Thesis for the Degree of Doctor of Philosophy

Interference Mitigation Schemes for Coexistence Problem in Wireless Body Area Networks

BeomSeok Kim

Department of Computer Engineering
Graduate School
Kyung Hee University
Seoul, Korea

August, 2016

Interference Mitigation Schemes for Coexistence Problem in Wireless Body Area Networks

BeomSeok Kim

Department of Computer Engineering
Graduate School
Kyung Hee University
Seoul, Korea

August, 2016

Interference Mitigation Schemes for Coexistence Problem in Wireless Body Area Networks

by
BeomSeok Kim

Advised by
Prof. Jinsung Cho, Ph.D.

Submitted to the Department of Computer Engineering
and the Faculty of the Graduate School of
Kyung Hee University in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy

Dissertation Committee:

Prof. Chi-Geun Han, Ph.D. (Chairman)

Prof. Sungwon Lee, Ph.D.

Prof. Jeong Geun Kim, Ph.D.

Prof. Choonhwa Lee, Ph.D.

Prof. Jinsung Cho, Ph.D.

Abstract

Ubiquitous healthcare and/or lifecare services have attracted a great deal of attention in recent years due to rapid advances in wireless communication technologies which have led to low-power, highly reliable, and miniaturized sensor nodes. As a result, Wireless Body Area Network (WBAN) became the next generation of wireless technology for Wireless Personal Area Network (WPAN). WBAN is communication technology that provides both medical and consumer electronics (CE) services by using sensors which function in/on/around a human body. For the standardization of WBANs, The IEEE 802.15 Working Group (WG) constructed Task Group 6 (TG6) in November 2007 and completed a working baseline document in February 2012. To provide both medical and CE services simultaneously, the IEEE 802.15.6 standard defines various requirements such as low power consumption, low latency, low duty cycle, Quality of Service (QoS), scalability and reliability, which are more strict than other communication technologies in WPAN. Especially, reliable communication is one of the most important requirements in WBANs because medical services are directly related to the safety of human lives.

In general, WBANs are densely deployed in a populated area such as a hospital or a healthcare center, and each WBAN has both intra- and inter-network mobility due to postural body movement and body-centric operation of WBANs. For these reasons, a WBAN may dynamically coexist with a varying number of other WBANs, and thus they may suffer from interference among themselves which then lead to significant performance deterioration, referred to as the *Coexistence problem.* In addition, aspects of the coexis-

tence problem can be aggravated through intra- and inter-network mobility of WBANs which are main reasons of frequently changed network condition. In order to solve this problem, the IEEE 802.15.6 classifies coexistence environment into three different conditions (dynamic, semi-dynamic, and static) according to mobility of coexisting WBANs, and the IEEE 802.15.6 also defines three different coexistence mitigation schemes (beacon shifting, channel hopping, and active superframe interleaving) to handle coexistence conditions. In addition, the standard defines two-hop star topology extension to help handling of link loss caused by coexistence problem. However, the IEEE 802.15.6 does not specify detailed algorithms for these coexistence mitigation and handling schemes. Moreover, the standard also does not consider a variety of requirements for different services and variabilities of network conditions.

In order to overcome the shortcomings of coexistence mitigation schemes in the IEEE 802.15.6 standard and to satisfy requirements of WBANs, this thesis proposes three different coexistence mitigation schemes. The first scheme is an adaptive contention-based channel access scheme which focuses on mitigating the coexistence problem on a single channel. When multiple WBANs are densely deployed in narrow region and they occupy the same channel at the same time, a contention complexity may increase, and it can be the major reason of performance deterioration. To solve this problem, the first scheme provides a priority-based channel access which helps to reduce contention complexity and to improve communication performance. Based on the first scheme, the second scheme focuses on coexistence mitigation by performing multiple channel usage. Due to limited bandwidth, the performance of a WBAN which occupies single channel has some limits while performing the first scheme. To resolve these limitations, the second scheme provides an adaptive channel estimation algorithm to select the best channel. Based on the proposed channel selection scheme, coexisting WBANs can efficiently mitigate coexistence problem by performing multi-channel usage. Meanwhile, a WBAN may suffer from frequent link loss due to interference among sensors deployed over a human body and

frequently changed channel condition by postural body movement, and this problem can cause unreliable communication and excessive power consumption. In order to solve this problem, the thesis proposes a relay node selection scheme which flexibly selects the relay node by using Analytical Hierarchy Process (AHP) that takes into account multitude of decision factors. The performance of three different schemes are validated through extensive simulations.

Acknowledgment

First of all, I thank God. He gives me everything in every way. I am deeply indebted to my advisor, Prof. Jinsung Cho, who is the greatest teacher in my life. He accepts me as the fourth Ph.D. candidate and giving me the great opportunity to work with him. He showed the essence of study (e.g., thinking, analyzing, and writing) to me and gave me many pieces of advices. In addition, I can learn affective morality from his guidance on the Ph.D. degree course. Based on his advices and teaching, I can successfully finish my work through his invaluable help.

I would like to express my cordial thanks to Prof. Chi-Geun Han, Prof. Sungwon Lee, Prof. Jeong Geun Kim, and Prof. Choonhwa Lee who gave me their insightful comments and research direction to improve my current and future work significantly.

I would like to thank all the members of Mobile & Embedded System Lab who have contributed immensely to my personal and academic life at Kyung Hee University. I would like to especially thank Dae-Young Kim and Byoungseon Kim who are the best friends in my research life. Without their careful comments, supports, and valuable feedback, I may not have finished my work. I would also like to thank Jinhyuk Kim, Young-Sun Seo, Hak-Soo Kim, Wee Yeon Kim, Yohan Kim, Kyung Won Lee, Yong Kyu Baek, Jong-Hyeon Choi, Kunryun Cho, and Sung Hyun Kim.

I pay sincere thanks to my friends in Chasse members, Won-Kyung Jeong, Yong-Jang Seo, Jin-Won Kim, Jong-Hyuk Choi, Ji-Hoon Kim, and Ji-Yeh Lee, who have broad shoulders. I also thank to Membership Training members in Dept. of Computer Engineering, Sanghoon Han, Na-Hyung Lim, and Myung-Seop Kim. I also thank my colleagues, Jinsoo Wang, Byoung-Yong Ryu, Jae-Myun Kim, Seung-Yoon Choi, Young-Soo Hur, Sang-Hoon Lee, Hang-Ki Cho, and Lim Hur.

Finally and most important of all I would like to thank my wife, Hyun-Ah Moon, who have been an inspiration to me. I also thank my family.

