first scenario tackles various traffic rates, whereas the second scenario considers various slot lengths. The fourth section concludes the chapter and the evaluation results.

4.2 Simulation environment

Simulation is a cost-effective method through which to evaluate network behaviour by testing a combination of network features [61, 62]. A simulation method is used to develop, manage and deploy network systems throughout their entire lifecycle [61, 62]. Various simulation environments have been used in the literature to evaluate the performance of WBAN. The most appropriate simulators are: TinyOS, NS2, NS3, OPNET, QualNet, and the OMNET++. OMNeT++ is not a simulator in itself, but it provides the environment and tools to develop other specialised simulators called frameworks, such as Castalia and MiXim [63]. Castalia is a framework that is specifically targeted towards WBAN. MiXim supports various wireless networks including WSN but it is geared towards supporting the mobility in wireless networks, which is why it is called the mixed simulator [63].

It is essential to study the potential of the proposed scheduling protocols in achieving a reliable and energy efficient WBAN by comparing their performance against the related TDMA based MAC protocols proposed in the literature for WBAN. However, the IEEE 802.15.4 and the IEEE 802.15.6 standards are chosen as the benchmark to evaluate the performance of the proposed protocols. This is because, firstly, neither the WBAN de-facto standards nor the new dynamic TDMA scheduling techniques presented in Section 2.4 avoid the deep fade in WBAN channel. Secondly, all the proposed dynamic scheduling techniques presented in Section 2.4.2 are based on the supeframe structure of the IEEE 802.15.4 and IEEE 802.15.6, and as long as the problems of the static slot allocation adopted by the standard have not been solved so to suit WBAN communication, then the WBAN de-facto standards are chosen in the performance evaluation process of the proposed protocols.

Despite that both Castalia and MiXim offer IEEE 802.15.4 standard for WSN communication, Castalia is chosen for evaluating the performance of the proposed work [63]. This is because, Castalia provides the synchronised beacon enabled mode of the IEEE 802.15.4 standard, which is the mode that is going to be used for comparing the proposed protocols with IEEE 802.15.4. MiXim, however, supports the unsynchronised version beaconless mode of IEEE 802.15.4 which is not suitable for the reliability requirement of WBAN (refer to Section 2.2.2) [63], and it is not related to the topic of

this thesis. More importantly, Castalia supports WBAN by offering the IEEE 802.15.6 standard which is not supported by MiXim and the other simulators. Moreover, Castalia is a simulator developed by same the team who studied the channel properties of WBAN in [11] and [12]. Based on empirical analysis, Boulis et al. in [11] and [12] provide statistics for a path loss model between sensors deployed on different positions on a person, who been asked to perform different daily activities. The developed path loss model for WBAN channel is included in a detailed manual prepared by Boulis et al. for Castalia simulator [64]. The online Castalia manual in [64] explains in detail how the Castalia simulator can be installed and used. Castalia simulator provides a specific scenario for WBAN. It provides the synchronised beacon enabled mode of the IEEE 802.15.4 standard, as well as the basic characteristics of IEEE 802.15.6 standard. For those reasons, Castalia open source simulator is used as the simulation tool for conducting the evaluation experiments.

4.2.1 Topology and simulation parameters

To carryout the simulation experiments, the latest version of Castalia open source simulator, Castalia-3.3 [64] is used with the parameters described in Table 4-1. The WBAN topology is composed of six nodes: one controller at the right hip and five nodes (four at the four limbs and one in the middle of the chest). The adopted topology is depicted in Figure 4-1.

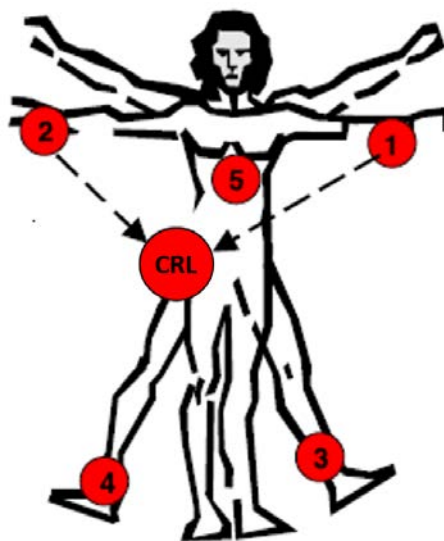


Figure 4-1: The proposed star topology scenario [11].

Table 4-1: Simulation parameters.

Parameter	Value
Simulator	Castalia 3.3
Simulation time (s)	500
Number of nodes	6 (1 controller and 5 nodes)
Total number of TDMA slots	15 slots
slotsMinValue	2
Buffer size (byte)	32
Traffic model in normal situation	CBR (normal traffic)
Traffic rate (p/s) (normal situation)	5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Traffic model in emergencies	Poisson traffic
Slot sizes (ms)	1.875, 3.75, 7.5, 15
Duty cycle	100%
MAC packet length (byte)	142
IEEE 802.15.4 related configurations	
GTS(s)	3
SO values	4, 5, 6, 7
IEEE 802.15.6 related configurations	
RAP	2 slots
Scheduled access	15 slots
MAC Packet length (byte)	1000

The study in [13] shows statistics about the duration of the deep fade for each node's link and how frequent the signal falls below receiver sensitivity for that link. The five nodes send 105 bytes data packet (including overhead) to the controller at CBR in normal situations. In emergencies however, the traffic follows the Poisson traffic model. It is worth mentioning that the IEEE 802.15 TG6 provides no specific mechanism or values for parameterising the IEEE 802.15.6 superframe [5, 15], but IEEE 802.15 TG4 does [14, 30, 31, 33, 34, 35, 36]. As it is stated in [14, 30, 31, 33, 34, 35, 36], IEEE 802.15.4 slot size duration depends on the value of the SO parameter, which is responsible for calculating the active period duration of the IEEE 802.15.4 superframe. Moreover, the IEEE 802.15.4 superframe consists of 16 time slots, therefore each one of the five nodes

can be allocated three slots at maximum once the network is established. All compared MAC protocols adopt 15 time slots TDMA schedule. The slots lengths are calculated according to the SO values of the IEEE 802.15.4. The slot that remains after excluding the 15 slots for CFP, will be used for CAP wherein nodes contend for accessing the channel. Indeed, both IEEE 802.15 TG4 and IEEE IEEE 802.15 TG6 working groups recommended that when configuring the IEEE 802.15.4 and IEEE 802.15.6 superframe structures there should be a minimum value for the contention based access before the contention free period starts. According to our intensive simulations for the IEEE 802.15.6, it is found that for a successful IEEE 802.15.6 operations, RAP should be at least two slots. All the algorithms examined are allowed to operate within 100% duty cycle. However, DSBS and DSBB allow the nodes to sleep further in their active period when their links encounter deep fade. All the simulation experiments run 20 times, to acquire a reasonable confidence interval. The following subsection presents the metrics upon which the proposed protocols will be evaluated.

4.2.2 Performance metrics

The performance of the proposed protocols will be evaluated according to multiple criteria. The metrics chosen are:

- **Reliability:** The reliability of the network will be analysed by measuring the packets loss. Packets loss is the total number of packets dropped during simulation. The lower the value of the packets' loss, the better the performance of the protocol [34, 65, 66]. Packets' loss is calculated for each node in the network as follows:

$$Packets\ loss = \sum sent\ packets\ from\ Ni - \sum received\ packets\ from\ Ni \quad (6)$$

- **Timeliness (ms):** This metric is measured by evaluating the average end-to-end delay. The average end-to-end delay is the time taken by each packet to travel from the source node to the controller. This type of delay is normally analysed for all packets received at the central controller from each node in the network, and hence the average is calculated as follows [23, 34]:

$$\text{Average end to end delay} = \frac{\sum(\text{arrive time} - \text{send time})}{\text{number of received packets from } Ni} \quad (7)$$

The lower the end to end delay value, the better the performance of the protocol.

- **Energy efficiency (nJ):** WBAN nodes are resource constrained, the trade-off between reliability and the energy efficiency of the proposed protocols will also be analysed through simulation. Energy efficiency is measured by calculating the total energy consumed by the overall network. As shown in (8), the total energy (E_{total}) consumed by an RF energy model is the total sum of energies consumed by a sensor when performing the four operations, which are: transmitting (E_{tx}), in receiving (E_{rx}), being idle (E_{idle}) and in sleeping (E_{sleep}) [34].

$$E_{total} = E_{tx} + E_{rx} + E_{idle} + E_{sleep} \quad (8)$$

The lower total energy consumed by a protocol, the better is its performance.

4.3 Performance evaluation in normal situations

Performance evaluation enables us to check the validity and potential of the proposed solution to achieve a reliable and energy efficient WBAN. In this section, the performance of the proposed protocols is evaluated in the context of the normal situation. This section should provide an answer to the fourth research question presented in Section 1.4 for normal situations. It is crucial to evaluate the performance of the proposed techniques on various traffic rates that can be followed by sensors in various WBAN applications. It is also essential to evaluate the performance of the proposed protocols on different lengths of the TDMA schedule. To achieve this, the proposed protocols are evaluated in two scenarios. In the first scenario, the performance of the two protocols is evaluated with respect to various CBR values, which vary from 5 p/s to 100 p/s. To implement the second scenario, instead of changing the number of slots in the TDMA schedule, the performance of the protocols is evaluated with respect to various slots lengths. This is because the time

slot is the basic building block of any TDMA schedule, and considering various sizes of the time slot stretches or diminishes the length of the TDMA schedule according to the chosen slot size. More importantly, it is crucial to achieve a healthy trade-off between reliability and energy efficiency for WBAN. Thus, evaluating the performance of the protocols on different slot lengths helps in choosing the most suitable slot length for the TDMA schedule, which helps in parametrising the protocols. These two scenarios are illustrated in detail in the following sections.

4.3.1 Scenario 1: The impact of traffic rate

In this scenario, the performances of DSBS, DSBB, IEEE 802.15.4, and IEEE 802.15.6 are examined over eleven traffic rates, which vary from a very low traffic rate (5 p/s) up to very high traffic rate (100 p/s). All the protocols work through 100% duty cycle with 3.75 ms slot size ($SO = 5$ for IEEE 802.15.4). Given that each packet takes around $1.208437 \approx 1.21$ ms from the moment it is transmitted until the node receives the acknowledgment frame, each slot can occupy up to three packets.

As it can be seen from Figure 4-2, DSBS and DSBB achieve less packets loss as opposed to the IEEE 802.15.4 and IEEE 802.15.6 standards at all traffic rates. This is because, on the one hand, the proposed techniques avoid the deep fade in the channel, which is the primary source of packet loss in WBAN, and on the other hand, they distribute the time slots between nodes according to nodes' requirements. As mentioned previously, at the beginning of each IEEE802.15.6 superframe and before the nodes follow the 15 TDMA slots schedule, nodes follow contention based channel access in RAP of two slots. Consequently, during this period, nodes will transmit altogether, which causes collision, increases packet loss and therefore will deteriorate the performance of the IEEE 802.15.6 standard. Moreover, the IEEE 802.15.6 MAC frame size implemented in Castalia-3.3 simulator is around 1000 bytes, which is very large compared to 142 bytes (including data packet overhead), adopted by DSBS and DSBB. Therefore, 3.75 ms slot length is not sufficient to transmit the long MAC IEEE 802.15.6 packet and the transmission will be deferred constantly to the next superframe. Hence, there will not be enough space for saving packets in the nodes' buffer, because other packets will be waiting for transmission, which causes a buffer overflow and increases packets' loss. This explains why IEEE 802.15.6 perform worse than all other protocols.

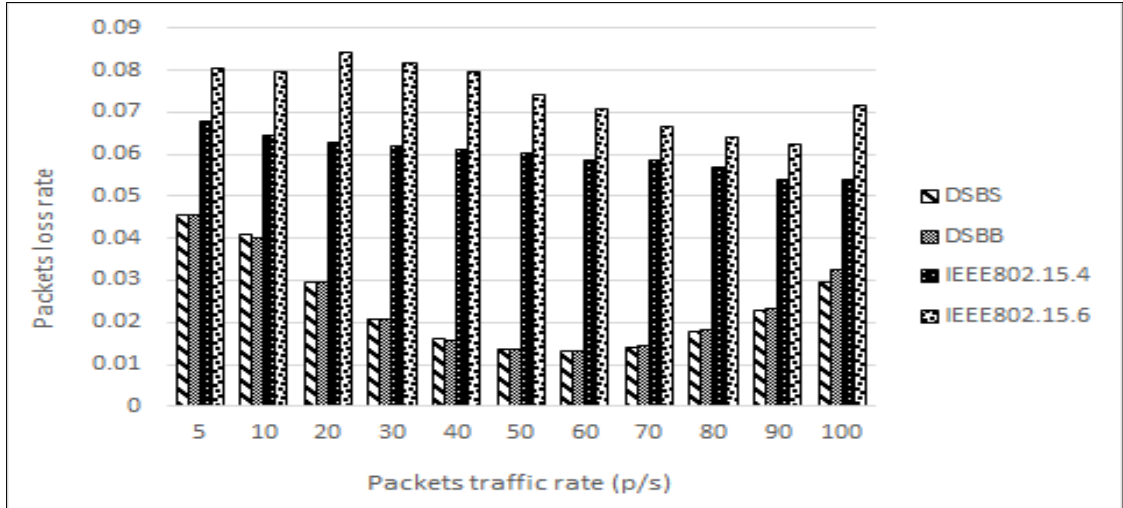


Figure 4-2: Packets loss rate in a normal situation with an increasing CBR(s).

Figure 4-3 depicts the results of the end-to-end delay. Apart from 5 p/s, 10 p/s, 90 p/s, and 100 p/s, the proposed protocols cause a slight increase in the delay compared to the legacy standards. This is because the proposed protocols allow the nodes to sleep dynamically whenever their links encounter deep fade. Although this guarantees successful packets delivery because the nodes access the medium only when their links are in a good status, dynamic sleep according to the link status delays the transmission of the data packets. At 5 p/s, 10 p/s, 90 p/s, and 100 p/s however, the proposed protocols outperform the IEEE 802.15.6 standard. This is due to two reasons: Firstly, the IEEE 802.15.6 MAC frame size implemented in Castalia-3.3 simulator is around 1000 bytes, which is very large compared to the 142 byte adopted by DSBS and DSBB. Therefore, 3.75 ms slot length is not sufficient to transmit the long MAC IEEE 802.15.6 packet and the transmission will be deferred constantly to the next superframe, which increases the packets delay. Secondly, due to the contention based channel access in the two RAP slots adopted by the IEEE 802.15.6, the collided packets have to be re-transmitted by the IEEE 802.15.6, which increases the packets delay. At 5 p/s, 10 p/s, 90 p/s and 100 p/s, the number of packets that are deferred for transmission on the subsequent superframe, and the number of packets that are re-transmitted due to collision are more than the number of packets that are delayed for transmission due to the sleep period adopted by the DSBS and DSBB. This explains why at 5p/s, 10ps, 90 p/s, and 100 p/s the proposed protocols outperform the IEEE 802.15.6 standard.

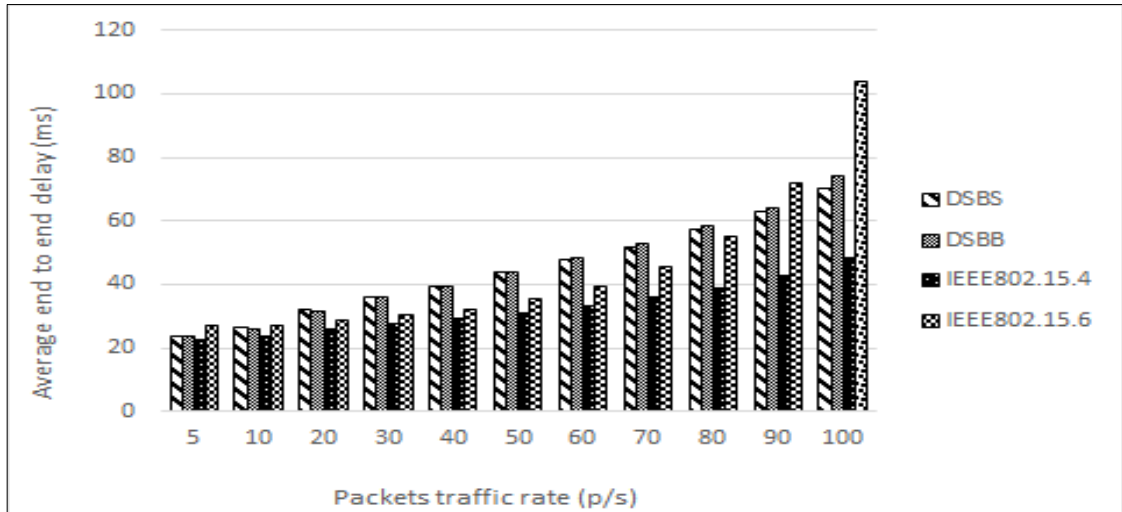


Figure 4-3: Latency in a normal situation with an increasing CBR(s).

Although the proposed protocols increases packet's latency, it is necessary to check whether this delay exceeds the delay requirements of WBAN, which is as it is stated in [5], 250 ms in normal situation. Figure 4-4 depicts the rate of packets that are received after 250 ms in a normal situation. It can be noticed that by following the proposed protocols, around 6% of the packets are received after 250 ms at maximum (at 100 p/s traffic rate). This is only 3% higher than the performance of the IEEE 802.15.4. The maximum number of packets received after 250 ms is caused by the IEEE 802.15.6 at 100 p/s, and it is around 13%, this is because of the deferred packets transmission due to the short slot size compared to the long length of the MAC packet of the IEEE 802.15.6, and due to packets re-transmission due to the contention based access in the first two slots of the IEEE 802.15.6 superframe as it is explained previously.

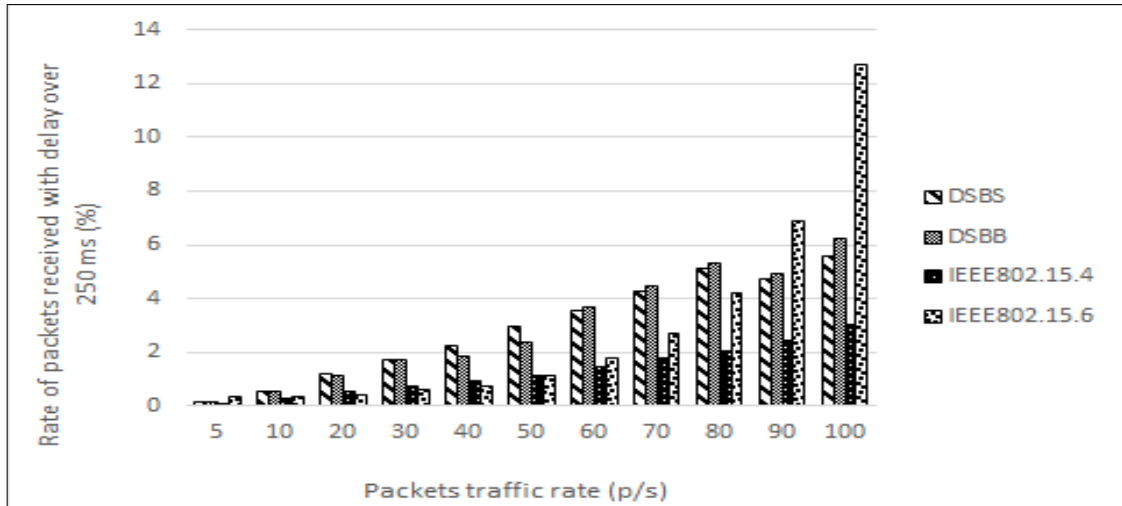


Figure 4-4: Rate of packets received with a delay over 250 ms in a normal situation.

Figure 4-5 shows that both DSBS and DSBB achieve less energy consumption compared to IEEE 802.15.4 and IEEE 802.15.6 at all traffic rates. This is because the proposed techniques allow the nodes to save energy while sleeping during their active time slots, which also avoids un-useful packets re-transmissions. Moreover, nodes are given time slots according to their needs, which would avoid an idle listening process that might occur if nodes are given more time than they actually need. Looking carefully at the results, it is noticed that DSBS achieves less energy consumption compared to DSBB. This is because DSBB assigns slots based on the number of the packets in the node's buffer, which increases the probability of a node to get extra slots and use the channel for a long time and consequently consume more energy. According to these experiments, IEEE 802.15.6 has the worst performance with respect to energy consumption. This is because nodes spend two slots in RAP during the contention based access period, which adversely increases energy consumption. Nodes need to stay idle while other transmit, which in return might lead to collision and consequent re-transmission, which dissipates energy.