BeomSeok Kim, August 2016

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

Wireless Body Area Network (WBAN) is a communication technology that provides both medical and consumer electronics (CE) services by using sensors in, on, or around a human body [1]. WBAN aims to actualize ubiquitous healthcare and/or lifecare services which are a part of typical Internet of Things (IoT) applications. Thus, it is recognized as a core technology of human-centric wireless communication for both future medical applications and smart quality of life (QOL) management applications.

To standardize WBAN, the IEEE 802.15 Working Group established Task Group 6 (TG6) in November 2007 [2], and they completed the baseline document in February 2012 [3]. In the baseline document, three different physical (PHY) layers and a medium access control (MAC) layer are defined in order to provide both medical and CE services simultaneously, and it also defines extensive and different requirements. As shown in Figure 1.1, WBANs have wide range of requirements, which include requirements for another wireless communication technologies such as Bluetooth (IEEE 802.15.1), UWB (IEEE 802.15.3), and ZigBee (IEEE 802.15.4). Especially, a WBAN has to provide reliable communication because medical services are directly related to safety of human lives.

In general, WBANs are densely deployed in popular area, and they have both intra- and inter-network mobility. Thus, the performance of WBANs are suffer from interference from each other, referred to as the *coexistence problem.* In order to solve the coexistence

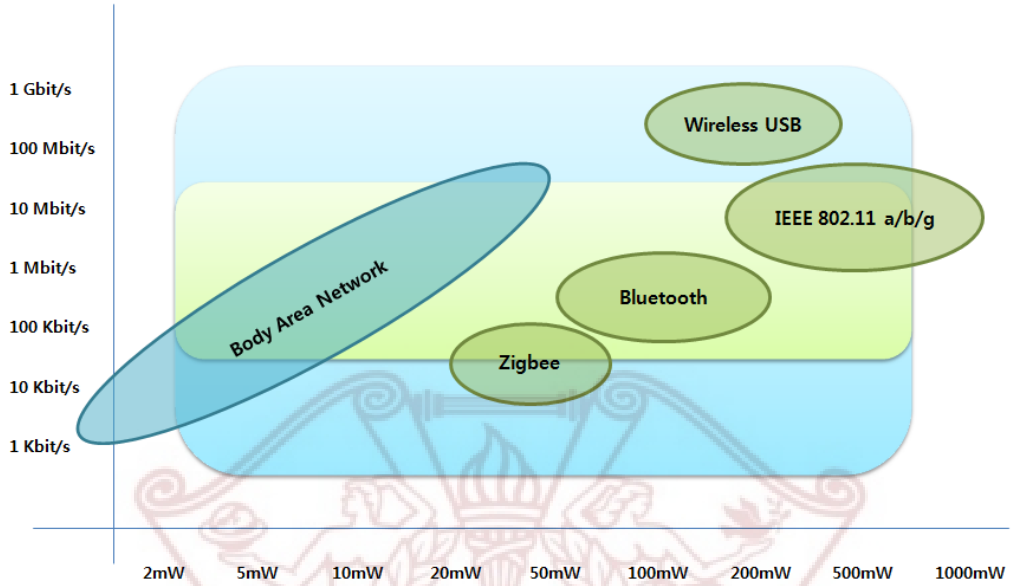


Figure 1.1: Requirements of WBANs.

problem, the IEEE 802.15.6 classifies coexistence environment into three different conditions (dynamic, semi-dynamic, and static) according to mobility of coexisting WBANs. In addition, it also defines three different coexistence mitigation schemes (beacon shifting, channel hopping, and active superframe interleaving) to handle coexistence conditions. However, coexistence mitigation schemes in the IEEE 802.15.6 do not provide detailed algorithms, and they cannot be fundamental solutions for the coexistence problem. To efficiently solve the coexistence problem in WBANs,therefore, this thesis handles following subjects: a priority-based contention-based channel access algorithm on a single channel, a channel selection scheme for multi-channel usage, and a flexible relay node selection. These schemes are developed considering with organic operation among them, which may create synergy effects for handling the coexistence problem in WBANs.

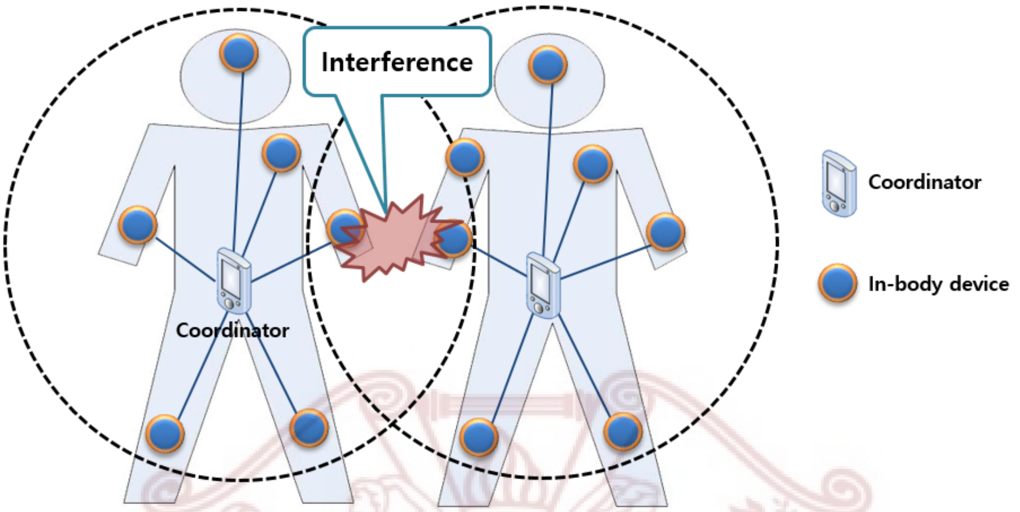


Figure 1.2: The coexistence problem in overlapped WBAN environment.

1.2 Contribution

The first part of the thesis deals with an adaptive contention-based channel access mode which focuses on coexistence mitigation on single channel. The MAC protocol in the IEEE 802.15.6 has a hybrid superframe structure operating in single channel manner. The superframe structure uses both contention-free channel access mode and contention-based channel access mode. Contention-free channel access mode operates based on time-slot reservation that its performance is more sensitive to coexistence environment because it is designed without considering external interference. Therefore, contention-free channel access mode is not suitable to be applied coexistence environment in WBANs. In contention-based channel access, in contrast, each node accesses channel with carrier sense multiple access/collision avoidance (CSMA/CA) which is relatively strong to interference or collision. However, contention complexity may increase when a number of WBANs are densely deployed in narrow region, and it can lead to quantities of collision and increase of latency. In order to this problem, the proposed channel access mode classifies the contention-based access period into four levels by the priority of packet which is defined in the IEEE 802.15.6. The proposed channel access scheme can disperse contention complexity and reduce power consumption.

The second part of the thesis concentrates on coexistence mitigation through multi-channel usage. In general, frequency bands in WBANs are divided into a number of channels, which means that a WBAN can simultaneously transmit with their neighbor WBANs at the same time when they does not use the same channel. However, the IEEE 802.15.6 MAC protocol uses only single channel which results in physical bandwidth limitation and heavy collisions. More specifically, this problem may be aggravated under coexistence environments in WBANs. To overcome restriction of single channel MAC protocol, the thesis propose an channel selection scheme which provides an efficient channel scanning and an adaptive channel estimation. Based on the proposed channel selection scheme, WBAN MAC protocol can operate in multi-channel manner, and it can help to mitigate coexistence problem efficiently.

Under coexistence environment, a WBAN suffers from frequent link loss due to interference among sensors scattered over a body. In addition, the channel condition can frequently change by postural body movement, which causes increase of packet drops, retransmission, and eventually power consumption. In order to handle this problem, the IEEE 802.15.6 defines a two-hop star topology extension to help establish a new link. However, the two-hop star topology extension does not specify how a relay node should be selected. In addition the standard also does not consider requirements for different service applications and variabilities of network conditions in WBANs. To overcome shortcomings of the two-hop star topology extension, the last part of the thesis presents a relay node selection which flexibly selects the relay node by using Analytical Hierarchy Process (AHP) that considers a multitude of decision factors, such as average SNR, remaining energy ratio, and traffic load. In addition, the relay node selection can adaptively satisfy the requirements of WBAN in various scenarios.

1.3 Organization

The reset of the thesis is organized as follows:

Chapter 2 briefly introduces background for the IEEE 802.15.6 standard and its requirements. In addition, this chapter also presents the MAC protocol in the IEEE 802.15.6 and describes the coexistence problem in WBANs. After that, we present existing coexistence mitigation schemes in the IEEE 802.15.6.

Chapter 3 depicts the proposed channel access scheme for mitigating coexistence problem in a single-channel scenario. This chapter first analyzes a contention complexity of traditional contention-based channel access schemes. Based on results of analysis, this chapter validates the performance of the proposed channel access scheme through extensive simulation respectively.

Chapter 4 illustrates an adaptive channel estimation algorithm for a multi-channel scenario, which is based on two-state Markov model with an exponentially controlled channel history.

Chapter 5 describes the proposed relay node selection scheme. This chapter analyzes existing relay selection schemes and presents the proposed relay node selection for the two-hop star topology extension in the IEEE 802.15.6 standard which exploits AHP to satisfy the requirements of WBAN in various scenario under the coexistence environment. Results of extensive simulation are also presented and they shows that the proposed relay node selection scheme can provide flexibility and adaptability for various WBANs scenarios.

Finally, chapter 6 concludes the thesis with future directions and opened research issues from the proposed comprehensive works.

Chapter 2

Background

In this chapter, the thesis overviews the IEEE 802.15.6 standard for WBAN and introduces requirements of WBANs. In addition, the thesis also presents coexistence mitigation schemes in the standard and analyzes their unsolved coexistence problems.

2.1 Requirements of WBANs

As mentioned above, the IEEE 802.15.6 standard defines the PHY and MAC layers for short range, wireless communication in and around the body area. The standard aims to support a low complexity, low cost, ultra-low power and highly reliable wireless communication for use in close proximity to, or inside, a human body (but not limited to humans) to satisfy an evolutionary set of entertainment and healthcare products and services.

The standard intends to address both medical/healthcare applications and other non-medical applications with diverse requirements. The medical applications cover continuous waveform sampling of biomedical signals, monitoring of vital signal information, and low rate remote control of medical devices. The non-medical applications include video and audio, bulk and small data transfer, command and control for interactive gaming etc. Dependent on the application, the WBAN devices may require a network of anywhere from a few sensor or actuator devices communicating to the coordinator. In another example, potentially hundreds of medical and CE sensors can communicate with the coordinator as a gateway which is connected to backbone network such as local, metropolitan, wide area network.

Devices for the above applications are usually highly constrained in terms of resource such as CPU processing power, battery capacity and memory size and operate in unstable environments. At the same time, medical sensors and actuators may have to be physically small to be wearable or implantable. The coordinator may also have some form of resource constraints. However, they are typically less constrained than the medical sensors or actuators.

The devices can operate various environments such as medical/wellness facilities (e.g., hospital, healthcare center, silver town) and home. In addition, multiple WBANs may operate in narrow area simultaneously. Therefore, they may suffer from interference. In this operating environment, a WBAN should provide both medical and CE applications/services simultaneously with various sensor devices located in, on, or around a human body.

Because of the space limitation and location dependent characteristics of medical information, it is unlikely to deploy redundant medical sensors for vital information collection. As a result, there is little redundancy in the traffic. In addition, the traffic flow in WBANs can be asymmetric due to the fact that the major medical traffic is point-to-multipoint (e.g. stimuli) or multipoint-to-point (e.g. ECG) depending on the application philosophy. During diagnosis, doctor may investigate a parameter in a command/response mode. The "downstream" traffic (commands) is coming from the coordinator to a particular sensor or actuator.

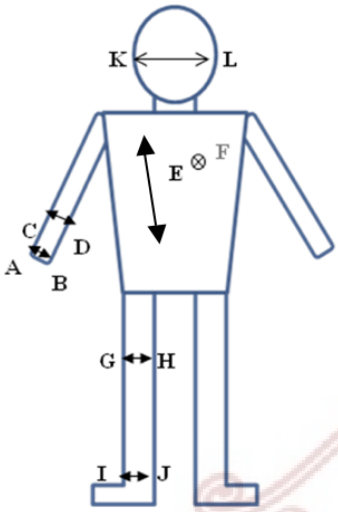
WBAN services and its applications have amount of different requirements in terms of their traffic characteristics. For example, Most of medical applications (e.g., bio-medical and vital signals sensing) have periodic traffic pattern with small size data, and applications for the aged or disabled person (e.g., motion detection, fall detection) can be event-driven, and thus they have bursty traffic pattern. Some applications with delay-tolerant characteristics collect sensing value and transmit collection of sensing data with sensing log information. Some medical sensors alert emergency when the sensing data is abnormal. Some real-time applications require prioritization of messages to guarantee deadline (e.g., emergency, ECG, EMG for critical patient)

WBANs can serve remote clinic applications which can be "open loop" or "closed loop". In the former case, a set of vital data, which is collected from medical sensors, may be transmitted from the coordinator to the doctors. Based on the set of vital data, doctors can command clinic actions to actuators in the network through diagnosis based on sensing data. "Close loop" control have to satisfy delay requirement (100ms to seconds). In these applications, the second case of emergency can occur when the packets do not arrive within the specified interval.