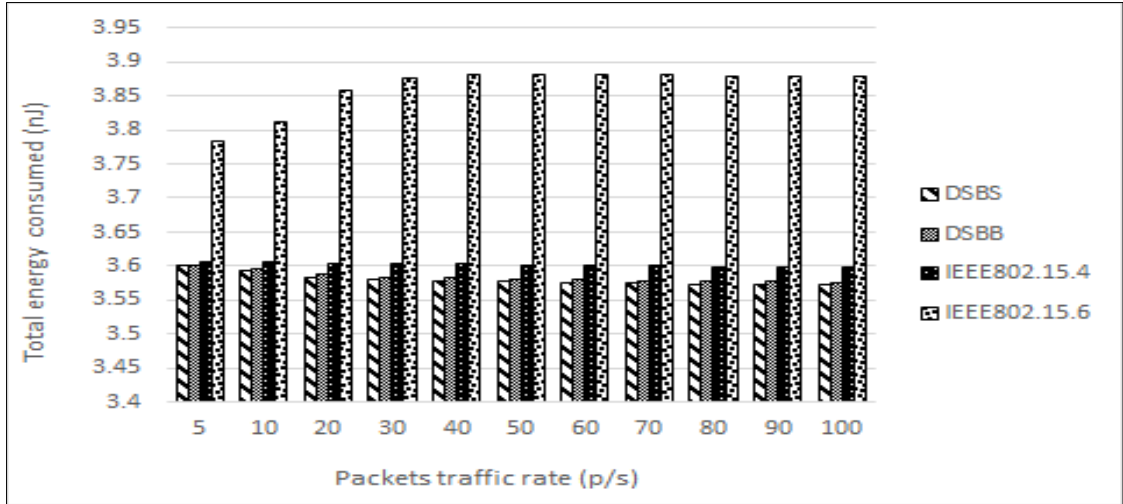


Figure 4-5: Total energy consumption for nodes with an increasing CBR(s).

4.3.2 Scenario 2: Changing the slot size

Results achieved in Section 4.3.1 call for analysing the effect of the duration of accessing the channel on the performance of the proposed protocols. In essence, the performance of the proposed protocols should be investigated with longer slot durations and different slot lengths. For this purpose, four values of SO were chosen, wherein each value contributes to a different value for the slot time length. Those values are respectively: SO= 4 (1.875 ms slot length), SO= 5 (3.75 ms slot length), SO=6 (7.5 ms slot length) and SO= 7 (15 ms slot length). To reflect the heterogeneity of a WBAN network, different traffic rates are simulated: Node 1 sends 5 p/s, Node 2 sends 30 p/s, Node 3 sends 40 p/s, Node 4 sends 15 p/s and Node 5 sends 1 p/s. The remaining experimental parameters are identical to those adopted in Scenario1 and presented in Table 4-1.

Figure 4-6 reveals that for all slot lengths, both DSBS and DSBB outperform IEEE 802.15.4 and IEEE 802.15.6. This means that the proposed protocols achieve more reliable WBAN than these standards regardless of the slot size thanks to fair slot distribution mechanism. It can be noticed also that the gap between the performance of the proposed protocols and IEEE 802.15.6 diminishes at 15 ms slot size. This is because the 15 ms slot offers the IEEE 802.15.6 MAC frame enough time to be

transmitted during the current superframe duration, which improves the performance of the IEEE 802.15.6.

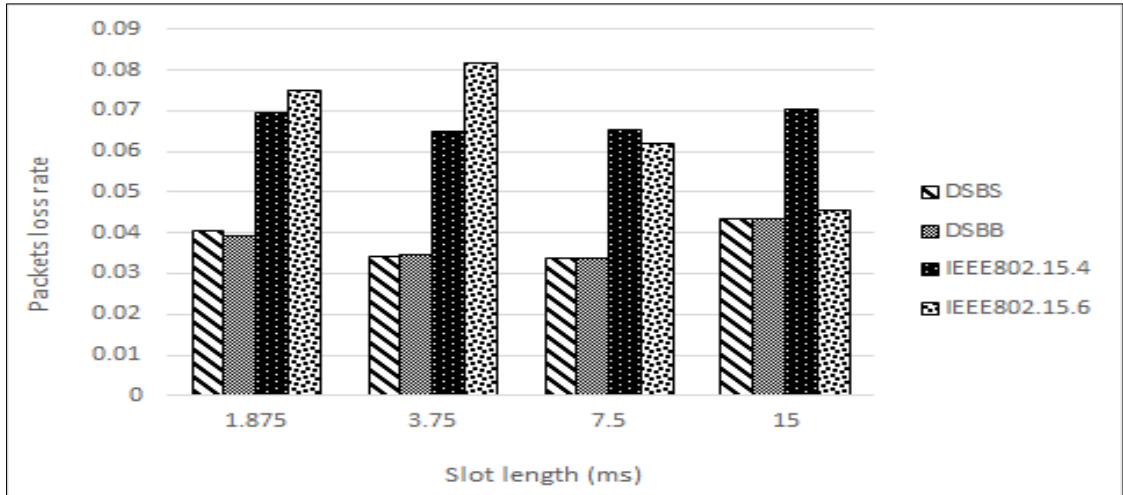


Figure 4-6: Packets loss rate for different slot sizes.

Figure 4-7 reveals that apart from the 1.875 ms slot length, the proposed protocols result in a slight increase in the delay at the rest of the slot sizes as opposed to the legacy standards. As it is explained previously, the proposed protocols allow the nodes to sleep dynamically whenever their links encounter deep fade, and dynamic sleep according to the link status delays the transmission of the data packets. At the slot length of 1.875 ms however, the proposed protocols outperform the IEEE 802.15.6 standard. In fact, 1.875 is very short slot size, which is not sufficient to transmit the very long IEEE 802.15.6 MAC frame size, and therefore the transmission will be deferred constantly to the next superframe, which increases the packets delay as opposed to the performance of the proposed protocols and the IEEE 802.15.4 standard.

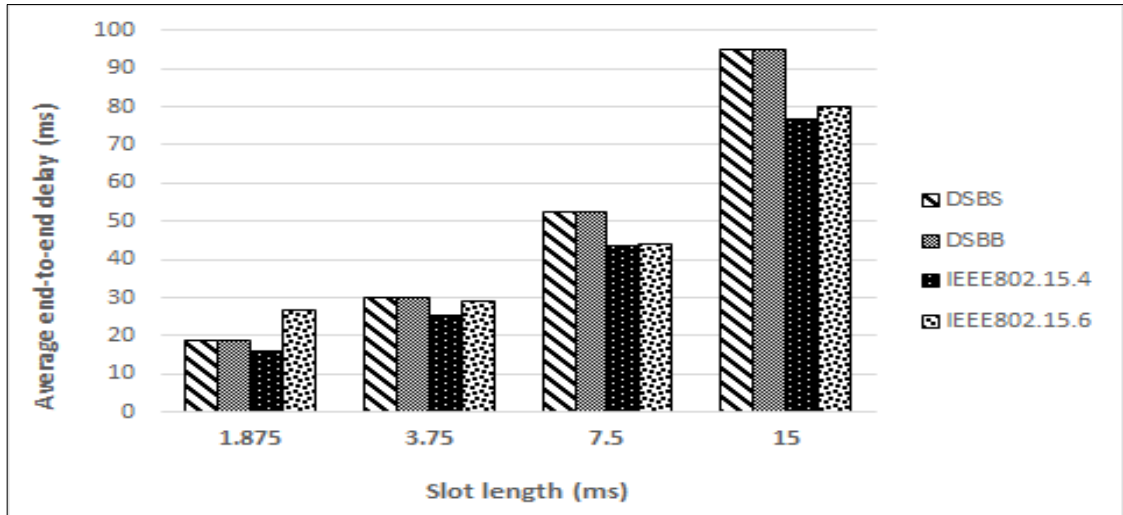


Figure 4-7: Latency in a normal situation using various slot sizes.

Although Figure 4-7 reveals that the proposed protocols result in a slight increase in the delay, it is worth investigating whether the increase in the delay caused by the proposed protocols exceeds the delay requirements of WBAN in normal situation that is 250 ms at maximum [5]. This is depicted in Figure 5-8. It can be noticed that by following the proposed protocols, around 10% of the packets are received after 250 ms at maximum. This is only 5% higher than the performance of the IEEE 802.15.4 and the IEEE 802.15.6. However, it is worth noting that this slight increase in the delay is accompanied by a dramatic decrease in packets loss as it is depicted in Figure 4-6, and a decrease in energy consumption as it is explained in Figure 4-9.

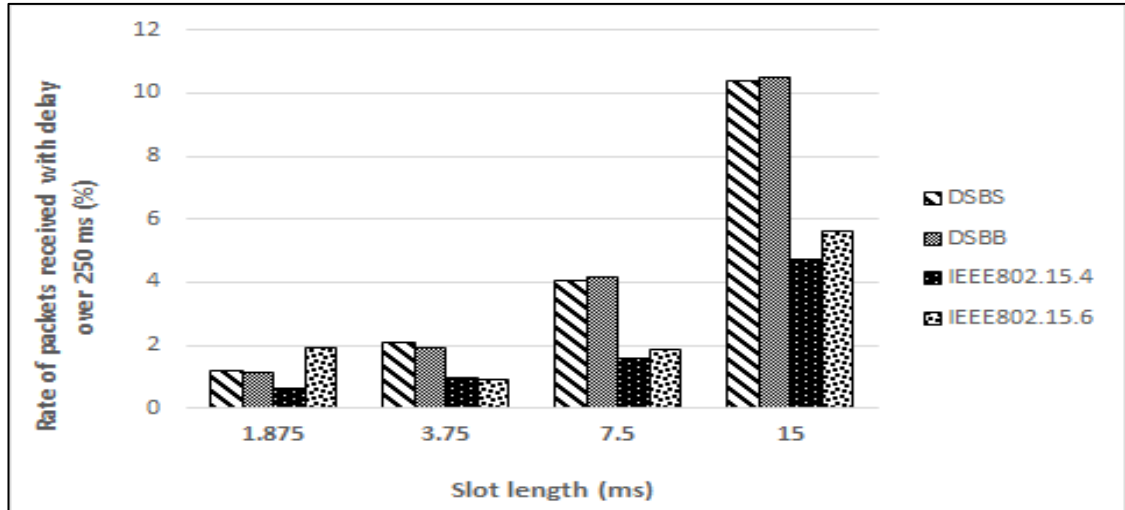


Figure 4-8: Rate of packets received with a delay over 250 ms in a normal situation.

Figure 4-9 reveals that for all slot lengths, both DSBS and DSBB achieve less energy consumption regardless of the duration of the slot length. As it is explained in Section 4.3.1, this is because DSBS and DSBB allow the nodes to sleep dynamically during their active sessions according to their links status. DSBS still outperforms DSBB. This is because DSBS offers the nodes some time slots based on the number of time slots they consumed while sleeping during the previous rounds. Thus, nodes will be given systematically long time opportunities to stay active, which avoids energy dissipation. Looking carefully at Figure 4-9, it is noticed that at 15 ms, nodes consume the least power due to the longer time periods the nodes might sleep when they face fading, which saves more energy. IEEE802.15.6 consumes much more energy as opposed to the other protocols, due to the longer period in performing a contention based access in the two slots RAP, as it is explained in Section 4.3.1.

Results achieved confirm that the proposed protocols improve WBAN performance in terms of reliably and energy efficiency in a normal situation, with only 5% (at maximum) of the packets received after 250 ms in normal situation compared to IEEE 802.15.4 standard.

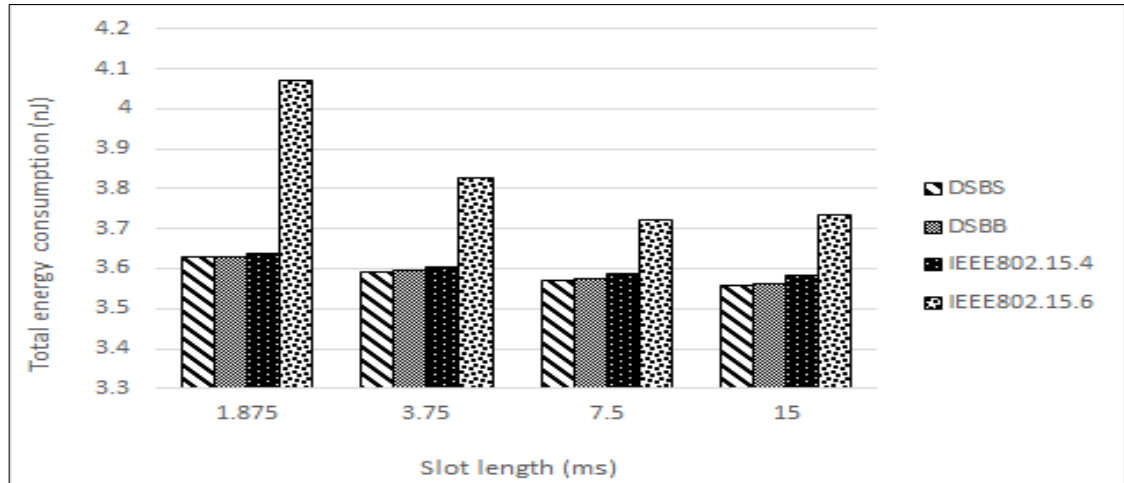


Figure 4-9: Total energy consumption in a normal situation using various slot sizes.

4.4 Conclusions

This chapter presented the approach followed to evaluate the performance of the proposed protocols and justified why the simulation approach is adopted in general and the Castalia simulator in particular. It presented the topology adopted in simulations, the performance metrics and the adopted simulation setup. In this chapter, the performance of the proposed protocols is evaluated in the context of the normal situation, and it is compared against the performance of the IEEE 802.15.4 and IEEE 802.15.6. The heterogeneity of WBAN traffic rates as well as various slots lengths are considered in the evaluation process. Results revealed that the two proposed techniques improve WBAN reliability and energy efficiency significantly regardless of the traffic rate and the slot size. This provides an answer to the fourth research question presented in Section 3.4 for normal situations. The two proposed techniques reduce packet loss up to 61% and 68% compared to the IEEE 802.15.4 and IEEE 802.15.6 respectively. They also reduce energy consumption up to 0.62% and 7.3% compared to the IEEE 802.15.4 and IEEE 802.15.6. The achieved results are accompanied with a slight increase in the end-to-end delay. Only 3% of the packets are received after 250 compared to the IEEE 802.15.4 in the scenario of changing the traffic rate, and only 5% of the packets are received after 250 as opposed to IEEE 802.15.4 and IEEE 802.15.6 in the scenario of changing slot size. In the next chapter, the performance of the proposed protocols is evaluated in the emergency context. Chapter 5 will answer the fourth research question presented in Section 1.4, but for emergencies.

Chapter 5: WBAN in Emergency Situations

5.1 Introduction

While some medical sensors work in a normal situation, other medical sensors might suddenly require high QoS and exclusive resources when emergency situations occur. Usually the throughput of the nodes in emergencies increases at the expense of severe energy consumption because nodes related to the monitoring context require more time to access the medium in order to transmit their data in a near real-time. Nevertheless, as WBAN is comprised of a very vulnerable medium, allocating nodes in emergencies extra slots is very problematic. This is because if the node in an emergency has a poor link status and is allowed to access the valuable medium for longer time periods, more sensitive information will be lost, which adversely reduces WBAN reliability and dissipates energy consumption. In addition, the extra slots offered to the nodes in emergencies usually are taken from the rest of the nodes that sense less important information, i.e. operate in a normal situation or which sense environmental information. Consequently, in emergency situations not all the nodes in the network will have the chance to use the medium.

The two proposed TDMA protocols in this thesis, consider both the buffer and the channel status of the nodes regardless of the context they operate within. In the previous chapter the performance of the proposed protocols is evaluated in the context of the normal situation only. This chapter evaluates the performance of the proposed protocols in emergencies, hence this chapter should provide an answer to the fourth question presented in Section 1.4, but for the context of emergencies. This chapter should also answer the fifth research question, which questions whether it is possible to satisfy the increased load in emergencies without increasing energy consumption.

In order to evaluate the performance of DSBS and DSBB in emergencies, first we ought to define the emergency situation, and how it can be distinguished from the normal one, how it can be detected, and what happens when it occurs. These are discussed in the

second section and the third section respectively. The fourth section illustrates the methodology of applying emergency in simulation and evaluates the performance of the protocols in an emergency in three different scenarios which vary in the adopted slot length. The fifth section concludes the chapter and the evaluation results.

5.2 Emergency in WBAN communication

An emergency is a variation in the behavior of the current context in a way that could lead to life threatening situations [26]. It could occur when patients with a life threatening disease suddenly changed their activity, or his ambient environment encountered an unpredictable extreme high or low temperature, pressure, oxygenation, humidity, and so on. In such circumstances, information related to the monitoring context should be transmitted with the highest QoS, without packet loss, and at acceptable latency requirements while considering energy efficiency. For instance, if a patient with heart attack falls down, or performs an exercise, the medical staff should focus on the heart rate data than other sensors data. Therefore, real-time transmission of the data from the ECG sensor device should be guaranteed, while other sensors' data such as EMG will become less important [28, 29].

5.3 Emergency detection

The controller detects the context variation in WBAN through data processing and analysis. In normal situations, sensor nodes operate within a standard data rate and duty cycle to sample and transmit data to the controller. After collecting the data from all nodes, the controller processes and analyses the received data, and can detect the change in the activity or the context by following one of the context recognition algorithms that are applied to the sensors data. Some of these algorithms can be found in [67]. Using such algorithms is independent from designing MAC protocols; and how those algorithms operate is beyond the scope of this thesis. After analysing the data, if the controller detects an abnormality in a physiological signal, it requests more data from the sensor to perform precise recognition. To achieve that, the controller orders the associated sensors to increase their sampling rate, which results in increasing their traffic rate [26, 28, 29].

5.4 Emergency in simulation experiments

This section explains how the emergency is investigated in the simulation. In normal situations, nodes send data packets at CBR. In emergency situations however, nodes' traffic rate increases and turns to random, and according to the literature, such as the work in [26, 29], their traffic rate follows the Poisson model in which packets inter-arrival rate follows an exponential distribution. Apart from the traffic rate, the simulation experiments parameters are identical to those presented in Section 4.2.1. At the beginning of the simulation, WBAN is set to operate in a normal situation during which nodes follow the CBR traffic model. Each node chooses a traffic rate (R) randomly from the range [1-10] p/s, where the inter-arrival time (T) is static, and $T = 1/R$. When emergency is detected, two consequences occur: (1) the traffic rate λ of those nodes related to the monitoring context increases (in accordance to the increase of their sampling rate), (2) nodes' traffic rate λ jumps abruptly from CBR with static inter-arrival time to Poisson traffic rate λ with inter-arrival time of exponential distribution. The emergency was applied at two different simulation periods: the first period lasted for 100s from 50-150s, during which the inter-arrival time follows the exponential distribution of mean 0.02 and rate $\lambda = 50$ p/s. The second period lasted for 150s from 300-450s, during which the inter-arrival time follows the exponential distribution of mean 0.01 and rate $\lambda = 100$ p/s. In those periods, two nodes are chosen to have an emergency. The nodes were chosen in a way that could enable us to evaluate the performance of DSBS, DSBB, IEEE 802.15.4 and IEEE 802.15.6 at all possible cases that might occur regarding the channel status. As different scenarios involve different nodes in an emergency with different links status, the combinations of nodes in emergency vary according to the nodes general links status. Based on the intensive simulation of parameters presented in Table 4-1, for five nodes positioned in a WBAN, whose links average path loss presented in [4], nodes' links status can be categorised as it shown in Table 5-1, where N_1, N_2, N_3, N_4, N_5 refer to the five nodes. According to this categorisation, there are five nodes with four different links' status. If we chose to apply emergency on two nodes, then we will have seven possible scenarios of two nodes in an emergency with different links' status. The possible nodes' combinations are presented in Table 5-2.

The selected nodes are as follows: N_1 and N_2 , N_1 and N_4 , N_1 and N_5 , N_2 and N_3 , N_2 and N_4 , N_3 and N_4 , N_3 and N_5 . The performance of the protocols was evaluated using those seven scenarios. Experiments were applied on three slot sizes: 3.75 ms, 1.875 ms, 7.5 ms, and the experiments were repeated 20 times. It is worth mentioning here that this chapter does not consider prioritising nodes based on the sensitivity of their data or their relation to the monitoring context. In other words, all nodes will have the chance to use the channel, even if they are not in an emergency. The distribution of slots will run according to DSBS and DSBB techniques explained in Section 3.3 and Section 3.4 respectively. This is because the goal of this section is to evaluate whether increasing the channel access duration to nodes in an emergency based only on their channel and buffer status could improve WBAN QoS and energy efficiency, and whether DSBS and DSBB can cope with both emergencies and normal situations. Considering nodes prioritisation based on their context is discussed in Chapter 6. The protocols performance has been evaluated in terms of packets loss rate, latency and energy efficiency. The following subsections present the results of the protocols' performance at each slot length by applying the simulation parameters in Table 4-1 and triggering the emergency over the nodes in seven scenarios.

Table 5-1: Classification of the links' status of the nodes.

Link status	The node
Nodes with very good link status	N_2
Nodes with good link status	N_4
Nodes with bad link status	N_1 and N_5
Nodes with very bad link status	N_3

Table 5-2: Scenarios of the nodes in an emergency.

Scenario	The involved nodes
A node of a very good link with a node of a good link	N_2 and N_4
A node of a very good link with a node of a bad link	N_2 and N_1 or N_2 and N_5
A node of a very good link with a node of a very bad link	N_2 and N_3
A node of good link with a node of a bad link	N_4 and N_1 or N_4 and N_5
A node of good link with a node of a very bad link	N_4 and N_3
A node of a bad link with a node of a bad link	N_1 and N_5
A node of a bad link with a node of a very bad link	N_1 and N_3 or N_5 and N_3

5.4.1 Results of 3.75 ms slot length

Figure 5-1 depicts the results for reliability performance in terms of packets loss. It is clear that our proposed protocols outperform the legacy IEEE 802.15.4 and IEEE 802.15.6 at all scenarios regardless of which nodes have been chosen for an emergency. This is because nodes encountering emergency situation as all other nodes avoid the deep fade in the channel and therefore avoids losing their packets. Moreover, nodes are allocated extra slots based on their links 'status and buffer status, which is also beneficial for the node in an emergency to cope with the increased traffic rate. It can also be noticed that even for a node with very good link, i.e. N_2 , the proposed protocols still outperform the legacy standards, because they always avoid the deep fade in the channel, and thus their probability of losing packets is always less than the legacy standards. This means that avoiding the deep fade in the channel and re-allocating the nodes extra slots based on their channel status and buffer status can tolerate to both normal and emergency situations.

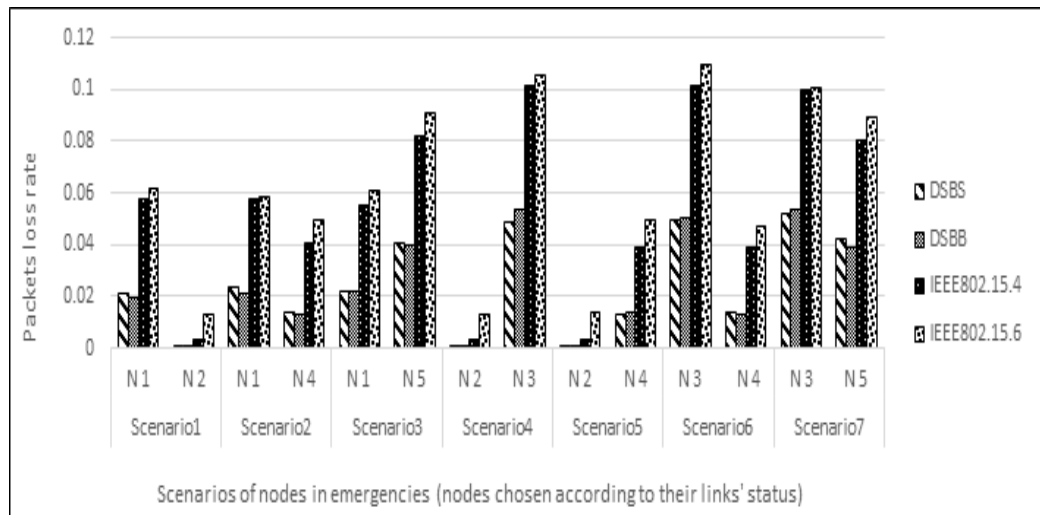


Figure 5-1: Packets loss rate in an emergency for 3.75 ms slot size.

As for the end-to-end delay, Figure 5-2 shows that all algorithms outperform IEEE 802.15.6, due to the long length of the MAC frame size of the IEEE 802.15.6. However, the proposed algorithms perform worse than the IEEE 802.15.4 at all nodes apart from the nodes with very good links i.e. N_2 . This is rational, because nodes have to sleep

whenever their links face fading in the channel, and therefore the data packets are scheduled for the next TDMA round, which increases the delay of the packets. On the other hand, N_2 faces fewer sleep opportunities due to its very good link status, which explains why its packets have less delay. It can be noticed from Figure 5-2 that in most cases DSBB outperforms DSBS. This is because in DSBB allocates the nodes time slots based on the number of packets in their buffer. If the node that has to be allocated extra slots is also in an emergency, then that node will have more opportunities to send its increased traffic load, which decreases the delay of its packets.

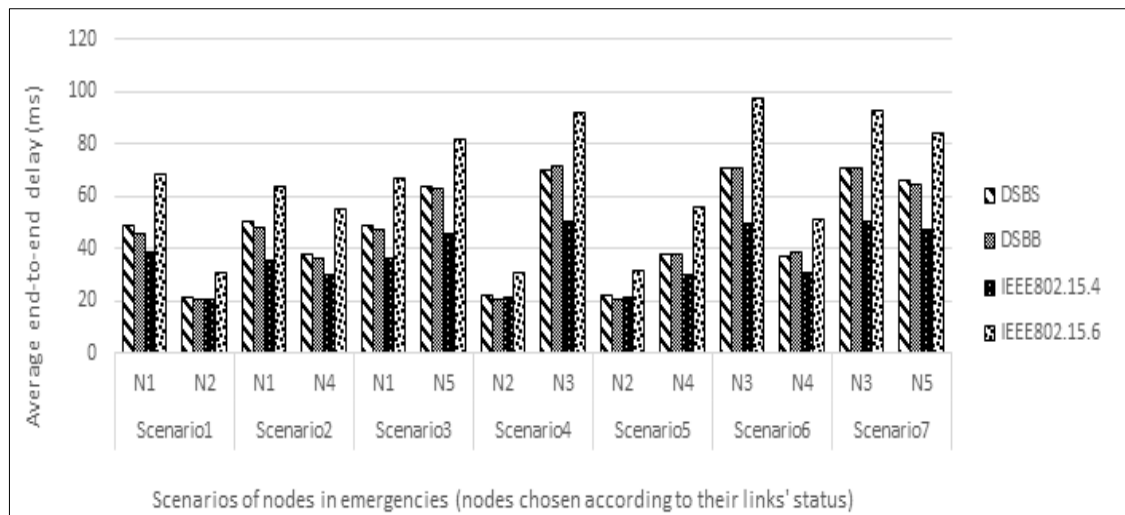


Figure 5-2: Latency for nodes in an emergency with 3.75 ms slot size.

Figure 5-3 reveals that although the latency of the DSBS and DSBB is increased, the maximum rate of packets that are received after 125 ms is less than 20%. It can be noticed from Figure 5-3 that the maximum rate is at N_3 . This is because N_3 has a bad link status and therefore will have more sleep periods than the other nodes. The maximum rates at IEEE 802.15.4 and IEEE 802.15.6 are respectively 10% and over 25%. By comparing the results with the IEEE 802.15.4, results indicate that the increase in the delay in DSBS and DSBB is acceptable as the difference in the maximum rate is fewer than 10%. However, this slight increase in the delay is accompanied by a noticeable decrease in the packets loss.

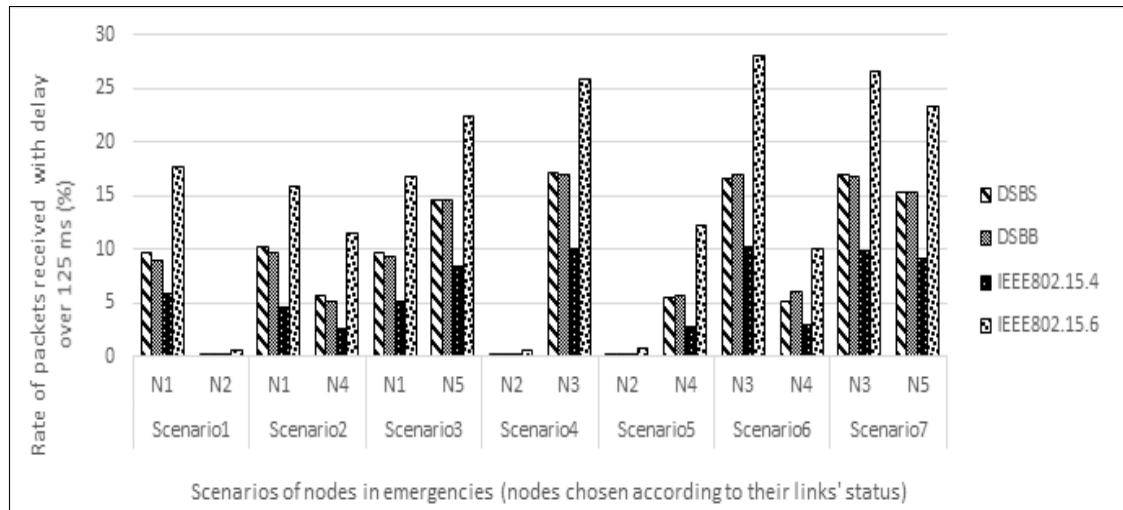


Figure 5-3: Rate of packets received with a delay over 125 ms for 3.75 ms slot size.

Figure 5-4 depicts the results of total energy consumption. It is clear that IEEE 802.15.6 performs worse than all other algorithms, due to the contention based access followed in its first two RAP slots. It can be noticed that at all nodes DSBS incurs less energy consumption compared to DSBB and the legacy standards. This is because DSBS gives nodes in emergency fewer opportunities to use the channel than the DSBB. Following DSBS, the duration of the extra slots which are allocated to nodes equals to the duration of the deep fade that the nodes faced during the previous TDMA round. This could not be enough time for nodes in an emergency to send their data packets due to the increased traffic loads, which also explains why DSBS results in more delay and packets loss than the DSBB. DSBB outperforms IEEE 802.15.4 at all nodes apart from the nodes with very good links status i.e. N_2 where DSBB consumes slightly more energy than IEEE 802.15.4 and DSBS. This is because DSBB allocates the nodes extra slots based on the current buffer size. Despite that N_2 presents a very good link status, its link could face fading at some point, and as it is in an emergency, it will have a high load of packets in its buffer based on which it will be acquired extra slots. Therefore, N_2 will have more opportunities to use the channel, which results in a slight increase in its energy consumption compared to other protocols.

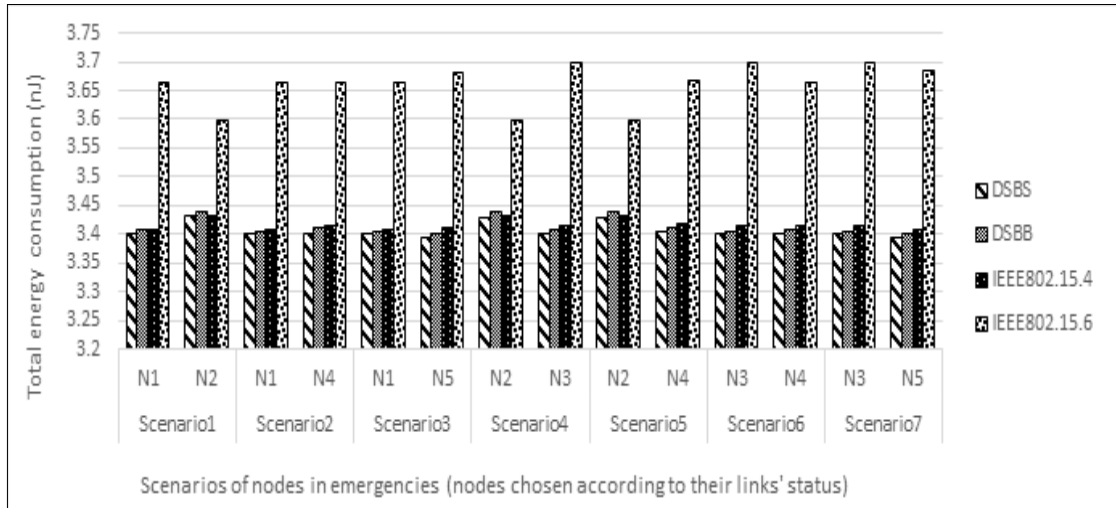


Figure 5-4: Total energy consumption for 3.75 ms slot size.

5.4.2 Results of 1.875 ms slot length

The achieved results for 1.875 ms slot length almost match those achieved for 3.75 ms slot size.

Figure 5-5 reveals that the proposed protocols outperform the legacy standards in terms of packets loss in all scenarios, regardless of which node is in an emergency. This is because regardless of the scenario, nodes avoid using the medium when their links encounter a deep fade. Those nodes are re-allocated extra slots in the next round accordingly considering also their buffer status. This gives the nodes a chance to relax the pressure on their buffer, and thus avoids buffer overflow, which decreases packets loss as opposed to the legacy standards of WBAN.

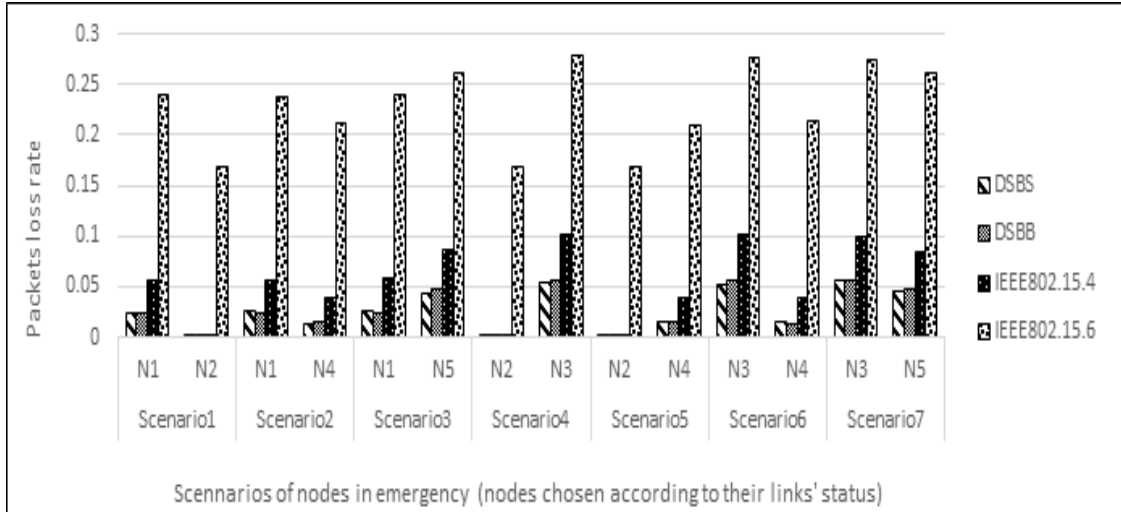


Figure 5-5: Packets loss rate in an emergency for 1.875 ms slot size.

Figure 5-6 shows that apart from nodes of very good links i.e. N_2 , DSBS and DSBB result in a slight increase in the end-to-end delay compared to the IEEE 802.15.4. As it is explained in Section 5.4.1, this is due to the sleep period of the nodes during their active sessions according to the occurrences of the deep fade in the medium. However, N_2 faces fewer sleep opportunities due to its very good link status, which explains why DSBS, DSBB and the legacy standards have a close performance. It is clear from Figure 6-6 that the proposed protocols outperform the IEEE 802.15.6 at all scenarios. As it is explained in Section 5.4.1, this is due to the long size of the MAC frame of the IEEE 802.15.6, which cannot fit in the very short slot size of 1.875 ms, and therefore packets will be transmitted within multiple TDMA schedules, which increases their end-to-end delay. Unlike the results depicted in Figure 5-2, it can be noticed from Figure 5-6 that in most cases, DSBB performs worse than DSBS. This because DSBB allocates the nodes extra time slots according to the number of packets in their buffer, which also depends on the slot size, as it is explained in Equation 5 in Section 3.4. In fact the capacity of 1.875 ms slot size is very limited due to its very short size, hence 1.875 cannot carry enough number of packets from the buffer. This means that packets transmission will always be deferred to the subsequent TDMA rounds, which increases packets delay.

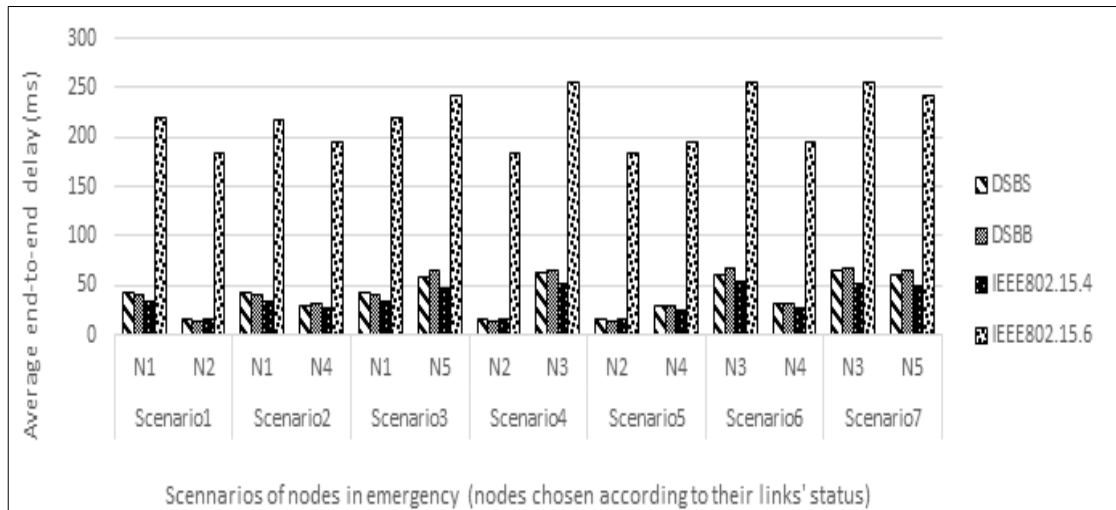


Figure 5-6: Latency in an emergency for 1.875 ms slot size.

Figure 5-7 shows that although the latency of the DSBS and DSBB is increased, the maximum rate of packets that are received after 125 ms is around 18%. The maximum rates at IEEE 802.15.4 and IEEE 802.15.6 are respectively 15% and over 50%. This means that at maximum, DSBS and DSBB result in around 3% more packets with delay over 125% compared to the IEEE 802.15.4. The maximum rate can be noticed at N_3 and N_5 . This is because both N_3 and N_5 have a poor link status and therefore will have more sleep periods than the other nodes. Results indicate that the increase in the delay in DSBS and DSBB is acceptable pairing in mind that it is accompanied by a noticeable decrease in the packets loss.

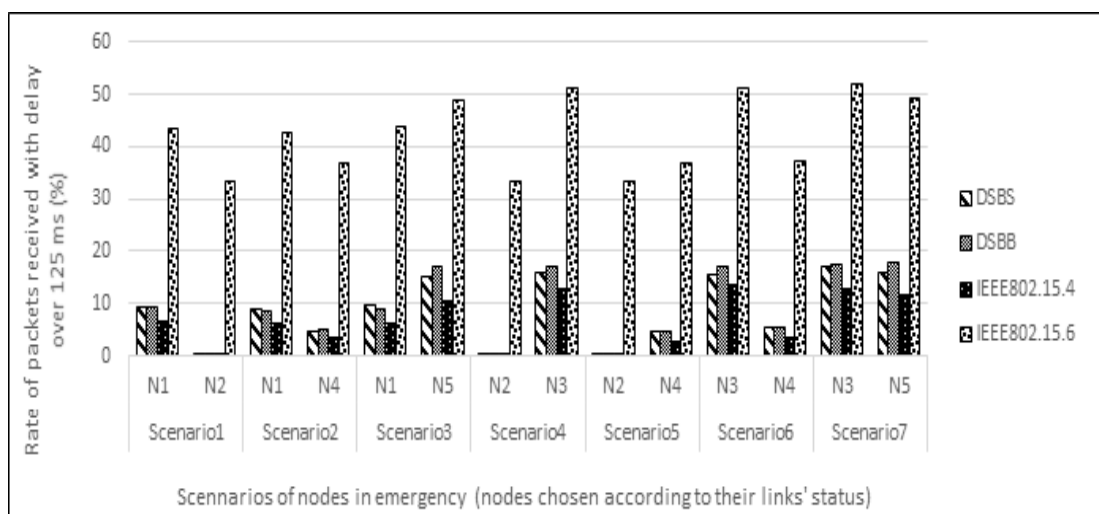


Figure 5-7: Rate of packets received with a delay over 125 ms.

It is shown in Figure 5-8 that the DSBS consumes less energy than both standards in all scenarios. This is because by following DSBS, the nodes are offered opportunities to sleep when their links encounter deep fade in the medium, which saves energy. Not only DSBS outperforms the standards, but also it outperforms DSBB. As it is explained in Section 5.4.1, this is because DSBS offers the nodes in emergency fewer opportunities to use the channel compared to DSBB. Following DSBS, the duration of the extra slots which are allocated to nodes equals to the duration of the deep fade that the nodes faced during the previous TDMA round, which means not always the nodes will have the chance to use the medium for a long time, which saves energy. DSBB however, outperforms IEEE 802.15.4 at all nodes apart from the nodes of very good link status, where DSBB consumes slightly more energy than IEEE 802.15.4 and DSBS which is similar to the results of Figure 5-4 and due to the same reasons. IEEE 802.15.6 performs worse than all other algorithms, due to the contention based access followed in its first two RAP slots.

Similar to the results achieved in Section 5.4.1, the overall results achieved for 1.875 ms slot length confirm that that avoiding the deep fade in the channel and re-allocating the nodes extra slots based on their channel status and buffer status can tolerate both normal and emergency situations, even in very short time slot size.