WBANs also aim to provide CE applications (e.g., video, audio, social network, and games) which include real-time multimedia. In the real-time application, QoS (Quality of Service) is one of the most important requirement. Therefore, higher throughput and lower end-to-end latency should be stisfied.

To deal with these requirements of WBANs specifically, the IEEE 802.15.6 published Technical Requirement Document (TRD) [5]. Detailed requirements of WBANs are described as follows:

- Network composition and mobility: A WBAN provides a very short communication range of at least 3 m, as well as the network configuration should be efficiently scalable up to 256 devices which may be in close proximity to, or inside, a human body. Some examples of WBAN links are shown in Figure 2.1. The nodes located on the torso and head will not move much relative to each other, however the nodes located on extremities: legs and arms may move relative to each other and the nodes on the torso and the head. In addition, the network should be workable without requiring complex set up procedure (simple wireless connection and disconnection) and shall tolerate dynamic insertion and de-insertion of nodes into a network.



Link	Description
A - B	Through the hand
C - D	Through the wrist
E - F	Torso, front to back
G - H	Through the thigh
I - J	Through the ankle
K - L	Left ear to right ear
M – N	Glucose sensor to Glucose pump

Figure 2.1: An example of network composition in WBANs.

- Extremely low-power: In some applications, the device in a WBAN should operate based on battery and they should alive in months or years without recharge or replace. In addition, some devices which also are supplied power from battery require tens of hours life due to characteristics of the application and their physical size. For example, cardiac defibrillators and pacemakers have to operate more than 5 years, and swallowable camera pills generally operate more than 12 hours. Most of CE devices have requirement of 100-200 hours for non-active mode and several hours for active mode. Due to this requirement, low power consumption for WBAN devices is one of the most important issue. More specifically, ultra-low power operation is essential requirement for improve lifetime of implanted devices because it is difficult to replace or recharge batteries of in-body sensors. In general, peak power consumption and average power consumption shall be minimized to support small form factor battery and maximize battery life. In addition, idle listening and overhearing consumes a significant amount of power in wireless communication. Meanwhile, reducing duty cycle rate of sensor devices, which shut down radio and CPU resource for most of the time, is necessary. To minimize idle listening, overhearing, packet collision and control overhead, therefore, advanced duty cycling techniques for sensor devices in WBANs are required. A sleep mode is advantageous to reduce duty cycle rate, in particular for low duty cycle devices that have sporadic traffic pattern. In addition, the coordinator which controls wakeup and sleep time of sensor nodes can reduce frequent wakeup of sensor nodes. These mechanisms should be supported by the MAC and PHY layers, and TRD defines low duty-cycle (i.e., sampling rate) to reduce the average transmission power consumption (e.g., $< 1\%$ or $< 10\%$).

- Transmission rates and traffic patterns: Due to the fact that WBANs provide both medical and CE services, requirements of various transmission rates should be satisfied (e.g., $10Kbps$–$100Mbps$). In addition, WBANs have to provide different traffic patterns for both medical and CE services. For example, most of medical services tend to be periodic in nature (e.g., packet generation interval: $1ms$–$1000s$). In contrast, CE services occasionally transmit packets which are generated with sporadic and bursty traffic in general. Therefore, WBANs should provide not only variable transmission rates but also different traffic patterns.

- Latency: In WBANs, some medical and CE services have to satisfy real-time communication which require QoS. Therefore, throughput and latency should be provided for real-time services. In detail, medical applications require the maximum latency of less than 125 ms, and non-medical applications require the maximum latency of less than 250 ms. In addition, jitter (variation of one-way transmission delay) should be less than 50 ms.

- Reliable communications: Reliability is one of most important requirements in WBANs because medical services in WBAN are directly related to the safety of human lives. However, network conditions frequently change due to the variability of WBAN environment, and it can harmfully affect reliable communications in WBANs (e.g., link loss, collision, and signal attenuation). To guarantee reliable communications, therefore, the IEEE 802.15.6 defines the maximum values of Packet Error Rate (PER). The PER shall be less than or equal to 10% for a 256 octet payload with a link success probability of 95% over all channel conditions. A link success probability of 95% is defined as the PER averaged over the channels that result in the 95% best performance at a given Eb/N0 for a channel models, i.e., the PER performance due to the worst 5% channels at a given Eb/N0 should not be included in the average PER calculation. Note that Eb is computed as the average multi-path signal energy, averaged over the channel realizations for each channel mode. Meanwhile, capability of providing reliable and immediate reports in emergency situations and alarm message, which have the highest priority than other messages, should be provided. One such requirement is to transmission an "Emergency" condition that the WBAN node has detected. In medical applications, this might be WBAN sensor detection of heart beat stoppage, excessively low or high blood pressure or temperature, excessively low or high blood glucose level in a diabetic patient.

- Scalability: Sensor devices in a WBAN can coexist with other WBAN devices and different type of devices such as smart phone. The devices need to normally operate in coexistence situation that devices can be interfere from others to deal with interference ingress (interference coming into the PHY layer) and interference egress (interference caused by the PHY layer). The attributes may be controlled by MAC or L3 layer . The devices have to provide normal operation in large interference, dynamic environment in mobility. Both medical application in hospital, small clinic, healthcare center and home have to be considered, along with wearable entertainment applications. MAC and PHY should support co-located operation of at least 10 randomly distributed WBANs in a volume of 6*6*6 meters. In particular, implantable WBAN and wearable WBAN should gracefully coexist in-and-around the body. A fair bandwidth sharing among collocated WBANs and graceful degradation of service is desirable for high duty cycle application, while uncoordinated operation is acceptable for low duty cycle applications. Medical applications should have higher priority than CE applications in serious coexistence situation.

In summary, WBANs have more extensive and different requirements than other wireless communication technologies due to providing both medical and CE services simultaneously. Especially, extremely low-power consumption, reliability, and scalability should be satisfied because WBANs deal with medical services which are closely related to user's lives.

2.2 MAC protocol in IEEE 802.15.6

To standardize WBAN, the IEEE 802.15 Working Group (WG) established Task Group 6 (TG6) in November 2007 [2] and completed a working baseline document in February 2012 [3]. In the baseline document, three different physical (PHY) layers are defined to provide various frequency band such as narrow band which includes Medical Implant Communications Service (MICS) band and Industrial Scientific and Medical (ISM) band, Human Body Communication (HBC) band, and Ultra Wide Band (UWB) in order to provide various transmission rate. In addition, the IEEE 802.15.6 also defines a medium access control (MAC) layer which are designed to provide integrated management for those three different PHY layer.

In the IEEE 802.15.6 MAC protocol generally exploits a time reference-based superframe structure. The time axis is divided into superframes of equal length and each superframe is composed of allocation slots of equal length. An allocation interval is referenced in terms of the numbered allocation slot, and a point of time is referenced in terms of the numbered allocation slots preceding. The time reference-based superframe

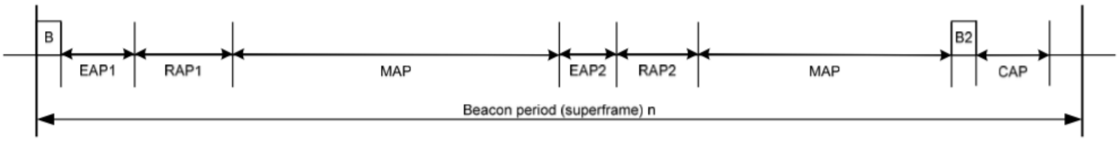


Figure 2.2: Beacon mode with beacon periods.

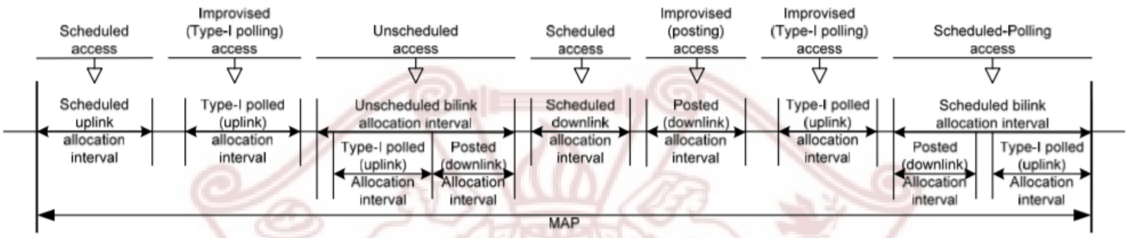


Figure 2.3: Allocation interval and access methods permitted in a MAP.

structure can be classified into two difference modes: *Beacon mode with superframes* and *Non-beacon mode with superframe.* In addition, the IEEE 802.15.6 additionally provides *Non-beacon mode without superframes* which does not consider superframe periods. The detail of each access mode is as follows.

In Beacon mode with superframes, coordinator organize applicable access period in each superframe as illustrated in Figure 2.2, where B srands for beacon. Coordinator maintains more than one inactive periods after each active superframe, if there are no allocation intervals scheduled in the inactive periods. In an active superframe, coordinator transmits a beacon and provides access periods: exclusive access period 1 (EAP1), random access period 1 (RAP1), managed access period (MAP), exclusive access period 2 (EAP2), random access period 2 (RAP2), another managed access period (MAP), and contention access period (CAP). In EAP1, RAP1, EAP2, RAP2, and CAP, all sensor nodes access channel by using CSMA/CA or slotted Aloha. Especially, the standard define priorities for different traffic types in order to give transmission priority in contention-based channel access as shown in Table 2.1. Each traffic types have different minimum and maximum contention window value, and higher priority traffic type can be preferentially transmitted than lower priority traffic type. In contrast, as depicted in Figure 2.3, MAP is operated based on time referenced allocation which is similar to time division multiple access (TDMA), and it can be classified into scheduled up/down/bilink allocation intervals, unscheduled bilink allocation intervals. In addition, MAP also provide improvised access methods such as type-I, type-II, immediate polled allocation intervals, and posted allocation interval. On the other hand, in an inactive periods, coordinator does not transmit any beacon and does not provide any access periods.

In non-beacon mode with superframes, coordinator has only a MAP in any superframe as illustrated in Figure 2.4.

In non-beacon mode without superframes, coordinator provides unscheduled bilink allocation intervals comprising type-II polled allocation and/or posted allocations, as presented in Figure 2.5. After determining that coordinator for the next frame exchange is operating in non-bacon mode without superframes, each node treats any time interval

Table 2.1: Priorities and minimum/maximum CE values according to traffic type

	Priority	Traffic type	CW	
			MinCW	MaxCW
Lowest	0	Background (BK)	16	64
	1	Best effort (BE)	16	32
	2	Excellent effort (EE)	8	32
	3	Video (VI)	8	16
	4	Voice (VO)	4	16
	5	Medical data or network control	4	8
	6	High-priority medical data or network control	2	8
Highest	7	Emergency or medical implant event report	1	4

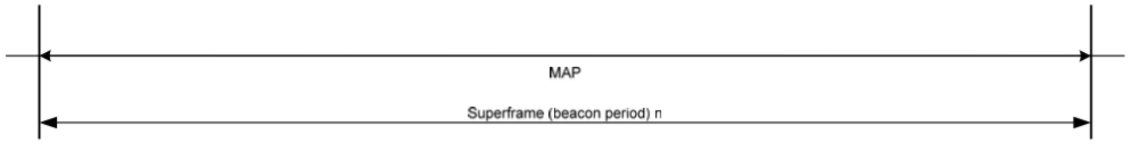


Figure 2.4: Layout of access phases in a superframe for non-beacon mode.

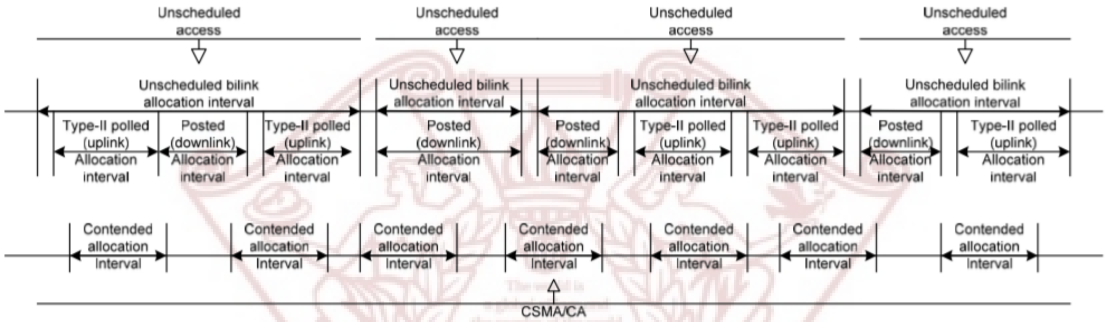


Figure 2.5: Allocation intervals and access mothods permitted for non-beacon mode without superframes.

as a portion of EAP1 or RAP1 and employs CSMA/CA based random access to obtain a contended allocation.