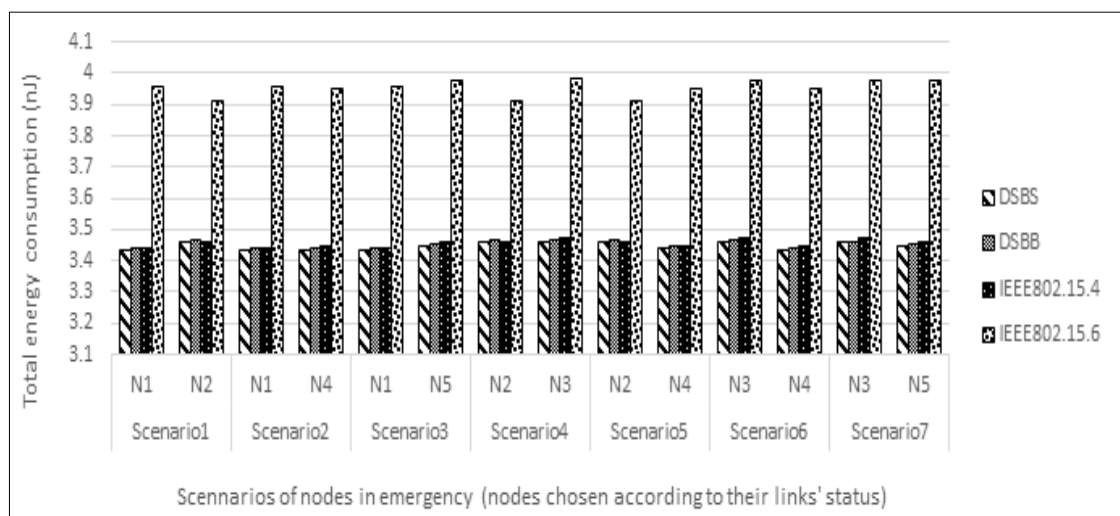


Figure 5-8: Total energy consumption for 1.875 ms slot size.

5.4.3 Results of 7.5 ms slot length

Figure 5-9 to Figure 5-12 reveal that at the longer slot size, i.e. at 7.5 ms, the proposed algorithms still outperform the legacy standards. The only change that we notice is in the performance of the IEEE 802.15.6, which now outperforms the IEEE 802.15.4, because this slot size suits its packet length as it is explained in Section 4.3.2.

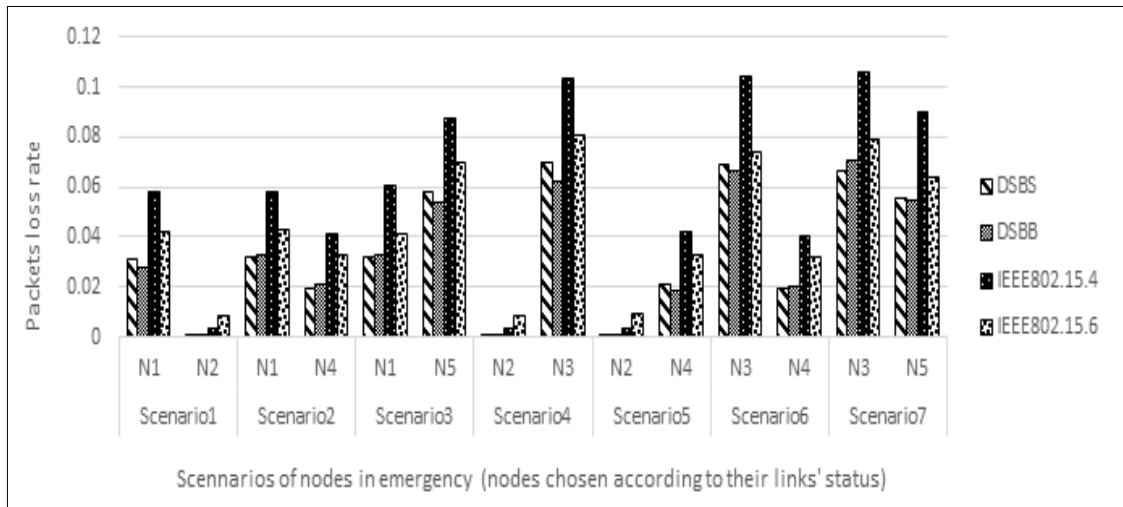


Figure 5-9: Packets loss rate in an emergency for 7.5 ms slot size.

Similar to the results achieved in Section 5.4.1 and 5.4.2, DSBS and DSBB perform worse than the standards in terms of the end-to-end delay. This is because DSBS and DSBB allow the nodes to sleep during their active sessions according to their links' status, which delays the transmission of the nodes' packets to the subsequent TDMA round. However, it can be noticed that DSBB outperforms DSBS because of the longer size of the time slot compared to 1.875 ms. This matches the results achieved in Figure 5-2, and confirms that the longer the length of the time slot the better is the performance of DSBB. This is rational, because as it is explained in Section 4.4, the allocation of the extra time slots performed by DSBB depends on the slot size of the TDMA schedule as well as the number of packets in the nodes' buffer. The longer the slot size, the larger its capacity to carry packets from the nodes buffer, which explains why DSBB outperforms DSBS.

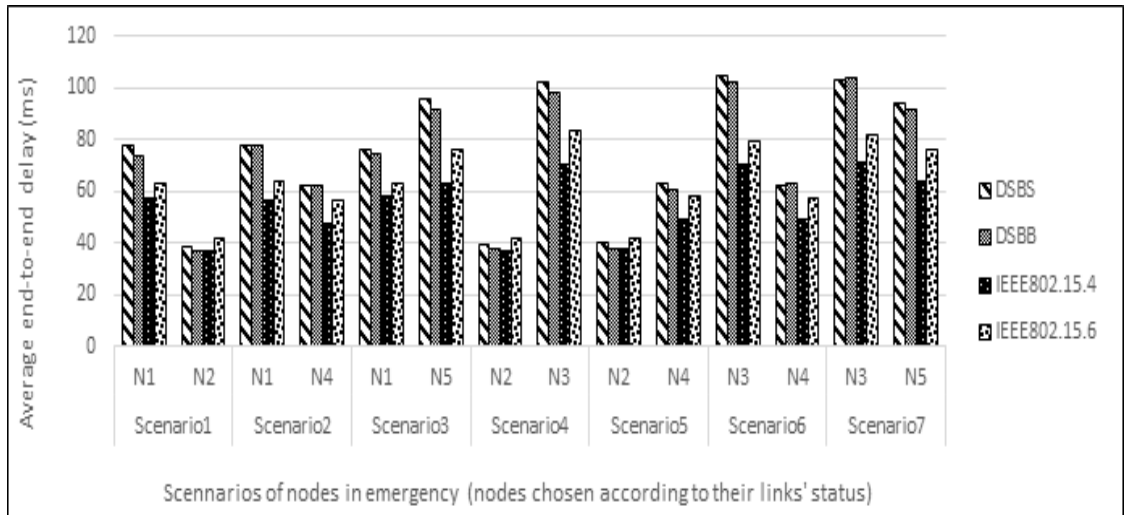


Figure 5-10: Latency in an emergency for 7.5 ms slot size.

The increase in the end-to-end delay is acceptable because according to Figure 5-11, the maximum rate of packets with delay over 125 ms is fewer than 15% at IEEE 802.15.4, and it is fewer than 20% at IEEE 802.15.6 whilst DSBS and DSBB has 10% more packets with delay over 125 ms compared to the IEEE 802.15.4. This increase in the packets end-to-end delay is accompanied by a decrease in the packets loss as shown in Figure 5-9.

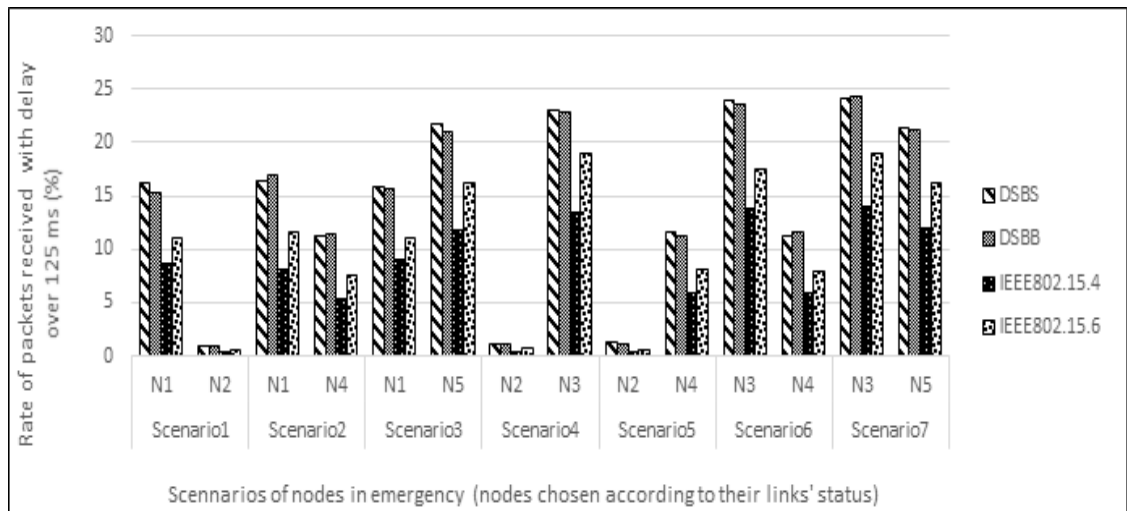


Figure 5-11: Rate of packets received with a delay over 125 ms for 7.5 ms slot size.

When it comes to energy consumption, the results depicted in Figure 12 are similar to those achieved in Figure 5-4 and Figure 5-8. DSBS consumes less energy than all other protocols and at all scenarios. Only at nodes with very good links, DSBB consumes slightly more energy than IEEE 802.15.4 due to the same reasons presented in Section 5.4.1. IEEE 802.15.6 still performs worse than all other algorithms, due to the contention based access followed in its first two RAP slots.

Similar to the results achieved in Section 5.4.1 and Section 5.4.2, the overall results achieved for 7.5 ms slot length confirm that avoiding the deep fade in the channel and re-allocating the nodes extra slots based on their channel status and buffer status can tolerate both normal and emergency situations, and regardless of the slot size.

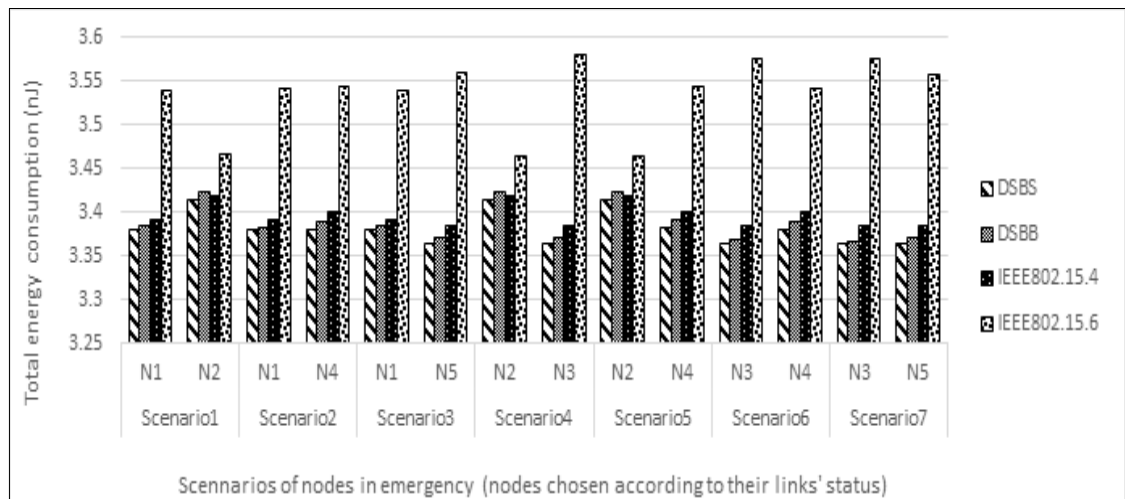


Figure 5-12: Total energy consumption for 7.5 ms slot size.

Results achieved in this section not only confirm that the proposed protocols allow all the nodes to access the medium regardless of the context, but also improves that WBAN reliability and energy efficiency in both normal and emergency situations regardless of the slot size. This provides an answer to the fourth and the fifth research questions presented in Section 1.4.

5.5 Conclusions

While it is common that the increased transmission opportunities increase throughput, at the expense of increased energy consumption, the proposed algorithms proved a guarantee of the QoS in WBAN while decreasing energy consumption in both normal and emergency situations. Results reveal that Both DSBS and DSBB achieve less packets loss and energy consumption as opposed to IEEE 802.15.4 and IEEE 802.15.6, while allowing all nodes to access the channel in emergency situations. This provides an answer to the fourth and the fifth research questions presented in Section 3.4. The two proposed techniques reduce packets loss up to 63.4% and 90% with respect to their counterparts in IEEE 802.15.4 and 802.15.6 with an energy reduction up to 13% compared to the IEEE 802.15.6. Regarding the end-to-end delay, both DSBS and DSBB outperform IEEE 802.15.6, but have a slight increase in the delay over the IEEE 802.15.4 at all nodes, apart from nodes with very good links' status where their performances are close to IEEE 802.15.4. However, the increase in the delay is acceptable and meets the delay requirements, as the percentage of packets received with a delay over 125 ms increased only 10% at maximum over the IEEE 802.15.4. We can tell from the achieved results, that 3.75 ms slot length contributes in the best performance amongst the other two slot sizes. Actually, longer slot sizes expose the nodes with poor links to more chances to face deep fade and longer durations in the vulnerable medium. Using the proposed protocols, the nodes are going to sleep in order to avoid losing packets, which increases the delay of their packets. On the other hand, very short slot sizes, such as the 1.875 ms will not give nodes enough time to access the medium, and it is very likely that if the node faces fading during this short period, it continues facing it in the next TDMA schedule, because the fading lasts for at least 10 ms. Other efforts in literature, tended to adopt a longer slot size, such as Liu et al. in [26] who adopted 10 ms slot length. This explains why in order to avoid continuous packet loss due to the longtime of deep fade, they thought about reordering the nodes in the TDMA schedule, which still does not reduce the effect of the deep fade as it is explained earlier. However, adopting shorter slot size, such as the 3.75 ms hinders the node from occupying the channel for long time, while at the same time offers the node enough time to access the channel, which also results in a TDMA with a shorter schedule length. Consequently, there will be no need for re-ordering nodes in the

TDMA schedule, as a node will not occupy the channel for a long time, and the rest of the nodes will get a faster chance to use the channel, which looks as if the order of the nodes is changed in the schedule.

Chapter 6: A Context-Aware Communication

6.1 Introduction

As stated previously, WBAN has several challenging characteristics, one of which is its vulnerability to context and environmental changes. Nodes operate in the same context can have different reliability requirements (Section 1.2, Section 2.3.5). Although the proposed protocols prove their resilience to the heterogeneous traffic in both normal and emergency contexts, it is not sensible to provide all the sensors in WBAN with identical conditions and resources, because less important data might arise before the critical data, resulting in untrusted WBAN communication. In fact, the proposed techniques do not consider traffic prioritisation in scheduling the nodes in accessing the medium according to their context.

Moreover, although experimental results achieved in Chapter 4 and Chapter 5 reveal that the proposed techniques improve the reliability and energy efficiency of WBAN in both normal and emergency situations, this improvement is accompanied with a slight increase in the delay. While a low percentage of latency in normal situations is not critical, it is crucial to receive the packets in emergencies in near real-time. Previous work tends to reduce the delay in emergencies in WBAN by proposing dynamic channel access techniques according to the context that might occur in WBAN. For example, the proposed work in [26, 28, 29] allocate nodes in emergencies more slots than other nodes in order to allow fast data transmission in near real time. This is achieved at the expense of other less important information sensed by nodes in a normal situation.

Context-aware WBAN is a network in which wearable and implanted sensors' situations can be described in accordance with the surrounding environment, according to which, their behavior can be modified [68]. Context awareness can assist in the interpretation of any physical and physiological data being monitored, and accounts for the current situation as it effects the body and the surrounding environment [68]. Thus, it can be used as a method to dynamically allocate the network resources to nodes, besides their channel

and buffer status. This involves prioritising nodes according to their situation, and according to the type and criticality of the data they sense. Various approaches can be adopted to assign priorities for heterogeneous nodes in different situations. A popular method is to check each node's situation against a specified threshold and then assigning priority values accordingly [23]. However, WBAN has two levels of variation in the reliability requirements of its sensors: amongst heterogeneous sensors and within the same sensor, as it might run in different situations i.e. normal situations and emergencies. Therefore, adopting a constant or fixed threshold value for overall WBAN components is unlikely to be sufficient in all cases, and hence novel dynamic threshold mechanism and values should be considered. This idea is thoroughly discussed in a published survey article proposed in [5]. Another method is to assign priorities for nodes according to their position on the human body. For example, ECG sensor is placed on the chest of the body and in the emergency context of the heart attack, ECG is assigned higher priority than the blood pressure sensors which is placed in the wrist. This approach is adopted in [69] and will be adopted in this chapter.

This chapter investigates whether considering context awareness in allocating the nodes the available bandwidth besides the link and buffer statuses is beneficial to WBAN. In essence, this chapter investigates whether allowing nodes in emergencies to use the vulnerable and dynamic medium of WBAN for a longer time at the expense of other nodes in a normal situation, decreases the delay of nodes in emergency and improves WBAN performance. Therefore, this chapter should provide an answer to the seventh research question presented in Section 1.4.

The second section of this chapter proposes a third technique, which schedules the nodes dynamically according to their context, while considering their channel and buffer status. The third proposed is called Dynamic Scheduling Based on the Context (DSBC) and it is going to be integrated to both DSBS and DSBB. The third section presents the evaluation methodology of DSBC technique, and discusses the experimental results. The fourth section concludes the chapter and the evaluation results.

6.2 Dynamic Scheduling Based on Context (DSBC) MAC

During the normal state of WBAN, and as explained in Section 3.2, nodes avoid channel deep fade by switching off their transceivers during their active sessions. Thereafter, in

the next round, time slots are distributed based on either the duration of their sleep period and their buffer status if the nodes are following DSBS, or based on the number of packets in the nodes' buffer if the nodes are following DSBB, as explained in Section 3.3 and Section 3.4 respectively. The controller CRL detects the occurrences of emergencies as it is explained in Section 5.3, and when an emergency occurs, the controller switches to the emergency state and follows the DSBC technique, which considers the traffic context. The pseudocode of DSBC is depicted in Figure 6-1 and it works as follows:

Throughout WBAN operations, the controller CRL records the number of times each node sleeps during its active session. In other words, CRL calculates the frequency of the occurrences of the deep fade in the link of each node. When an emergency occurs, those nodes that have slept most of the time during the previous TDMA rounds, i.e. their links encountered frequent occurrences of deep fade, will be prohibited from accessing the medium in the next TDMA round. Nodes which are prohibited from accessing the medium are called penalty nodes as they are banned from accessing the channel, and they will donate some or all their slots to nodes in an emergency. Consequently, in the next round, the number of extra slots E that should be offered to a node in emergency equals the number of slots offered by a penalty node. There could be more than one penalty node and more than one node in an emergency. The following definition describes how CRL decides that a certain node is a penalty node.

Definition 6: Let F be the frequency of the occurrences of the deep fade in the link of each node, and let N_E and N_P be the group of nodes in an emergency, and the group of penalty nodes, which will be prohibited from accessing the medium in the subsequent TDMA round, respectively. If for any node N_i , $F_i > TH$, then CRL decides that N_i is a penalty node and should be included in N_P , where TH is a dynamic threshold used by the CRL to decide which nodes have slept more than half of the previous network operations time. The value of TH changes dynamically according to the current time, and is calculated as follows:

$$TH = \frac{CurrentTime(T)}{2} + \alpha \quad (9)$$

where α is a number added to check which node has slept more than half the previous period. According to Definition 6, the following definition emerges:

Definition 7: If there are nodes in an emergency, i.e. $N_E \neq \emptyset$, and there are penalty nodes, i.e. $N_P \neq \emptyset$, and the number of emergency nodes is less than or equal the number of penalty nodes i.e. $|N_E| \leq |N_P|$, and the emergency nodes are different from the penalty nodes, i.e. $N_E \neq N_P$, then one penalty node offers all its original number of slots S to one node in an emergency. Hence, $\forall Ni \in N_E \leftarrow E$ where $E = S$ slots are taken from $Ni \in N_P$. If all emergency nodes are allocated extra slots E , then the remaining penalty nodes will use their slots to access the medium as usual.

Indeed, there are other three cases that should be discussed: (1) a penalty node is also in emergency, (2) the number of penalty nodes is less than the number of nodes in emergency, and (3) there are no penalty nodes at all.

If the node in an emergency is also a penalty node, then allocating that node more slots is not beneficial at all, because spending more time in accessing a very poor link increases the loss of sensitive data. Therefore, the emergency node will not get extra slots, instead it will be assigned only the original number of slots S it has been allocated once the network is established, and $E = 0$. This case can be summarised in the following definition:

Definition 8: If $N_E \neq \emptyset$, and $N_P \neq \emptyset$, and for any $Ni \in N_E$, if $Ni \in N_P$, i.e. $N_E \cap N_P \neq \emptyset$, then $Ni \leftarrow E = 0$

However, if the number of penalty nodes is less than the number of nodes in an emergency, i.e. $|N_P| < |N_E|$, then the distribution of extra slots over emergency nodes will be conducted according to the priority of emergency nodes. Nodes with higher priority will get extra slots from the penalty nodes before the rest of the nodes in an emergency. Nodes are prioritised according to their relevance to the monitoring context. For instance, in the context of a heart attack, the sensor that measures the heart rate activity will be assigned extra slots before the sensor that senses the temperature. When all the slots of the penalty nodes are offered to nodes in an emergency, and a number of emergency nodes remain without being allocated extra slots, then those remaining emergency nodes get extra slots from the rest of the nodes, which are in a normal situation, but which do not belong to the penalty group. Slots are distributed over the emergency nodes as long as there are enough slots to distribute over the rest of the nodes in a normal situation. This depends on the parameter of **slotsMinValue** that was identified in Chapter 3.

Likewise, if an emergency state is triggered, and there were no penalty nodes found, i.e. If $N_E \neq \emptyset$, but $N_P = \emptyset$, then the nodes in an emergency will be offered the maximum number of slots according to their priority which is related to their monitoring context. Extra slots E will be taken from nodes in a normal situation, keeping in mind that the rest of the nodes in a normal situation are offered the **slotsMinValue**.

Input: 1 controller CRL, a number of nodes N, TDMA schedule of n slots of capacity C
Data_Packets, each $N_i \in N$ is assigned equal number of slots S, where $S = n/N$, the minimum number of slots N_i can acquire is **slotsMinValue** and each N_i has a priority i .
Output: Context Aware, dynamic slot allocation TDMA schedule

```

1 // the following is performed by the controller CRL, to prepare the new time schedule
2 IF NOT ( $N_E = \text{NULL}$ ) //if there are nodes in an emergency, i.e.  $N_E \neq \emptyset$ ,
3   Sort ( $N_E$ , Priority); //sort emergency nodes according to their priority
4    $a \leftarrow 10$ ;  $TH \leftarrow (\text{getSimTime}(t)/2) + a$ ; //to calculate the dynamic threshold
5   IF NOT ( $List = \text{NULL}$ ) //check if deep fade occurred in the previous TDMA round
6     FOR each  $N_i \in list$  do the following //list of nodes slept during previous round
7        $++F_i$ ; //frequency of occurrences of deep fade
8       IF ( $F_i > TH$ ) //check if a node slept more than half the previous period
9          $CRL(N_p[item]) \leftarrow N_i(\text{ID})$ ; //include the node in the penalty group
10      END IF
11    END FOR
12  END IF
13   $NR \leftarrow N - (N_p + N_E)$ ; //nodes, which are neither in the penalty nor in the emergency group
14  //if num of penalty nodes is more than or equal num of emergency nodes
15  IF ( $N_p.length \geq N_E.length$ )
16    FOR each  $N_i \in N_E$  do the following
17       $E \leftarrow S$ ;  $S_i \leftarrow E + S$ ;  $n \leftarrow n - S_i$ ; //allocate  $N_E$  slots taken from nodes  $N_p$ 
18       $CRL.allocate(N_i) \leftarrow S_i$ ;  $CRL.allocate(N_p) \leftarrow 0$ ; //nodes in  $N_p$  get 0 slots
19    END FOR
20  END IF
21  //if num of penalty nodes is less than num of emergency nodes
22  ELSE IF ( $N_p.length < N_E.length$ )
23    FOR each  $N_i \in N_E$  do the following
24       $E \leftarrow S$ ;  $S_i \leftarrow E + S$ ;  $n \leftarrow n - S_i$ ; //S slots taken from available  $N_p$  nodes
25       $CRL.allocate(N_i) \leftarrow S_i$ ;  $CRL.allocate(N_p) \leftarrow 0$ ; //nodes in  $N_p$  get 0 slots
26    END FOR
27    NoPenalty( $NR, N_E, n$ ); //call this function when no penalty nodes remain
28  END ELSE IF
29  //if no penalty nodes found, i.e.  $N_p = \emptyset$ 
30  ELSE IF ( $N_p == \text{NULL}$ )
31    NoPenalty( $NR, N_E, n$ );
32  END IF ELSE
33 END IF
34  $CRL.send(CRLframe)$ ;  $CRL.delete(list)$ ;  $CRL.delete(N_E)$ ;  $CRL.delete(N_p)$ ; // new TDMA schedule
35
36 //this function executes when no penalty nodes available, so to distribute the slots according to the
37 //priority of emergency nodes as long as the remaining nodes get slots.MinValue
38 BEGIN NoPenalty ( $NR, N_E, n$ )
39   FOR each  $N_i \in NR$  do the following //the remaining nodes, not in penalty or emergency
40      $S_i \leftarrow \text{slotsMinValue}$ ;  $n \leftarrow n - S_i$ ;  $CRL.allocate(N_i) \leftarrow S_i$ ;
41   END FOR
42   WHILE ( $n > 0$ ) //if slots available, emergency nodes get slots according to priority
43     IF ( $n \text{ MOD } N_E > 0$ )
44        $E \leftarrow (n / N_E) + 1$ ;  $S_E \leftarrow E + S$ ;  $n \leftarrow n - S_E$ ;  $CRL.allocate(N_E) \leftarrow S_E$ ;
45     END IF
46     ELSE
47        $E \leftarrow (n / N_E)$ ;  $S_E \leftarrow E + S$ ;  $n \leftarrow n - S_E$ ;  $CRL.allocate(N_E) \leftarrow S_E$ ;
48     END ELSE
49   END WHILE
50 END NoPenalty

```

Figure 6-1: Dynamic Scheduling Based on Context (DSBC).

6.3 Simulation setup and evaluation methodology

DSBC is upgraded to DSBS and DSBB resulting in DSBSC and DSBBC, and therefore, the performance of DSBSC and DSBBC is compared with DSBS and DSBB as well as with the legacy standards. The aim of this section is to investigate the following issues: 1) whether distributing slots based on the context besides channel status and buffer status improve the performance of DSBS and DSBB in emergency especially in terms of the delay 2) and whether offering the nodes in emergency longer time in accessing the medium at the expense of nodes in normal situation, while considering the realistic channel behavior improves the performance of WBAN.

The protocols are compared against the reliability, which is measured in terms of packets loss, timeliness which is measured in terms of end-to-end delay and energy efficiency which is measured in terms of total energy consumption. The experiments of this section adopt the seven scenarios explained in Section 5.4, wherein each scenario the emergency situation is applied on two different nodes, which were chosen according to their channel status. The simulation parameters are identical to those presented in Table 4-1, only one new parameter is added, that is α which's value is set to 10. The IDs of the nodes are used to indicate their priority, i.e. N_1 is assumed to have higher priority than N_2 , N_2 is assumed to have higher priority than N_3 and so on. Experiments are conducted on three different slot sizes: short slot size with a length of 1.867 ms, medium slot size with a length of 3.75 ms and long slot size with a length of 7.5 ms, each experiment is allowed to run 20 times to acquire a reasonable confidence interval. The following subsections explain the results achieved for each performance metric.

6.3.1 Packets loss rate

Figure 6-2, Figure 6-3 and Figure 6-4 reveal that regardless of the slot size, the four proposed protocols outperform the legacy standards. However, DSBSC and DSBBC perform worse than DSBS and DSBB at all nodes apart from nodes with good link status, i.e. N_2 and N_4 where the performances of the algorithms are close. This is because by following DSBSC and DSBBC, the node in an emergency could also be a penalty, i.e. has a very poor link status, such as N_3 . N_3 might not get extra slots E at all, and it will get only the original number of slots S , which is not enough to send the increased number of

packets stored in its buffer, and, consequently, the packets will be lost due to a buffer overflow, not due to channel deep fade. Moreover, it is highly likely that if nodes such as N_1 and N_5 , are in an emergency, then there are no penalty nodes found, because according to Table 5-1, N_1 , N_5 , also have bad links 'status already. If N_1 , N_5 are not penalty nodes, then they will get extra slots from other nodes, as long as the rest of the nodes in the normal situation acquire **slotsMinValue**. However, if the link of the node, which had been allocated extra slots suddenly turns to poor afterwards, then the node of that link will sleep longer time than the other nodes as it is explained in Section 3.2, which causes a buffer overflow and more packets loss. Loosing packets could last during the whole emergency period. By following DSBS and DSBB however, nodes will continue getting extra slots according to only to their links and buffer statuses, which will occur interchangeably during WBAN operations, and thus all nodes at some points will be allocated extra slots, and if the nodes that acquire extra slots are also in emergency, then that is all that they need to send their urgent data as soon as possible. At nodes with good links' status, i.e. N_2 and N_4 , the proposed algorithms have a close performance with and without considering the traffic context. This is because the link status of N_2 is stable throughout the network operations, and whether N_2 gets extra slots according to its traffic context, or according to the channel or its buffer status, the transmission of N_2 will always succeed. The results of the end-to-end delay and energy consumption are presented in Section 6.3.2 and Section 6.3.3 respectively.

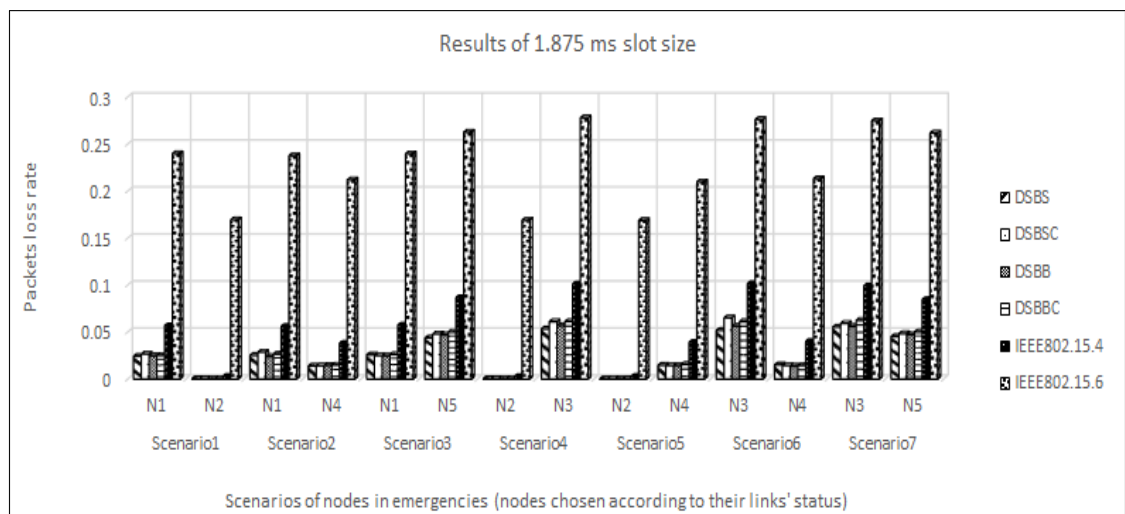


Figure 6-2: Packets loss rate for nodes in emergencies using 1.875 ms slot size.

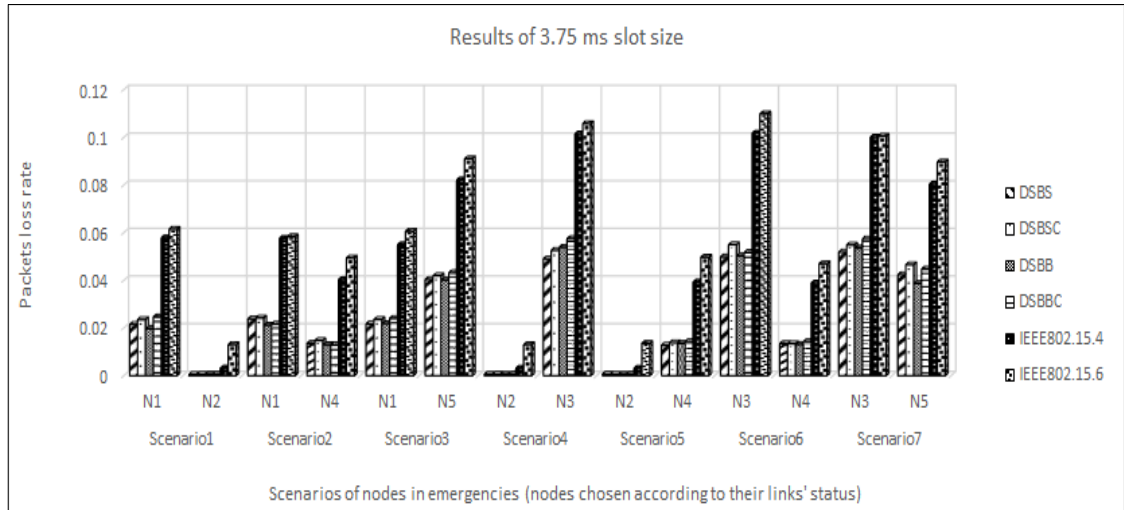


Figure 6-3: Packets loss rate for nodes in emergencies using 3.75 ms slot size.

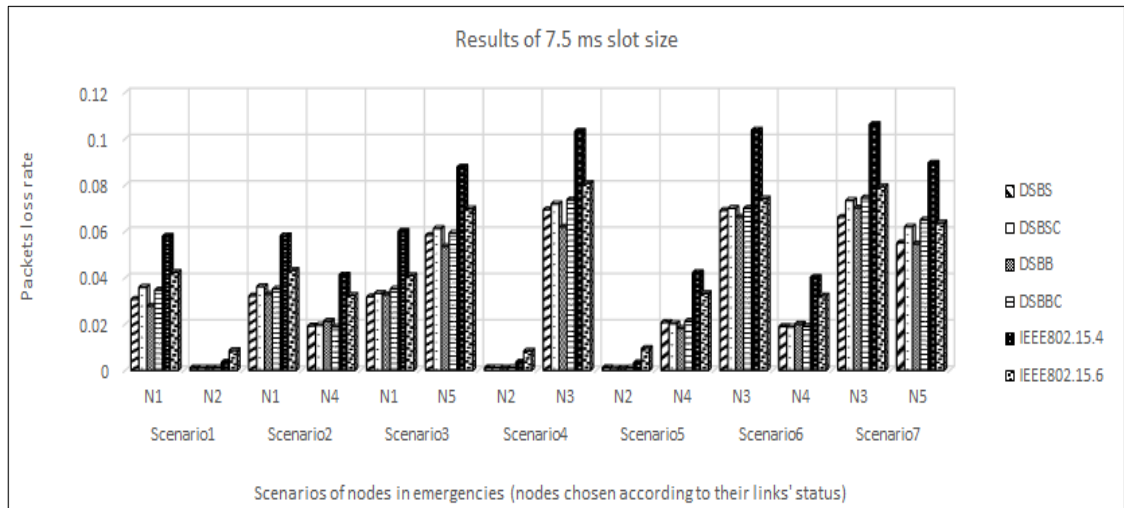


Figure 6-4: Packets loss rate for nodes in emergencies using 7.5 ms slot size.

6.3.2 Latency

As it is noticed in Section 6.3.1, the performances of both DSBS and DSBB almost follow the same pattern, therefore, in the following subsections both DSBS and DSBB are referred to as DSBC. Although the aim of proposing the DSBC is to improve the performance of DSBS and DSBB in emergencies especially in terms of the delay, Figure 6-5, Figure 6-6 and Figure 6-7 reveal that DSBC outperforms DSBS and DSBB only at nodes with good and very good links status, i.e. N_4 and N_2 respectively. This is rational as allocating extra slots to nodes with good and very good links status offers those nodes

longer time in successfully access the channel, which reduces their packets end-to-end delay. Besides DSBS and DSBB, DSBC outperforms the IEEE 802.15.4 and IEEE 802.15.6 at N_2 . This is because when emergency occurs, N_2 is allocated slots more than other in order to send its urgent as soon as possible, whereas in the normal state, N_2 gets extra slots based on its buffer and channel status, and because N_2 has a very good link status, it always succeeds in sending its packets at the lowest delay possible regardless of the context.

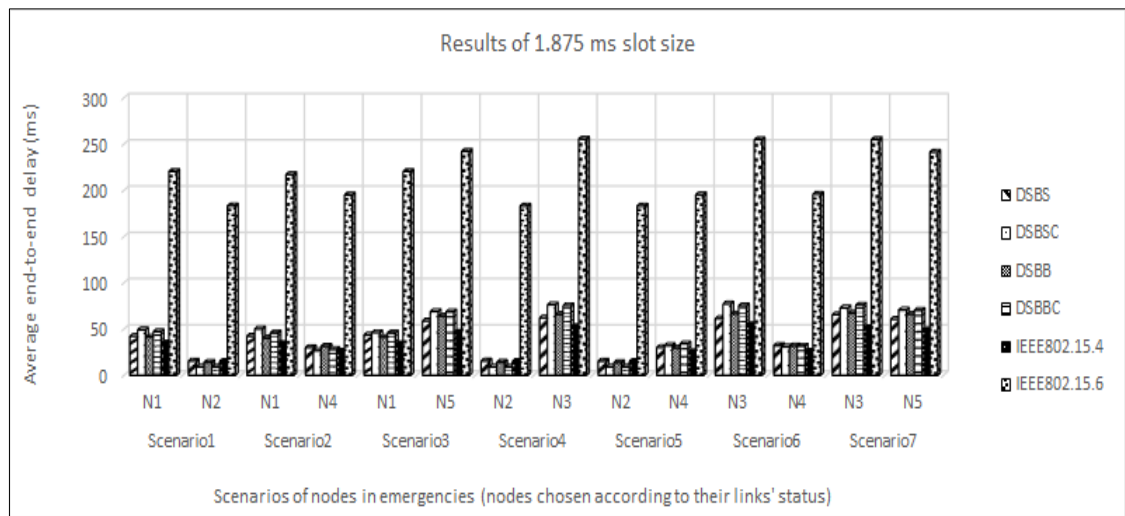


Figure 6-5: Latency for nodes in emergencies using 1.875 ms slot size.

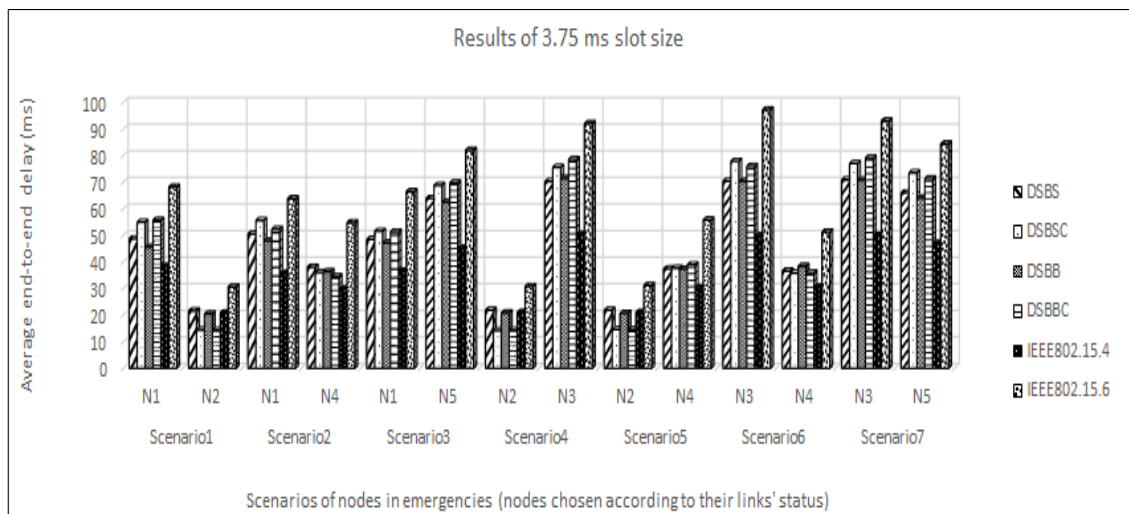


Figure 6-6: Latency for nodes in emergencies using 3.75 ms slot size.

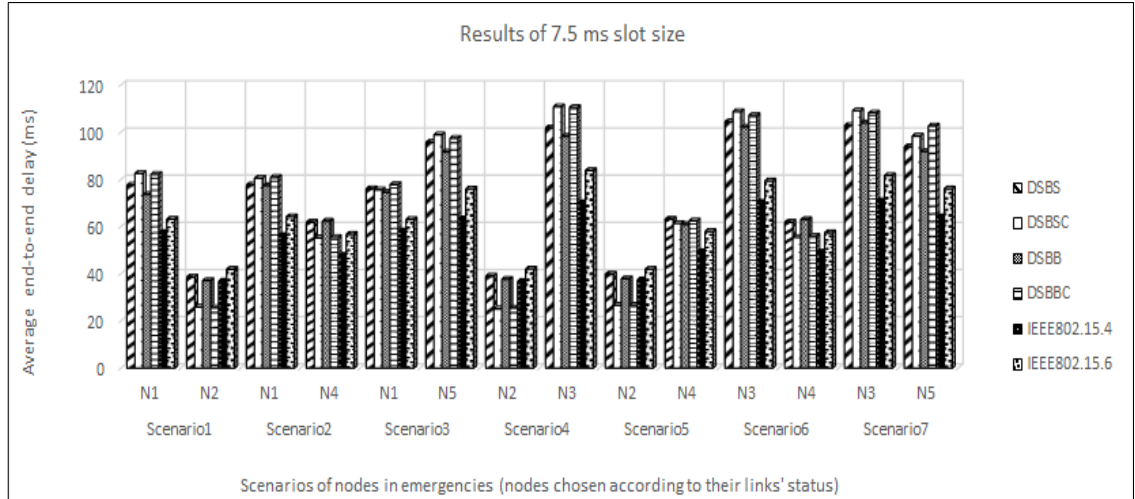


Figure 6-7: Latency for nodes in emergencies using 7.5 ms slot size.