2.3 Coexistence problem in WBANs

In general, WBANs are densely deployed in a populated area such as a hospital or healthcare center, and WBAN has inter-network mobility due to body-centric operation of WBAN. For this reason, WBAN may dynamically coexist with a varying number of other WBANs as shown in Figure 2.6. In this situation, coexisting WBANs may suffer from interference among them, which cause significant performance degradation, referred to as the *'Coexistence problem'*.

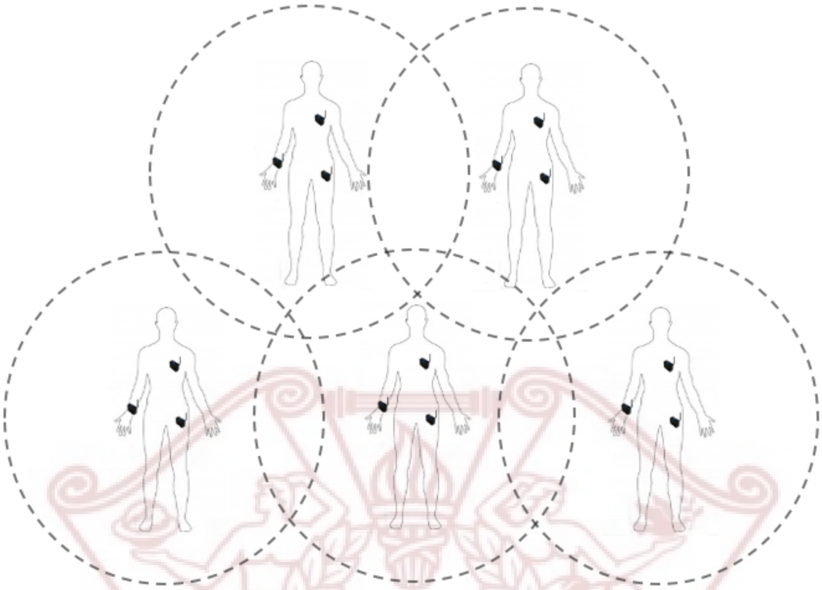


Figure 2.6: Coexistence of multiple WBANs.

2.3.1 Aspects of coexistence problem among WBANs

In early stage of WBAN development, the IEEE 802.15.4 protocol, a typical low-power protocol for WPANs, was considered for WBAN implementation. However, IEEE 802.15.4-based WBAN cannot handle coexistence problem because the IEEE 802.15.4 is designed without considering coexistence mitigation.

To identify aspects of coexistence problem among IEEE 802.15.4-based WBAN, J. Choi *et al.* performs preliminary experiments [4]. In these experiments, the authors have constructed experimental environment which composes two WBANs which consist of a coordinator and four sensor nodes which contains ATmega128 and CC2420. Each sensor node transmits dummy data to the coordinator with 14.4 kbps data rate. To compare performance of coexisting WBANs and non-coexisting WBAN according to channel access schemes, we consider four different scenarios as shown in Table 2.2. The authors assume

Table 2.2: Experimental scenarios

	Interfered (Scenario 1)	Non-interfered (Scenario 2)	Interfered (Scenario 3)	Non-interfered (Scenario 4)
Measurement WBAN	Non-beacon CAP	Non-beacon CAP	Beacon-enabled CFP	Beacon-enabled CFP
Interfering WBAN	Non-beacon CAP	-	Non-beacon CAP	-

that experiments in scenario 1 and 3 are interfered from the coexisting WBAN which is set to non-beacon CAP mode and interfering WBANs do not exist in scenario 2 and 4. Experiments in scenario 1 and 2 operate based on non-beacon CAP mode, and those in scenario 3 and 4 operate based on beacon-enable CFP mode. Based on these experimental setup, they measure the packet reception ratio (PRR).

Figure 2.7 illustrates results of scenario 1 and 2, and Figure 2.8 does results of scenario 3 and 4. When there is no interfering WBAN (scenario 2 and 4), more than 90% of PRR is obtained. On the contrary, PRR in scenario 1 and 3 is decreased due to interfering WBANs. Especially, in scenario 4 (beacon-enable CFP mode with interfering WBAN), PRR decreases dramatically because CFP operates based on time-slot reservation (GTS allocation) and it does not provide recovery process for failed transmission. Based on these experimental results, we can confirm that WBANs based on CAP mode is relatively strong to interference or collision due to CSMA/CA. On the other hand, WBANs based on CFP mode are sensitive to other coexisting WBANs because it is designed without considering external interferences.

In summary, through the preliminary study, they have found that IEEE 802.15.4-based WBANs may suffer from coexistence problem which occurs low transmission reliability. Especially, external interferences significantly influence reliability and performance of WBAN when it operates based on CFP mode.

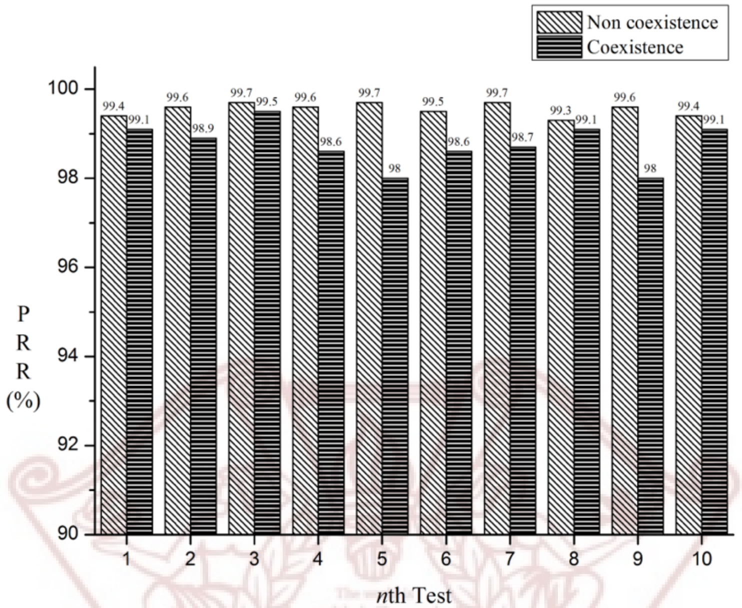


Figure 2.7: Results of scenario 1 and 2 (non-beacon CAP)