Results depicted in Figure 6-8, Figure 6-9, and Figure 6-10 are related to the results depicted in Figure 6-5, Figure 6-6, and Figure 6-7. DSBC outperforms DSBS, DSBB and the legacy standards only at N_2 and N_4 . However, it is only when both N_2 and N_4 are chosen to operate together in the same scenario, i.e. Scenario 5, DSBS or DSBB outperforms the performance of DSBC at N_4 . This is because in some cases, the number of penalty nodes is less than the number of nodes in an emergency. Therefore, the nodes have to distribute their slots over the nodes in an emergency, and the node with higher priority will take more slots than other nodes in an emergency, which means N_2 will get more slots than N_4 . As a result, N_2 will have longer chances to successfully use the medium compared to N_4 , which explains why if the two nodes are in an emergency and operate in the same scenario, the delay at N_2 is less than the delay at N_4 . This explains why at Scenario 5, N_4 has more packets received after 125 ms if it follows DSBC as opposed to DSBS and DSBB. For the remaining scenarios, Figure 6-8, Figure 6-9, and Figure 6-10 reveal that regardless of the slot length, DSBC increases the rate of packets received after 125 at all nodes apart from N_2 and N_4 .

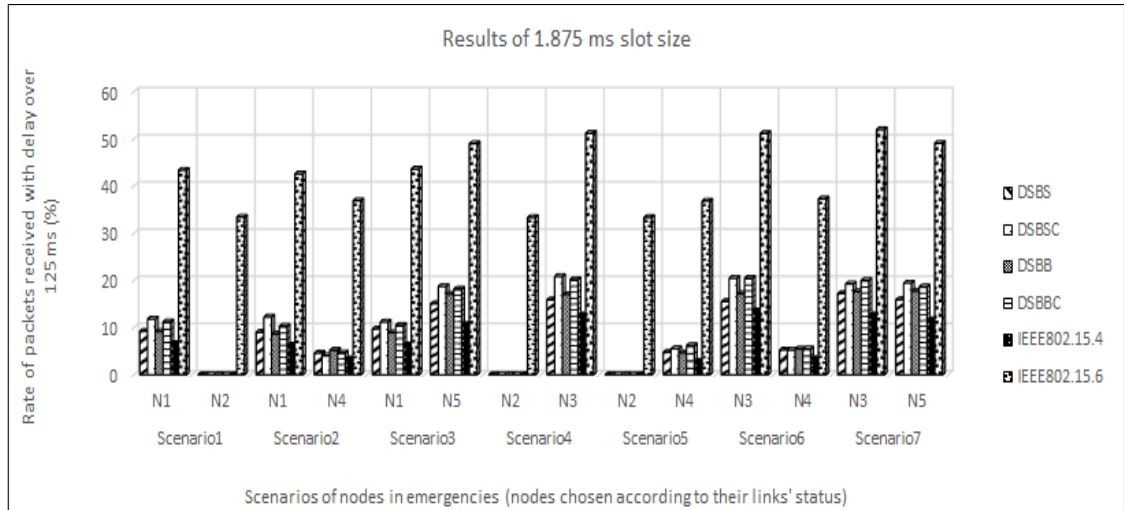


Figure 6-8: Rate of packets with a delay over 125 ms using 1.875 ms slot size.

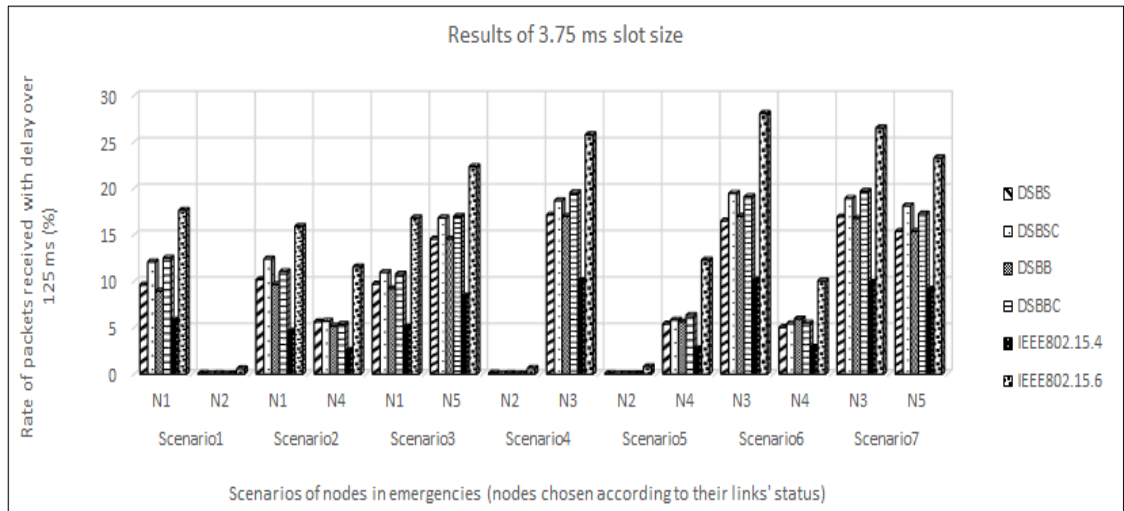


Figure 6-9: Rate of packets with a delay over 125 ms using 3.75 ms slot size.

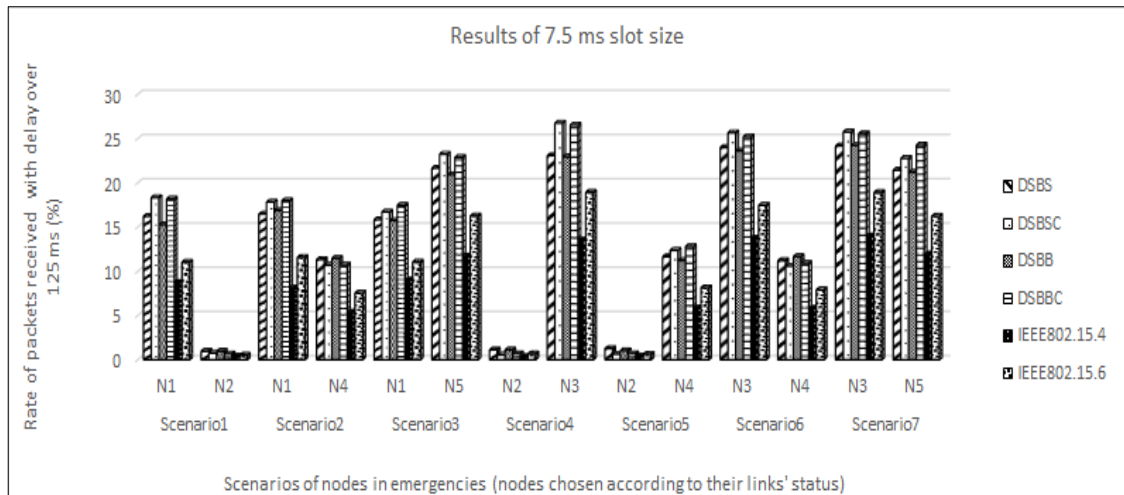


Figure 6-10: Rate of packets with a delay over 125 ms using 7.5 ms slot size.

6.3.3 Energy consumption

Figure 6-11, Figure 6-12, and Figure 6-13 reveal that in general and apart from nodes with good and very good link status, i.e. N_2 and N_4 , DSBC consumes slightly less energy compared to DSBS and DSBB. In fact, as it is stated in Table 5-1, N_3 and N_5 have poor link status. Therefore it is very likely they will be considered as penalty nodes when an emergency situation occurs, and therefore it is unlikely N_3 and N_5 acquire extra slots, instead they will be offered the original number of slots S they acquired once the network is established. This explains why DSBC consumes a bit less energy compared to the proposed protocols, especially when compared to DSBB at it is revealed in Figure 6-12 and Figure 6-13. Actually DSBB allocates the nodes extra slots based on the number of packets in their buffer, and because N_3 and N_5 are in an emergency, they have an increased number of packets in their buffer. Consequently DSBB offers N_3 and N_5 longer time to access the channel compared to DSBC, which results in more energy consumption as opposed to DSBC. However, although N_1 has also a poor link status, it is revealed in Figure 6-13 that DSBC performs worse than DSBS and DSBB at N_1 (Scenario 2 and Scenario 3). This is because according to its ID, N_1 has higher priority in using the medium compared to other nodes, which means that if it is not a penalty node, N_1 has to be allocated more slots compared to other nodes. This offers N_1 more time to access the medium, which increases its energy consumption.

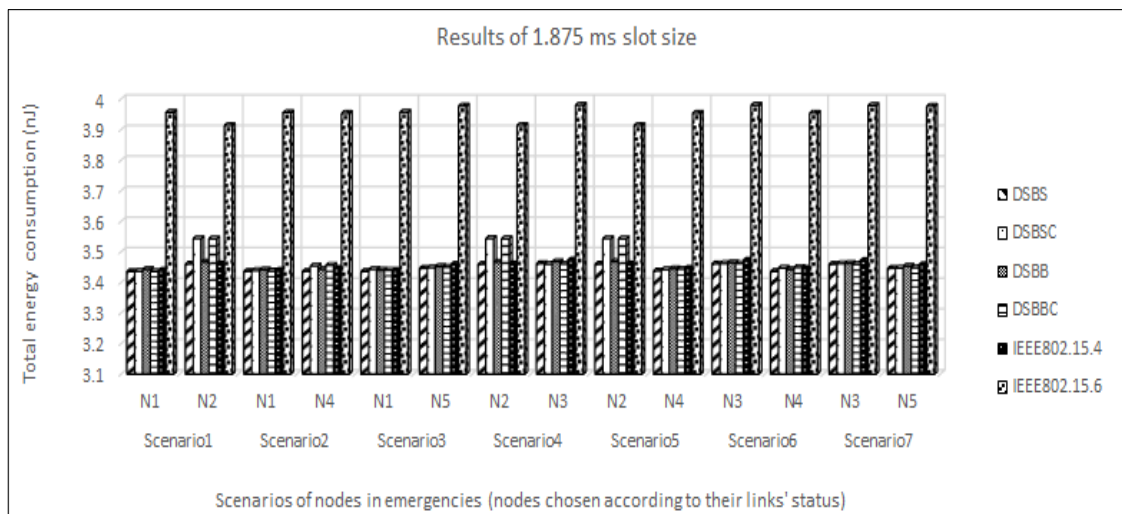


Figure 6-11: Total energy consumption in emergencies using 1.875 ms slot size.

It is clear from Figure 6-12 and Figure 6-13 that at scenarios, which involve N_2 and N_4 , DSBC performs worse than the proposed protocols. This is rational because N_2 and N_4 have very good and good links' status respectively, and thus when an emergency occurs, DSBC allocates N_2 and N_4 extra slots at the expense of the other nodes. This means that N_2 and N_4 will have a longer time in successfully accessing the channel, and consequently, N_2 and N_4 consumes more energy than other nodes. At the same time, DSBS and DSBB offer N_2 and N_4 extra slots only if they needed to sleep in the previous TDMA round due to deep fade, which is unlikely to occur at N_2 and N_4 because they have a very good and good link status respectively. Having more time to access the medium not only causes DSBC to perform worse than the IEEE 802.15.4 standard at N_2 and N_4 , but also causes DSBC to perform worse than the IEEE 802.15.6 at N_2 as it is revealed in Figure 6-13.

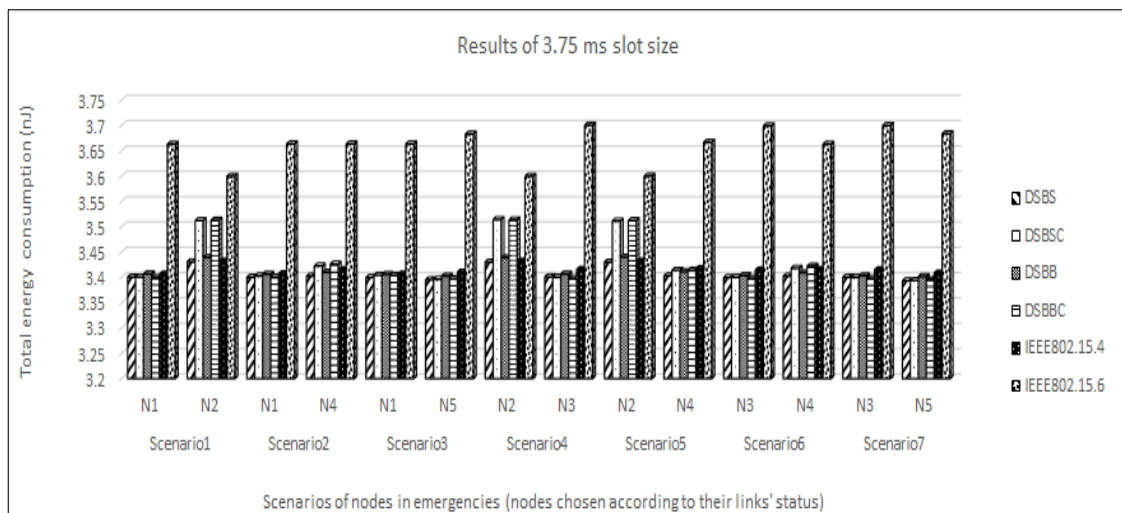


Figure 6-12: Total energy consumption in emergencies using 3.75 ms slot size.

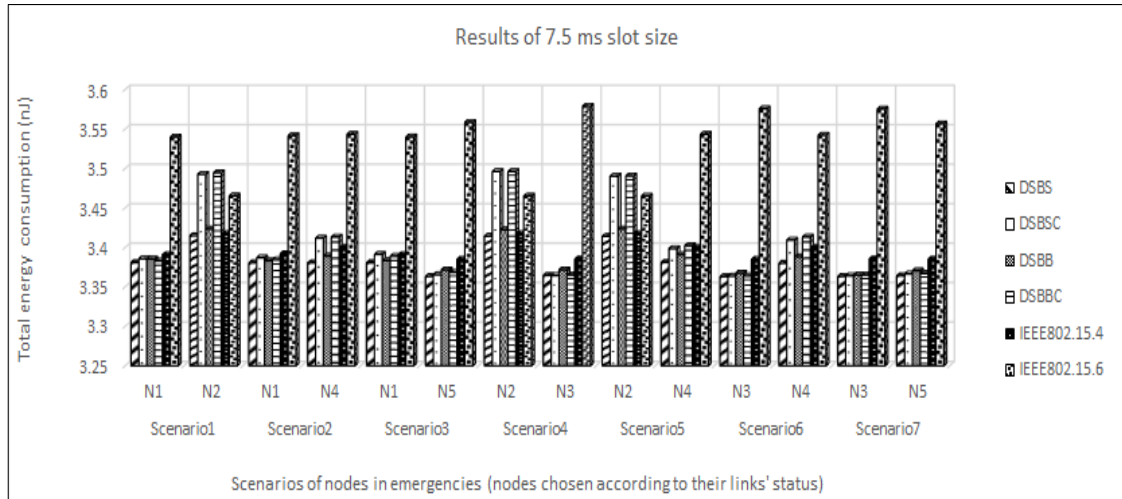


Figure 6-13: Total energy consumption in emergencies using 7.5 ms slot size.

6.4 Conclusions

According to the achieved results, upgrading DSBS and DSBB with context awareness technique does not improve the performance of WBAN in emergencies. Results achieved confirm that regardless of the slot length, if we consider the realistic behavior of WBAN medium, then allocating the nodes in emergency more bandwidth, while prohibiting other nodes from accessing the vulnerable WBAN medium does not improve WBAN performance in emergencies. This answers the seventh research question presented in Section 1.4. DSBC outperforms the proposed protocols only in terms of the end-to-end delay and only at nodes with very good links status, as those nodes will continue using the channel successfully. Nevertheless, this improvement is accompanied by a severe increase in energy consumption. On the other hand, according to the results achieved in Chapter 4, and Chapter 5, both DSBS and DSBB outperform the WBAN de-facto standards in terms of packets loss and energy consumption and at an acceptable delay performance. The improvements achieved in Chapter 4 and Chapter 5 apply to all nodes regardless of their links' status. More importantly, all the nodes have the chance to use the medium in both normal and emergency situations, and no node is prohibited from channel access regardless of its context. This contradicts the recommendation proposed in the literature, which states that offering nodes in emergencies more slots than other nodes improves WBAN reliability and timeliness. However, those claims can be true only if idealistic channel behavior is considered and not the realistic one. To sum up, it can be confirmed that due to the poor channel behavior of WBAN, considering traffic context in

emergencies degrades WBAN performance in terms of reliability, timeliness and energy instead of improving it. Considering only the link and the buffer statuses of the nodes are enough to improve the WBAN reliability and energy efficiency in both normal and emergency situations.

Chapter 7: Conclusions and Future Directions

7.1 Summary of the work done

This thesis outlined and discussed the state-of-the-art in WBAN reliability in general and the challenge of the deep fade phenomenon in particular. In addition, this thesis highlights the importance of tackling WBAN power efficiency, buffer constraints and heterogeneity of WBAN contexts and devises (Section 1.2, Section 1.3, Section 1.5, and Section 2.3.4).

Reliability and efficiency are vital to guarantee the success of the next generation of WBANs and their ability to support a rich portfolio of applications, especially in the e-health field where any loss or erroneous data could be fatal (Section 1.2, Section 1.3, Section 2.3.2). It is pointed out thoroughly in this thesis that neither static TDMA mechanisms adopted by WBAN de-facto standards, nor the dynamic TDMA slot allocation solutions proposed in literature provide a reliable and energy efficient WBAN (Section 1.1, Section 1.2, Section 1.3, Section 2.4).

In fact, the framework for channel access solutions in WBAN cannot be considered favorable for WBAN without avoiding the deep fade, such that the critical data could be achieved even though the medium is vulnerable. The requirements of the nodes in terms of their energy and buffer constraints, buffer loads, fairness optimised and utilised channel access should also be considered in both normal and emergency contexts (Section 1.1, Section 1.2, Section 1.3, Section 1.5, Section 2.5).

Accordingly, this thesis proposes two novel, generic and dynamic TDMA based MAC scheduling algorithms to improve the reliability and energy efficiency of WBAN (Chapter 3). In essence, the proposed techniques provide reasonable answers to the research questions presented in Section 1.4, and propose solutions for the drawbacks of the discussed TDMA techniques proposed in the literature for WBAN. The achieved answers for the research questions presented in Section 1.4 are as follows:

- The first two research questions presented in Section 1.4 have been answered by proposing the Adaptive Sleep TDMA MAC technique presented in Section 3.2, which enables the nodes to avoid deep fade in their links and without depending on the controller.
- The proposed DSBS and DSBB presented in Section 3.3 and 3.4 respectively provide a favourable solution for the third research question presented in Section 1.4. Both DSBS and DSBB exploit the deep fade of the links in WBAN and use it as a criterion to dynamically allocate slots to nodes (Section 3.3, Section 3.4). Besides the channel status, DSBS and DSBB schedule the nodes adaptively according to their needs, which depend on the load in their buffer.
- According to the results achieved in Section 4.3 and Section 5.4, the proposed protocols outperform the WBAN legacy standards in terms of packets loss and energy consumption and at an acceptable delay performance. This improvement applies to all nodes regardless of their links status, and more importantly, all the nodes have a chance to use the medium regardless of their context, and no node is prohibited from channel access whether it is in a normal situation or in an emergency. This provides an answer to the fourth research question presented in Section 1.4.
- Results achieved in Section 5.4 confirm that in addition to improving WBAN reliability and energy efficiency in normal situations, the proposed protocols guarantee better QoS in emergencies while minimising energy consumption. This answers the fifth research question presented in Section 1.4.
- All the protocols proposed in Chapter 3 do not require substantial amendments to the IEEE 802.15.4 and IEEE 802.15.6 superframe structures. Only one extra buffer field is added to the data packet format. This answers the sixth research question presented in Section 1.4.
- Results achieved in Section 6.3 provide a proof that allocating time slots to nodes according to their traffic context is not beneficial in improving WBAN performance. Considering only the status of the channel and the load in the nodes' buffer have the potential to improve WBAN reliability and energy efficiency in both the normal and

the emergency situations. This answers the seventh research question presented in Section 1.4

Additionally, the experimental results achieved in Section 4.3.2, Section 5.4, and Section 6.3 reveal that short slot lengths contribute to better performance. This is because a short slot gives nodes enough time to access the channel, while it reduces the probability that their links will experience deep fade in the channel. This work revealed that careful parametrisation of the slot size of TDMA is highly recommended when deploying WBAN MAC protocols.

As a final word, regarding WSN, we used to say: the lifetime of a sensor determines the lifetime of WSN, but in relation to WBAN we say: the behaviour of a sensor determines the lifetime of the human. Hence, if we cannot achieve the highest degree of reliability with 0% error as an acceptable QoS in WBAN, then it is better to shift to wired e-health networks despite their limitations on individual's movements. We must always remember that the main objective of WBAN is to improve and extend human life, it is not intended to offer luxury.

7.2 Challenging issues and future work

The new protocols proposed in this thesis provide a favorable solution to the research problem identified in Section 1.3, provide reasonable answers to the research questions listed in Section 1.4, and achieve the research aim and objectives listed in Section 1.5. As a consequence of doing this work, a number of new questions have been raised. Possible answers to those new research questions present sophisticated solutions, and tackling them is beyond the scope of a single PhD thesis. In this section the emerged challenging issues are examined in detail, and possible solutions are proposed and discussed in Section 7.2.1.

A crucial point that this thesis has not tackled is the loss of the control frames sent from the controller. The proposed protocols in this thesis depend on the frequent control frames sent from the controller to manage the network and to synchronise the nodes in the network (Section 3.2). In fact, if data packets sent from nodes could be lost due to the long durations and frequent deep fade occurrences in WBAN medium, the control frames sent from the controller could be lost too. Control frames carry sensitive information and they

are sent by the controller successively, and if a control frame is lost at some point due to deep fade in the medium for example, nodes will wait for the next control frame, which will be sent after the current TDMA schedule ends. This increases the end to end delay of the data packets sent from nodes. More importantly, multiple successive loss of control frames would result in erroneous network outputs, because the overall nodes would be disconnected from the network, which makes WBAN extremely untrustworthy. Therefore, it is crucial to consider this limitation and find solutions that guarantee successful transmission of the controller control frames.

The second challenging issue is that the proposed protocols are based on a re-active approach, which allows the nodes first to test the channel status by allowing them to transmit a data packet at the beginning of their time slots, and once a packet is lost, nodes realise that their links' encounter deep fade (Section 3.2). Although this method minimises packets loss, it does not eliminate it to its lowest level. Hence, other proactive ways should be integrated to the proposed protocols that assist the nodes links' status ahead before the actual packets transmission tasks place, and which gives the nodes a chance to take direct actions accordingly.

Despite the heterogeneity of WBAN sensor nodes, their physiological sensed data is correlated (Section 1.2, Section 2.4). For example, both the ECG and hemodynamic signals, such as blood pressure, have correlated information, due to the physiological correlation of the mechanical and electrical heart functions [42]. Physiological information also has a direct correlation with environmental information [28, 29]. Although correlation in physiological information is already considered in this thesis by adopting TDMA based channel access mechanisms (to avoid simultaneous transmission of sensors in emergencies (Section 1.2, Section 2.4)), correlation in the medical data can be harnessed to overcome various limitations in WBAN medium, one of which is the deep in WBAN medium. Therefore, other techniques that prioritise nodes in an emergency, while considering the correlation in the physiological information should be upgraded to the proposed protocols.

7.2.1 Solutions for the challenging issues

Regarding the first challenging issue, it is found that low bit rate traffic (up to 50 bps) such as security keys and passwords can be transmitted through the human body, without the need to implement a customised transmitter equipment. The interesting study in [70] reveals that devices with fingerprint sensors or touchpad can be used as transmitters to send data information through the human body, which will be received by wireless receivers that are in contact with the human body. For example, instead of manually typing a secret key or a password for the glucose or blood pressure monitors using a smartphone, the patients can touch their fingerprint sensor on the smartphone to directly transmit the secret key to the wearable devices on the body using the human body as a conductor instead of adopting RF wireless communication [70].

This idea can be of a great benefit for synchronising nodes in accessing WBAN medium, and could provide a potential solution for the first limitation of this thesis regarding the continuous loss of control frames sent by the controller. For example, as an alternative to the RF wireless medium, control frames from the controller could be sent through the human body to precisely schedule the wearable sensors placed on the human body. By receiving the control frame, the wearable sensors on the human body can send their data packets to the controller, by accessing the RF wireless medium of WBAN as usual. RF channel access occurs according to the time schedule received by wearable sensors in the control frame, and which is updated dynamically according to any of the two generic protocols proposed in this thesis. This not only would overcome the very vulnerable wireless medium of the WBAN, but would make the WBAN more immune to security attacks. This will improve WBAN reliability even more and make it more trustworthy. Moreover, this solution provides an opportunity to practically evaluate the potential of proposed protocols on a test bed rather than only simulation, which would provide more accurate results and could help in considering adopting the proposed protocols for WBAN in the future.

The second challenging issue could be tackled by implementing a learning algorithm in the controller, which studies the pattern of the occurrences of the deep fade in each node's link during the node's duty cycles. This is supposed to be a proactive solution, and it is assumed to help in resource allocation decision. This algorithm can be achieved by

adopting a Markov-Model of the fading with three states (bad, good, and excellent). Because the controller is a resource rich node, this limitation can also be tackled by integrating the controller with one of the machine learning techniques, such as the neural networks, through which the controller analysis the pattern in the links' status of the nodes.

Despite the possible problems that could occur due to data correlation in WBAN, existing interconnections can be harnessed by performing data fusion. The study in [42] was found to be the first and only study to mention this technique but for fault detection. Data fusion can be considered an initial step towards substituting the lost data packets of a specific node which's link encounters deep fade at a certain time. In this approach, a central specific node aggregates the decisions from the remaining network nodes. This so-called data fusion node can determine the abnormal status of other nodes by comparing data from a set of nodes [5]. The fusion node can achieve the lost data of some sensors by performing some derivations from other available data that has been sent by other sensors, i.e. substituting one piece of information for another, allowing a temporary flow of information. This could be considered a temporary solution, until the node's link return to its good status. This technique is very efficient, especially for data centric applications that require detection precision. Proposed data fusion mechanisms that harness the correlation in physiological data require statistical and data analysis techniques that test correlations in the data sets that carry the physiological information.

7.2.2 Suggested potential research areas

Another promising applications area where the proposed protocols can be used besides WBAN applications, is the industrial automation. In this realm, an evolving definition has emerged recently, that is the Factories of the Future (FoF). FoF is the European Union's main program for research and innovation in advanced manufacturing for realising the next (the fourth) industrial revolution [71]. FoF marks the beginning of a new era of manufacturing characterised by overall automation and complete use of technology in and outside manufacturing. In other words, FOF resembles the convergence of the mechanical age emerged by the industrial revolution and the digital age, in which huge amounts of data can be stored and retrieved in the blink of an eye [71, 72].

The main aim of FoF is to propose technologies that could fulfil two major requirements: the ultra-high reliability in terms of guaranteed message delivery for industrial automation with very low latency bounds down to 1 ms [73]. The literature states that the physical and MAC layers are the major contributors to the end to end delay in wireless industrial automation [74]. Therefore, it is important to design lower layers' protocols with the lowest possible level of latency, while achieving the highest possible reliability to fulfill FoF requirements.

The current commonly used industrial wireless communication solutions depend on the customised radio stacks of the IEEE lower layers technologies [74]. One example is the IEEE 802.15.4e standard, which is proposed as an amendment to the MAC layer of the IEEE 802.15.4 and published in 2012 to support industrial automation [75, 76]. IEEE 802.15.4e is basically proposed to solve two problems: 1) the high level of fading and interference due to the shared communication medium confined within one wireless channel, 2) energy dissipation by routers, which are always on regardless of their traffic [75, 76]. To solve those problems, the IEEE 802.15.4e adopts two schemes: The first scheme is called the Time Slotted Channel Hopping (TSCH) through which the IEEE 802.15.4e adopts both time synchronisation scheduling and channel hopping [75, 76, 77]. The main aim of TSCH is to achieve the highest possible level of reliability by facilitating multi-hopping mechanism as a way to avoid the effects of deep fading and compact interference in the medium of the short range industrial communication. The second aim is to achieve the lowest possible level of energy consumption by adopting excessive duty cycling mechanisms through the proposed synchronisation schedule [75, 76, 77]. Those two aims are the driving force for proposing DSBS and DSBB protocols in this thesis. Both DSBS and DSBB succeed in achieving a reliable and energy efficient WBAN considering only one channel to operate within, without the need to deploy the complexity of channel switching, channel allocation mechanisms, and channel overlapping and coexistence considerations.

In its second scheme, the IEEE 802.15.4e supports factory automation by proposing a highly efficient TDMA based MAC solution, which adopts a superframe structure of a fixed length time slots. In order to achieve a latency of less than 10 ms, the proposed superframe involves deterministic time slots, wherein each time slot is dedicated to one node [75, 76]. Hence, there will be no need for nodes addressing, which reduces the MAC header, and consequently reduces the packets delay. Experimental results achieved in

Section 6.4.1 reveal that with careful parametrisation of the TDMA schedule in terms of a slot length and schedule length, this goal is indeed attainable by adopting the proposed DSBS and DSBB protocols. This implies that the proposed protocols have potential in fulfilling the industrial automation requirements, as they can improve latency as well as reliability and energy efficiency.

Although the target area of this thesis is the WBAN medical field, the proposed protocols are generic and can be adopted by other areas that requires strict reliable and energy efficient short-range communications, such as the industrial arena. Therefore, one of the future research directions of the solutions proposed in this thesis is to evaluate the performance of DSBS and DSBB in industrial automation scenarios. Besides, hybrid ideas can be emerged by merging concepts from the IEEE 802.15.4e mechanisms and the concepts of the proposed protocols in this thesis. Merged concepts would help in achieving ultra-reliability and low latency for the aim of fulfilling the requirements of FoF.

Bibliography

- [1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *Communications magazine*, IEEE, vol. 40, pp. 102-114, 2002.
- [2] L. Selavo, A. Wood, Q. Cao, T. Sookoor, H. Liu, A. Srinivasan, et al., "Luster: wireless sensor network for environmental research," in *Proceedings of the 5th international conference on Embedded networked sensor systems*, 2007, pp. 103-116.
- [3] M. Kocakulak and I. Butun, "An overview of wireless sensor networks towards internet of things," in *2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC)*, Jan 2017, pp. 1–6.
- [4] T. Y. Kim, S. Youm, J. J. Jung, and E. J. Kim, "Multi-hop wban construction for healthcare iot systems," in *2015 International Conference on Platform Technology and Service*, Jan 2015, pp. 27–28.
- [5] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "Wireless body area network (wban): A survey on reliability, fault tolerance, and technologies coexistence," *ACM Comput. Surv.*, vol. 50, no. 1, pp. 3:1–3:38, Mar. 2017. [Online]. Available: <http://doi.acm.org/10.1145/3041956>
- [6] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless Body Area Networks: A Survey," *Communications Surveys & Tutorials*, IEEE, vol. 16, pp. 1658-1686, 2014.
- [7] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, et al., "A comprehensive survey of wireless body area networks," *Journal of medical systems*, vol. 36, pp. 1065-1094, 2012.
- [8] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, and R. Verdone, "A survey on wireless body area networks: Technologies and design challenges," *IEEE Communications Surveys Tutorials*, vol. 16, no. 3, pp. 1635–1657, Third 2014.

- [9] C. A. Chin, G. V. Crosby, T. Ghosh, and R. Murimi, "Advances and challenges of wireless body area networks for healthcare applications," in *2012 International Conference on Computing, Networking and Communications (ICNC)*, 2012, pp. 99-103.
- [10] M. Patel and J. Wang, "Applications, challenges, and prospective in emerging body area networking technologies," *Wireless Communications*, IEEE, vol. 17, pp. 80-88, 2010.
- [11] A. Boulis, Y. Tselishchev, L. Libman, D. Smith, and L. Hanlen, "Impact of wireless channel temporal variation on mac design for body area networks," *ACM Trans. Embed. Comput. Syst.*, vol. 11, no. S2, pp. 51:1–51:18, Aug. 2012. [Online]. Available: <http://doi.acm.org/10.1145/2331147.2331161>
- [12] A. Boulis, D. Smith, D. Miniutti, L. Libman, and Y. Tselishchev, "Challenges in body area networks for healthcare: the mac," *IEEE Communications Magazine*, vol. 50, no. 5, pp. 100–106, May 2012.
- [13] A. Boulis and Y. Tselishchev, "Contention vs. Polling: A study in body area networks mac design," in *Proceedings of the Fifth International Conference on Body Area Networks*, ser. BodyNets '10. New York, NY, USA: ACM, 2010, pp. 98–104. [Online]. Available: <http://doi.acm.org/10.1145/2221924.2221944>
- [14] *IEEE 802.15 WPAN TM Task Group 4 (TG4)*, IEEE Standard 802.15.4, 2003. [Online]. Available: <http://www.ieee802.org/15/pub/TG4.html>
- [15] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks*, IEEE Standard 802.15.6-2012, pp. 1–271, Feb. 2012.
- [16] M. Salayma, A. Al-Dubai, and I. Romdhani, "Reliability and energy efficiency enhancement in wireless body area networks for e-health," in *2016 19th Conference of Open Innovations Association (FRUCT)*, Nov 2016, pp. 203–211.
- [17] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "New dynamic, reliable and energy efficient scheduling for wireless body area networks (wban)," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.

- [18] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "Reliability and energy efficiency enhancement for emergency-aware wireless body area networks (wban)," *IEEE Transactions on Green Communications and Networking*, pp. 1–1, 2018.
- [19] H. Liu, A. Nayak, and I. Stojmenović, "Fault-tolerant algorithms/protocols in wireless sensor networks," in *Guide to Wireless Sensor Networks*, ed: Springer, 2009, pp. 261-291.
- [20] H. Ren and M. Q. h. Meng, "Understanding the mobility model of wireless body sensor networks," in *2006 IEEE International Conference on Information Acquisition*, Aug 2006, pp. 306–310.
- [21] G. Zhou, J. Lu, C. Y. Wan, M. D. Yarvis, and J. A. Stankovic, "Bodyqos: Adaptive and radio-agnostic qos for body sensor networks," in *IEEE INFOCOM 2008 - The 27th Conference on Computer Communications*, April 2008.
- [22] D. M. Barakah and M. Ammad-uddin, "A survey of challenges and applications of wireless body area network (wban) and role of a virtual doctor server in existing architecture," in *2012 Third International Conference on Intelligent Systems Modelling and Simulation*, Feb 2012, pp. 214–219.
- [23] G. Wu, J. Ren, F. Xia, and Z. C. Xu, "An Adaptive Fault- Tolerant Communication Scheme for Body Sensor Networks," *Sensors*, vol. 10, pp. 9590-9608, 2010. [Online]. Available: <http://www.mdpi.com/1424-8220/10/11/9590>
- [24] S. Ullah, B. Shen, S. Riazul Islam, P. Khan, S. Saleem, and K. Sup Kwak, "A study of mac protocols for wbans," *Sensors*, vol. 10, no. 1, pp. 128–145, 2010. [Online]. Available: <http://www.mdpi.com/1424-8220/10/1/128>
- [25] Y. Tselishchev, A. Boulis, and L. Libman, "Variable scheduling to mitigate channel losses in energy-efficient body area networks," *Sensors*, vol. 12, no. 11, pp. 14692–14710, 2012. [Online]. Available: <http://www.mdpi.com/1424-8220/12/11/14692>
- [26] B. Liu, Z. Yan, and C. W. Chen, "Medium access control for wireless body area networks with qos provisioning and energy efficient design," *IEEE Transactions on Mobile Computing*, vol. 16, no. 2, pp. 422–434, Feb 2017.

- [27] Y. Tselishchev, L. Libman, and A. Boulis, "Energy-efficient retransmission strategies under variable tdma scheduling in body area networks," in *2011 IEEE 36th Conference on Local Computer Networks*, Oct 2011, pp. 374–381.
- [28] S. Rezvani and S. A. Ghorashi, "Context aware and channel-based resource allocation for wireless body area networks," *IET Wireless Sensor Systems*, vol. 3, no. 1, pp. 16–25, March 2013
- [29] B. Liu, Z. Yan, and C. W. Chen, "Ca-mac: A hybrid context-aware mac protocol for wireless body area networks," in *2011 IEEE 13th International Conference on e-Health Networking, Applications and Services*, June 2011, pp. 213–216.
- [30] M. Salayma , A. Al-Dubai, I. Romdhani, and M. B. Yassein, "BARBEI: A new adaptive battery aware and reliable beacon enabled technique for IEEE 802.15.4 MAC," in *Advances in Network Systems (Advances in Intelligent Systems and Computing)*, M. Grzenda, A. Awad, J. Furtak, and J. Legierski, Eds. Cham, Switzerland: Springer Int., 2017, pp. 317–335.
- [31] M. Salayma, A. Al-Dubai, and I. Romdhani, "Battery aware beacon enabled ieee 802.15. 4: An adaptive and cross-layer approach," in *Federated Conference on Computer Science and Information Systems (FedCSIS)*. IEEEExplore, Conference Proceedings, pp. 1267–1272.
- [32] C. Otto, A. Milenkovic, C. Sanders, and E. Jovanov, "System architecture of a wireless body area sensor network for ubiquitous health monitoring," *Journal of Mobile Multimedia*, vol. 1, pp. 307-326, 2006.
- [33] S. C. Ergen. (2004). *Zigbee/IEEE 802.15.4 Summary*. Accessed: Sep. 10, 2004. [Online]. Available: <http://pages.cs.wisc.edu/~suman/courses/707/papers/zigbee.pdf>
- [34] W. Mardini, Y. Khamayseh, M. Salayma, M. Bani Yassein, and H. Mouftah, "Adaptive duty cycle (adc) energy efficient algorithm for zigbee networks," *International Journal of Computer Systems Science and Engineering*, CRL Publishing, vol. 32, no.1, pp. 5–19, 01 2017.
- [35] M. Salayma, W. Mardini, Y. Khamayseh, and M. Bani Yassein, "Ieee802.15.4 performance in various wsns applications," in *The Seventh International*

Conference on Sensor Technologies and Applications. SENSORCOMM 2013. IARIA, 2013, Conference Proceedings, pp. 139–144.

- [36] M. Salayma, W. Mardini, Y. Khamayseh, and M. Bani Yasin, "Optimal Beacon and Superframe Orders in WSNs," in *FUTURE COMPUTING 2013, The Fifth International Conference on Future Computational Technologies and Applications*, 2013, pp. 49-55.
- [37] E. Callaway, P. Gorday, L. Hester, J. A. Gutierrez, M. Naeve, B. Heile, et al., "Home networking with IEEE 802. 15. 4: a developing standard for low-rate wireless personal area networks," *IEEE Communications magazine*, vol. 40, pp. 70-77, 2002.
- [38] M. Bani Yassein, M. Kh Salayma, W. Mardini, and Y. Khamayseh, "Fibonacci backoff algorithm for ieee 802.15.4 zigbee," *Network Protocols and Algorithms*, Macrothink Institute, vol. 4, no. 3, 2012. DOI: <https://doi.org/10.5296/npa.v4i3.2094>
- [39] T. Rutherford and A. Socio, "*Population ageing: statistics*," House of Commons library (Standard not. Retrieved Jan 2, 2013, from: [www. Parliament. uk/topics/PopulationArchive](http://www.Parliament.uk/topics/PopulationArchive), 2012.
- [40] B. Latre, B. Braem, I. Moerman, C. Blondia, and P. Demeester, "A survey on wireless body area networks," *Wirel. Netw.*, vol. 17, no. 1, pp. 1–18, Jan. 2011. [Online]. Available: <http://dx.doi.org/10.1007/s11276-010-0252-4>
- [41] M. Patel and J. Wang, "Applications, challenges, and prospective in emerging body area networking technologies," *Wireless Communications*, IEEE, vol. 17, pp. 80-88, 2010.
- [42] A. Mahapatro and P. M. Khilar, "Online fault detection and recovery in body sensor networks," in *Information and Communication Technologies (WICT)*, 2011 World Congress on, 2011, pp. 407-412.
- [43] D. M. Barakah and M. Ammad-uddin, "A survey of challenges and applications of wireless body area network (wban) and role of a virtual doctor server in existing architecture," in *2012 Third International Conference on Intelligent Systems Modelling and Simulation*, Feb 2012, pp. 214–219.

- [44] J. Y. Khan and M. R. Yuce, "Wireless body area network (WBAN) for medical applications," *New Developments in Biomedical Engineering*. INTECH, January 2010.
- [45] G. V. Crosby, T. Ghosh, R. Murimi, and C. A. Chin, "Wireless body area networks for healthcare: A survey," *International Journal of Ad hoc, Sensor & Ubiquitous Computing (IJASUC)*, vol. 3, no. 3, June 2012. DOI : 10.5121/ijasuc.2012.3301
- [46] S. K. Garg, S. Schwartz, and S. V. Edelman, "Improved glucose excursions using an implantable real-time continuous glucose sensor in adults with type 1 diabetes," *Diabetes Care*, vol. 27, pp. 734-738, 2004.
- [47] J. Maloney and J. Santini Jr, "Implantable microchips for controlled drug delivery," in *Engineering in Medicine and Biology Society*, 2004. IEMBS'04. 26th Annual International Conference of the IEEE, 2004, pp. 2668-2669.
- [48] "IEEE approved draft standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements - part 15.4: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications for low rate Wireless Personal Area Networks (WPANs) amendment: Alternative physical layer extension to support Medical Body Area Network (MBAN) services operating in the 2360-2400 Mhz band," *IEEE P802.15.4j/D5.0*, November 2012 (Amendment of IEEE Std. 802.15.4- 2011), pp. 1–20, Feb 2013.
- [49] B. Malik and V. Singh, "A survey of research in WBAN for biomedical and scientific applications," *Health and Technology*, vol. 3, pp. 227-235, 2013. [46]
- [50] N. Alraji and H. Fu, "A Survey on Fault Tolerance in Wireless Sensor Networks," *Proceedings of the 2014 ASEE North Central Section Conference*, American Society for Engineering Education, 2014.
- [51] K. Takizawa, H.-B. Li, K. Hamaguchi, and R. Kohno, "Wireless patient monitoring using IEEE802. 15.4 a WPAN," in *IEEE International Conference on Ultra-Wideband*, 2007. ICUWB 2007, 2007, pp. 235-240.