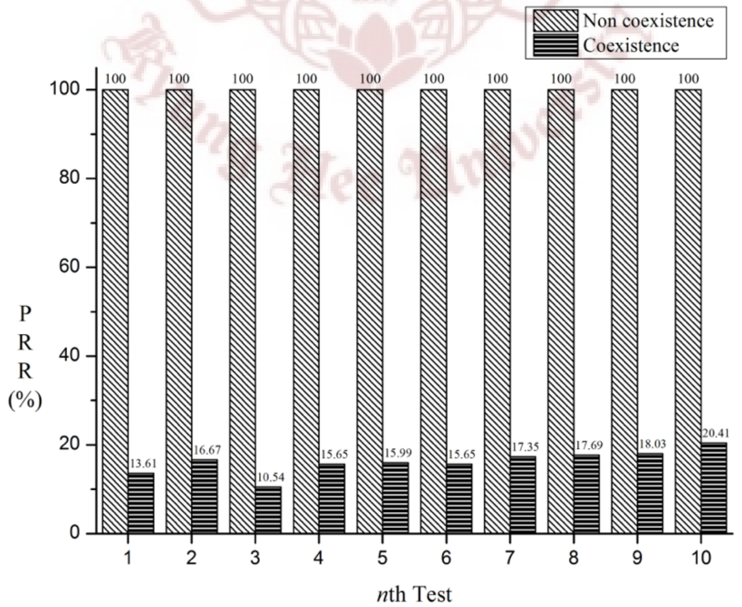


Figure 2.8: Results scenario 3 and 4 (beacon-enable CFP)

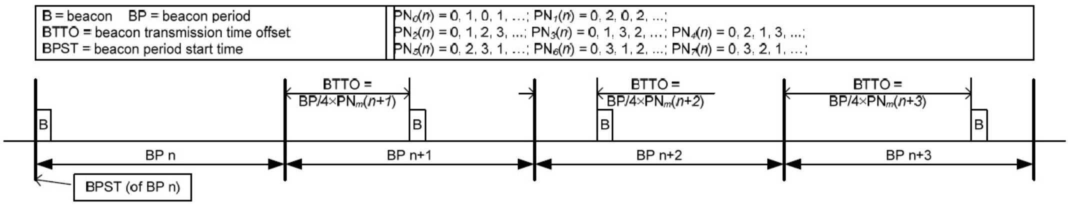


Figure 2.9: Beacon shifting.

2.3.2 Coexistence mitigation schemes

To deal with coexistence problems in WBANs, the IEEE 802.15.6 defines three different coexistence mitigation schemes [3]. In coexisting WBAN, collision of beacon transmission means that the coordinator cannot communicate with its member nodes until unit communication time because beacon message is used to announce essential information for communication between the coordinator and member nodes. In this point of view, to guarantee successful beacon transmission, the IEEE 802.15.6 defines the first coexistence mitigation scheme,*Beacon shifting*, that shifts beacon transmission time to avoid potential repeated beacon collision among neighboring WBANs which operate in the same channel. Figure 2.9 shows details of *Beacon shifting* scheme. In *Beacon shifting*, the coordinator selects one of *Beacon shifting index* (m) which indicates a set of *Beacon shifting phase* (PN_m) and *Beacon shifting sequence* for each beacon period (BP). After selecting *Beacon shifting index*, coordinator obtains beacon transmission time offset (BTTO) and adjusts beacon period start time (BPST) based on BP number and *Beacon shifting index*.

The second coexistence mitigation scheme in the standard is *Channel hopping*. In the coexistence situation, the coordinator can change its operating channel in the operating frequency band periodically by choosing particular channel hopping sequence that is not being used by its adjacent WBANs. To hop to a new channel, the coordinator generates a channel hopping sequence based on the maximum-length Galois linear feedback shift

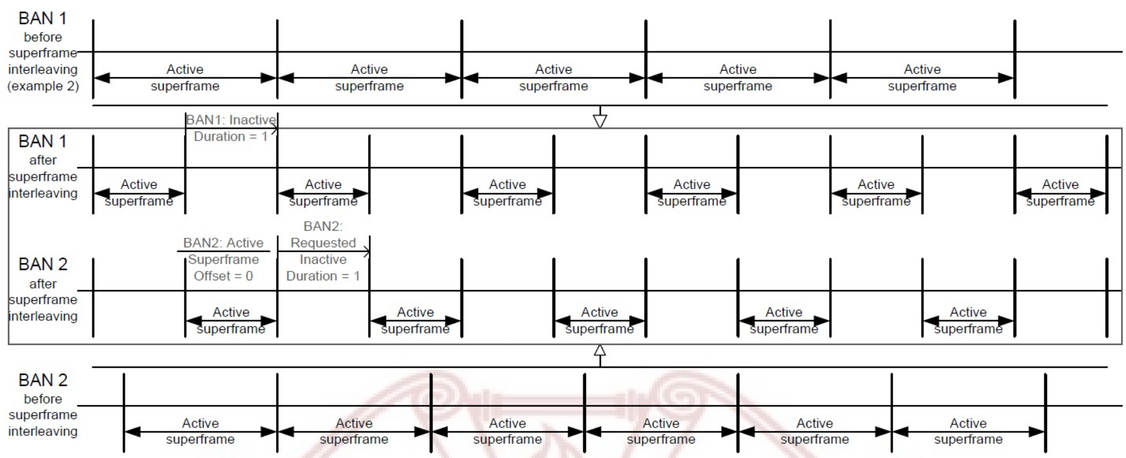


Figure 2.10: Active superframe interleaving.

register (LFSR). After getting the channel hopping sequence, the coordinator performs channel scanning over a given list of candidate channels in a specific frequency band. At the end of channel scanning, the coordinator selects an unused channel as the new operating channel. If there is no free channel, coordinator randomly selects the new channel and operates other coexistence mitigation schemes for the selected channel to avoid congestion.

Actually, a WBAN may share the same operating channel with its neighborhoods with or without interleaving their active superframes. In this situation, coexisting WBANs should avoid interference among them. To solve this problem, as shown in Figure 2.10, IEEE 802.15.6 proposes *Active superframe interleaving* which alternates Active period and Inactive period of superframe among coexisting WBANs with negotiating transmission time among their coordinators.

However, these schemes cannot be exploits due to the detailed protocols schemes are not provided in the standard.