- [52] D. Wang, D. Evans, and R. Krasinski, "Ieee 802.15.4j: extend ieee 802.15.4 radio into the mban spectrum [industry perspectives]," *IEEE Wireless Communications*, vol. 19, no. 5, pp. 4–5, Oct 2012.
- [53] C. N. Acedemy, *Network Basics Companion Guide*: Cisco Press, 2013.
- [54] J. Dong and D. Smith, "Coexistence and Interference Mitigation for Wireless Body Area Networks: Improvements using On-Body Opportunistic Relaying," *arXiv preprint arXiv: 1305.6992*, 2013.
- [55] H. Su and X. Zhang, "Battery-dynamics driven tdma mac protocols for wireless body-area monitoring networks in healthcare applications," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 4, pp. 424–434, May 2009.
- [56] A. El-Hoiydi, J.-D. Decotignie, C. Enz, and E. Le Roux, "Poster abstract: Wisemac, an ultra-low power mac protocol for the wisenet wireless sensor network," in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, ser. SenSys '03. New York, NY, USA: ACM, 2003, pp. 302–303. [Online]. Available: <http://doi.acm.org/10.1145/958491.958531>
- [57] O. Omeni, A. C. W. Wong, A. J. Burdett, and C. Toumazou, "Energy efficient medium access protocol for wireless medical body area sensor networks," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 2, no. 4, pp. 251–259, Dec 2008.
- [58] S. J. Marinkovic, E. M. Popovici, C. Spagnol, S. Faul, and W. P. Marnane, "Energy-efficient low duty cycle mac protocol for wireless body area networks," *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 6, pp. 915–925, Nov 2009.
- [59] G. Fang and E. Dutkiewicz, "Bodymac: Energy efficient tdma-based mac protocol for wireless body area networks," in *2009 9th International Symposium on Communications and Information Technology*, Sept 2009, pp. 1455–1459.
- [60] N. F. Timmons and W. G. Scanlon, "An adaptive energy efficient mac protocol for the medical body area network," in *2009 1st International Conference on Wireless Communication, Vehicular Technology, Information Theory and Aerospace Electronic Systems Technology*, May 2009, pp. 587–593.

- [61] L. F. Perrone and Y. Yuan, "Modeling and simulation best practices for wireless ad hoc networks," in *Proceedings of the 2003 Winter Simulation Conference*, 2003., 2003, pp. 685-693.
- [62] S. N. Technologies. 'QualNet Network Simulator Software', SCALABLE Network Technologies, 2018. [Online]. Available: <https://web.scalable-networks.com/qualnet-network-simulator-software>. [Accessed: 17-Apr-2018].
- [63] L. M. Feeney, "Towards trustworthy simulation of wireless mac/phy layers: A comparison framework," in *Proceedings of the 15th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*, 2012, pp. 295-304.
- [64] *Castalia: A Simulator for Wireless Sensor Networks and Body Area Networks*, Version 3.3, Nat. ICT, Sydney, NSW, Australia, May 2013, accessed: Mar. 14, 2018.[Online].Available: [https://github.com/boulis/Castalia/blob/master/Castalia User Manual.docx](https://github.com/boulis/Castalia/blob/master/Castalia%20User%20Manual.docx)
- [65] M. Ameen, A. Nessa, and K. S. Kwak, "QoS issues with focus on wireless body area networks," in *Convergence and Hybrid Information Technology*, 2008. ICCIT'08. Third International Conference on, 2008, pp. 801-807.
- [66] R. Szewczyk, J. Polastre, A. Mainwaring, and D. Culler, "Lessons from a sensor network expedition," in *Wireless Sensor Networks*, ed: Springer, 2004, pp. 307-322.
- [67] B. T. Korel and S. G. Koo, "A survey on context-aware sensing for body ensor networks," *Wireless Sensor Netw*, vol. 2, no. 8, pp. 571–583, 2010.
- [68] B. T. Korel and S. G. Koo, "Addressing context awareness techniques in body sensor networks," in *Advanced Information Networking and Applications Workshops*, 2007, AINAW'07. 21st International Conference on, 2007, pp. 798-803.
- [69] Y.-S. Jeong, H.-W. Kim, and J. H. Park, "Visual Scheme Monitoring of Sensors for Fault Tolerance on Wireless Body Area Networks with Cloud Service Infrastructure," *International Journal of Distributed Sensor Networks*, vol. 2014, 2014.

- [70] M. Hessar, V. Iyer, and S. Gollakota, “Enabling on-body transmissions with commodity devices,” in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, ser. UbiComp '16. New York, NY, USA: ACM, 2016, pp. 1100–1111. [Online]. Available: <http://doi.acm.org/10.1145/2971648.2971682>
- [71] E. Commission, “*Factories of the Future*”, Public Private Partnerships in research,2013.[Online].Available:http://ec.europa.eu/research/industrial_technologies/factories-of-the-future_en.html. [Accessed: 17-Apr-2018]
- [72] I.E.C. “*Factory of the Future*”, White Paper, International Electrotechnical Commission, 2015. [Online] <http://www.iec.ch/whitepaper/pdf/iecWP-futurefactory-LR-en.pdf>. [Accessed: 17-Apr-2018].
- [73] M. Bennis, M. Debbah, and H. V. Poor, “Ultra-reliable and lowlatency wireless communication: Tail, risk and scale,” *CoRR*, vol. abs/1801.01270, 2018. [Online]. Available: <http://arxiv.org/abs/1801.01270>
- [74] B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf, J. Huschke, I. Aktas, and J. Ansari, “Wireless communication for factory automation: an opportunity for lte and 5g systems,” *IEEE Communications Magazine* , vol. 54, no. 6, pp. 36–43, June 2016
- [75] *IEEE 802.15 WPAN™ Task Group 4e (TG4e)*, IEEE Standard 802.15.4e, 2012. [Online]. Available: <http://www.ieee802.org/15/pub/TG4e.html>
- [76] H. Kurunathan, R. Severino, A. Koubaa, and E. Tovar, “Ieee 802.15.4e in a nutshell: Survey and performance evaluation,” *IEEE Communications Surveys Tutorials*, pp. 1–1, 2018.
- [77] R. T. Hermeto, A. Gallais, and F. Theoleyre, “Scheduling for ieee802.15.4-tsch and slow channel hopping mac in low power industrial wireless networks: A survey,” *Computer Communications*, vol. 114, pp. 84–105, 2017.
- [78] S. Patel, H. Park, P. Bonato, L. Chan, and M. Rodgers, “A review of wearable sensors and systems with application in rehabilitation,” *Journal of NeuroEngineering and Rehabilitation*, vol. 9, no. 1, p. 21, 2012. [Online]. Available: <https://doi.org/10.1186%2F1743-0003-9-21>

- [79] Sensors Online, 'The Potential and Challenges of Wireless Sensor Nodes for Diverse Application Fields', 2009. [Online]. Available: <https://www.sensormag.com/embedded/potential-and-challenges-wireless-sensor-nodes-for-diverse-application-fields>. [Accessed: 30-Aug-2018].
- [80] EMSP Technische Universitaet Berlin, 'Wireless Body Sensor Networks', 2017. [Online]. Available: https://www.emsp.tuberlin.de/menue/forschung_research/current_projects/wireless_body_sensor_networks. [Accessed: 30-Aug-2018].
- [81] P. Khan, A. Hussain, and K. Kwak, "Medical applications of wireless body area networks," vol. 3, pp. 185–193, 01 2009.
- [82] D. Choudhary, R. Kumar, and N. Gupta, "Real-time health monitoring system on wireless sensor network," International Journal of Advance Innovations, Thoughts & Ideas, vol. 1, no. 5, 2015.

Appendix: A Typical WBAN Sensor and Wearable Devices

Minimising the size of electronic circuits has been a key role in the development of wearable devices. Recent advances in the field of micro-electro-mechanical systems have allowed researchers to develop small size circuits for health monitoring purposes. Such circuits include microcontroller, transceiver or radio transmission, sensing capability, and amplification. Figure A-1 is an example of such sensing device, which has the capability of capturing physiological information and transmit the data through wireless medium to a central unit using a low-power radio transceiver. Further size reduction into System-on-Chip implementations has been achieved by using batch fabrication techniques, which also decreased the cost of sensors. Continuous developments in the field of electronics are anticipated to lead to manufacturing of smaller, lighter and more comfortable wearable systems [78].

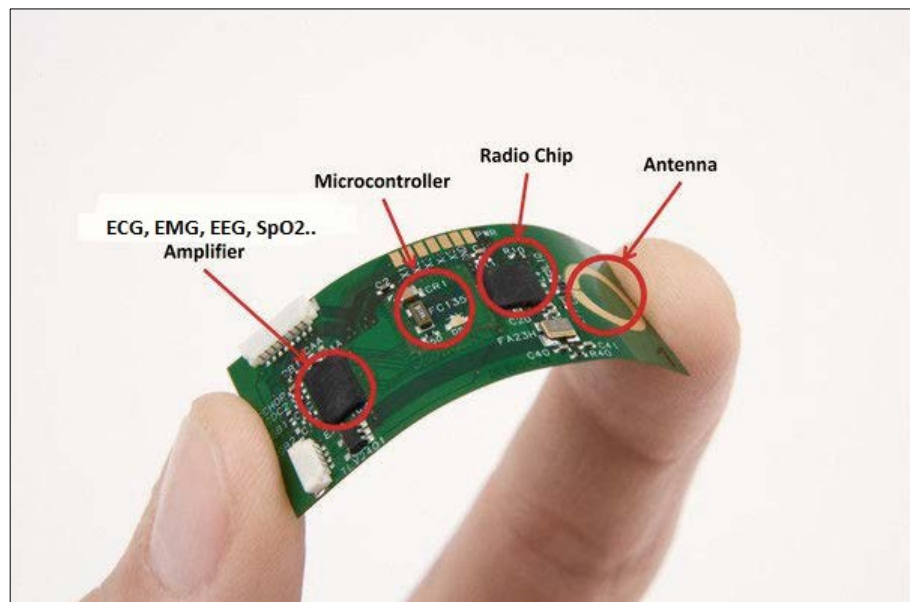


Figure A-1: A typical WBAN sensor device [78].

The electrocardiogram (ECG) is one of the most important biosignals that provide information about the cardiovascular system. Figure A-2 depicts an example of a first-

generation wireless ECG patch developed by Holst Centre/Imec in 2008. Holst Centre is an independent center that develops technologies and electronics for healthcare and Internet of Things [79]. Figure A-2 shows a wireless low-power ECG monitoring patch, which also integrates a low-power microcontroller, low-power radio, battery and antenna. The wireless ECG patch is implemented in ambulatory settings [79].



Figure A-2: Wireless ECG patch, developed at Holst Centre/Imec [79].

Figure A-3 depicts a new 12-lead ECG sensor device developed by the Electronics and Medical Signal Processing (EMSP) research group in Technische Universität in Berlin. The group is specialised in developing electronics for energy and automation, especially in the field of wearable healthcare technologies [80]. The device is designed for laboratory and ambulatory implementations, with special considerations to ensure a good signal quality. The device sampling rate is up to 1 kHz. The device integrates battery (life for more than 48 hours), wireless synchronisation capabilities with other sensor nodes, wireless data streaming to external devices, such as laptops and smartphones, active electrodes combining active pre-processing and filtering circuits, 3-axis acceleration sensor on each electrode [80].

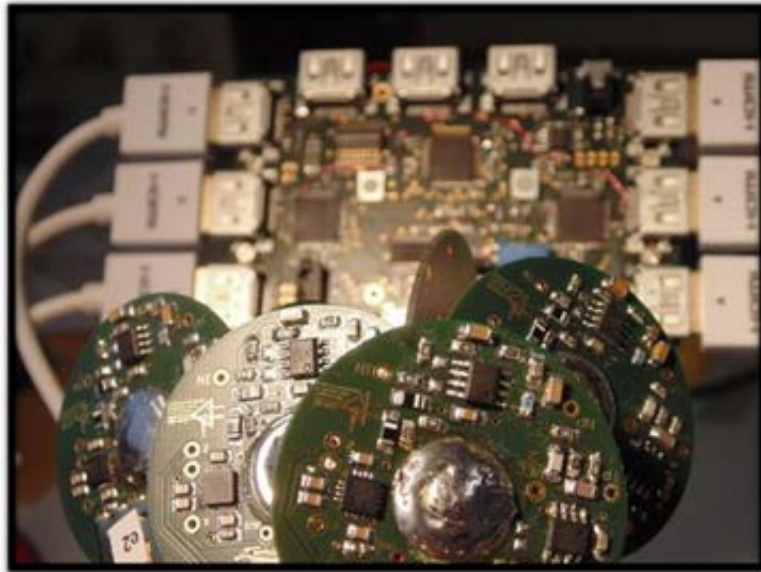


Figure A-3: ECG sensor developed by Technische Universitaet Berlin [80].

Figure A-4 shows another example of wireless biosignal sensor device, which is a pulse oximeter. This device is a low power and wearable device developed in 2004 by a medical research project at Harvard University, namely CodeBlue. This project tackles pre-hospital and in-hospital emergency care, disaster response and stroke patient rehabilitation. The device transmits periodic packets which carries heart rate, SpO₂ (blood oxygen saturation), and plethysmogram waveform data [81].

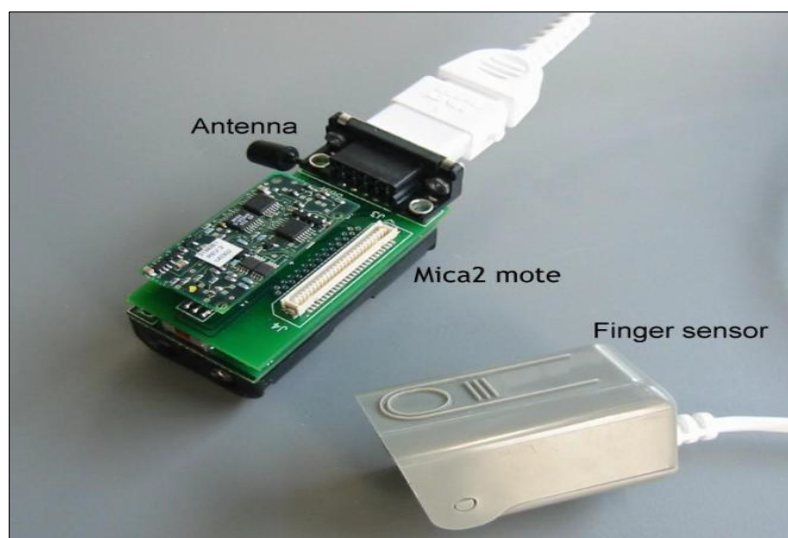


Figure A-4: Wireless pulse oximeter developed by CodeBlue [81].

Figure A-5 depicts low weight, low power consumed and comfortable to wear pulse oximeter developed by Deepak et al. in 2015. The device is designed to be used by patients in their daily life. The device integrates a microcontroller for controlling the processes in the sensor module. ZigBee technology is adopted for wireless communications. The data such as heart rate, SpO₂, battery information and wireless signal strength are stored in microcontroller and sent to base nodes [82].

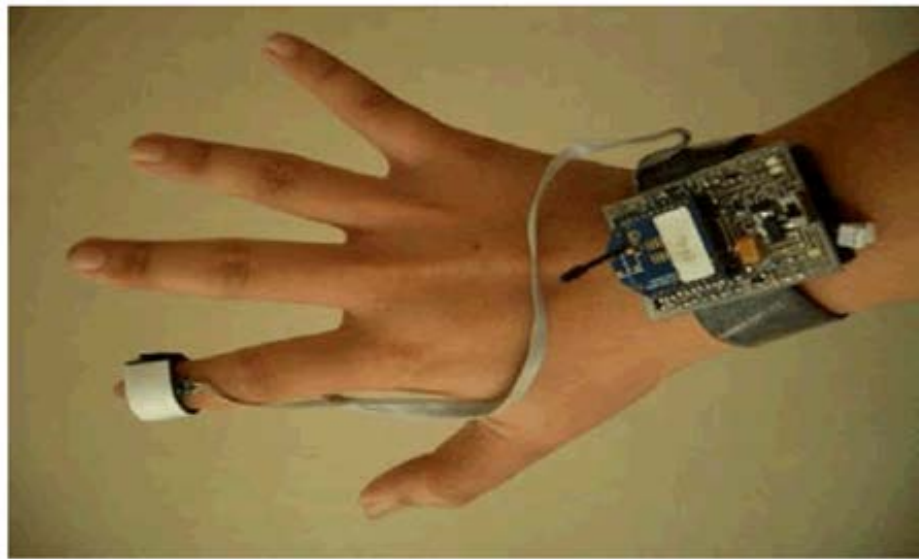


Figure A-5: Sensor node of pulse oximeter worn on wrist and finger print [82].

Figure A-6 depicts a Photoplethysmogram (PPG) device, which is dual pulse oximeter device developed by EMSP group. PPG provides information concerning pulse rate and wavevelocity, SpO₂ and respiratory activity. It can extract general information regarding arterial elasticity and aging. More information about the description of the device can be found in [80].

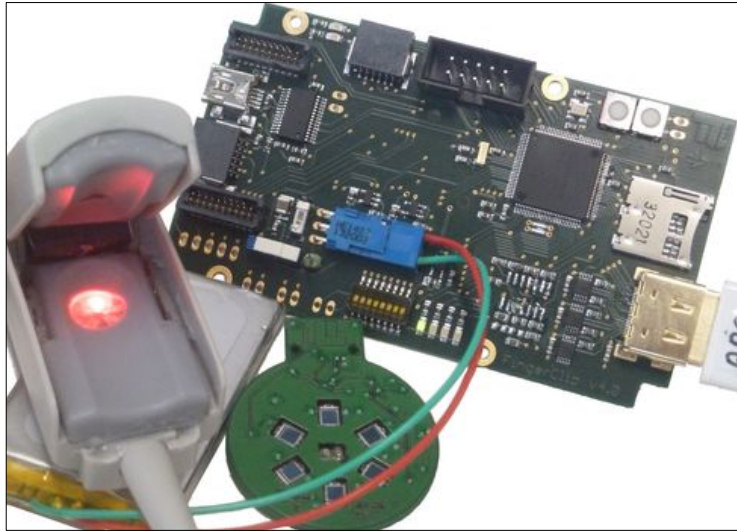


Figure A-6: Dual pulse oximeter developed by Technische Universitaet Berlin [80].

Figure A-7 depicts a new electrodermal activity (EDA) developed recently by EMSP group. EDA is assessed by measuring the electrical conductance of the skin. Skin conductance can be used as an indication of psychological or physiological arousal. The device has a sampling rate up to 8 kHz. The device integrates battery (life for more than 48 hours), 12 Bit ADC, wireless time synchronisation within WBAN, wireless data streaming to external devices, low power microcontroller, signal pre-processing capabilities. More information about the components of the device can be found in [80].

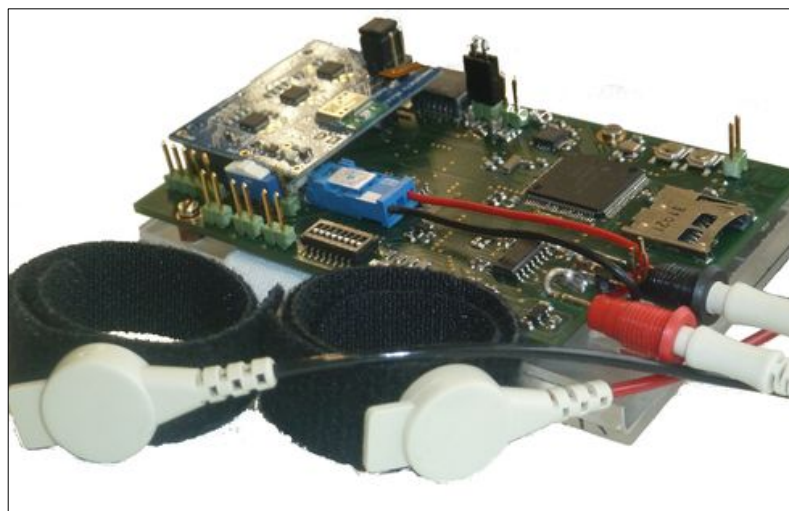


Figure A-7: EDA developed by Technische Universitaet Berlin [80].