2.3.3 Two-hop star topology extension

As mentioned above, network conditions of WBANs frequently change due to inter- and intra-network mobility, and these variabilities can cause link loss between the coordinator and sensor nodes. Frequent link losses decrease network stability and lead to network partitioning which cause unreliable communication. To tackle this issue, the IEEE 802.15.6 defines *Two-hop star topology extension* to help establish a new link [3]. The two-hop star topology extension provides the relay discovery and selection procedure, which can be either coordinator centric or relay node centric. Figure 2.11 shows details of both the coordinator centric and the relay node centric approach.

In the coordinator centric approach, the node initiates a procedure to find and establish a link to a relay node when it detects that the communication link with the coordinator is poor. This is achieved by overhearing *ACK* or *Management* frames originating from a relay node and destined to the coordinator, which indicates that the relay node is within the range of both the coordinator and the node and the link between the relay node and the coordinator is reliable. The node will then initiate the establishment of a new link with the discovered relay node by sending a *Connection Request* message to the relay node. If the relay node accepts the request, it forwards this message to the coordinator and sends an *ACK* to the node. When the coordinator receives the *Connection Request* message from the node, it sends a *Connection Assignment 1* message to inform the relay node of the updated radio resource allocation between the coordinator and the relay node. The coordinator also sends a *Connection assignment 2* message to inform the relay node of the additional radio resource allocation for the new link between the relay node and the node, which is then forwarded to the node. Finally, the node can send data to the coordinator through the relay node.

Figure 2.11 also illustrates the relay discovery procedure for the relay node centric approach. This approach provides the new relay link establishment to both connected and disconnected nodes. A relay node may optionally provide synchronization to the

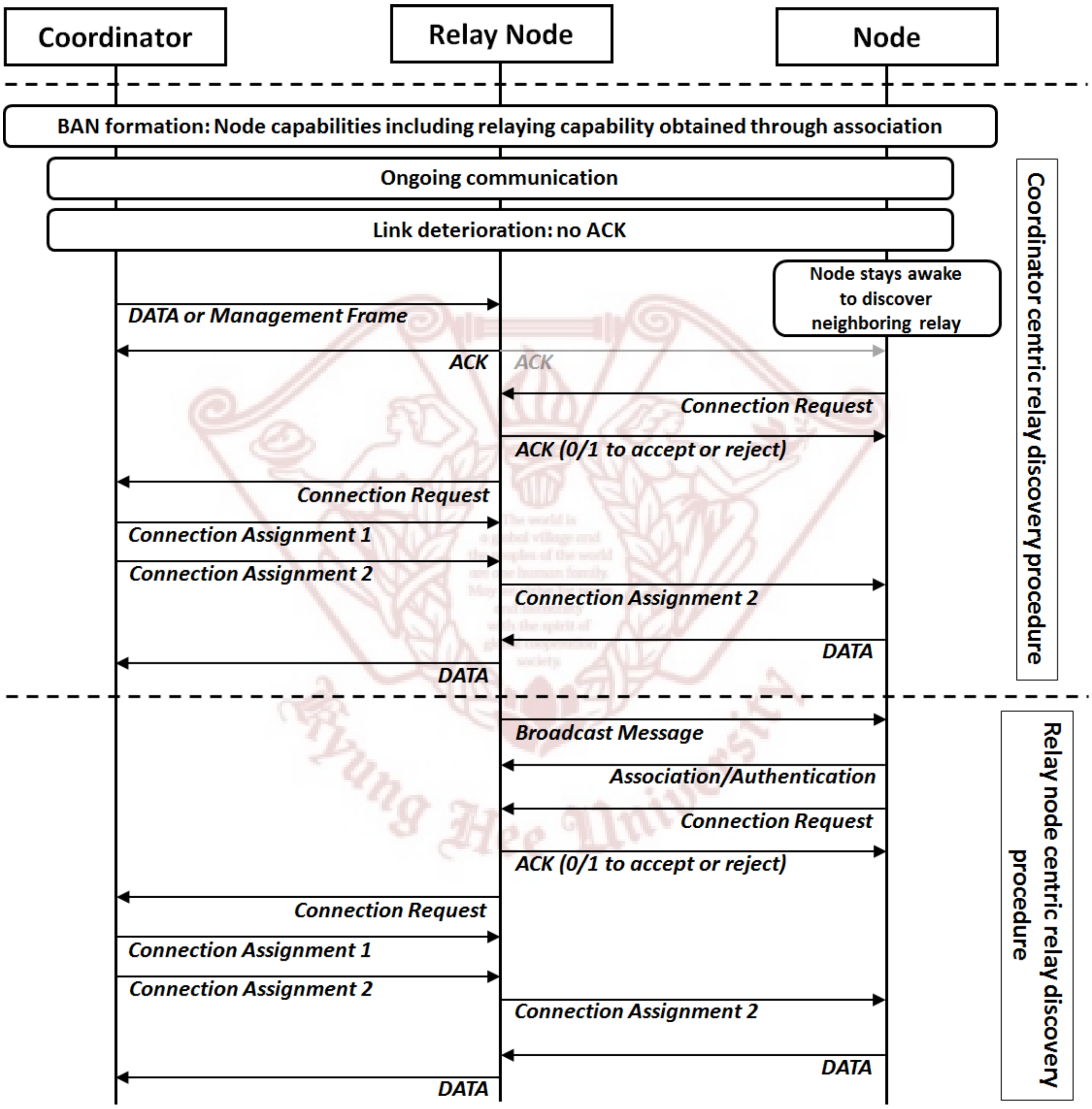


Figure 2.11: The relay discovery and selection procedure for the two-hop star topology extension of IEEE 802.15.6.

nodes in the WBAN (connected or disconnected) when it operates based on the Beacon-enable mode. This is done by having the relay node send a *Broadcast* message, which includes a timestamp and resource allocation specification. The purpose of the *Broadcast* message is to provide the disconnected nodes an opportunity to establish a connection with a suitable relay node in order to communicate with the coordinator. After the node receives the *Broadcast* message, it will authenticate the relay node. If the authentication is successful, the node transmits *Connection Request* message to the relay node to request for additional resources for communication between the relay node and the node. The next resource allocation procedure for the relay node centric approach is the same to as the coordinator centric approach.

Note that in both coordinator and relay node centric approaches, the node selects the first relay node that replies with an *ACK*. This means that the IEEE 802.15.6 standard does not consider multiple relay candidates to provide adaptiveness to continuously changing network condition, network lifetime, and latency. Moreover, IEEE 802.15.6 does not provide any provisioning to recover the direct link between the coordinator and the node when the network condition improves, which can eliminate the unnecessary power consumption of the relay node.

Chapter 3

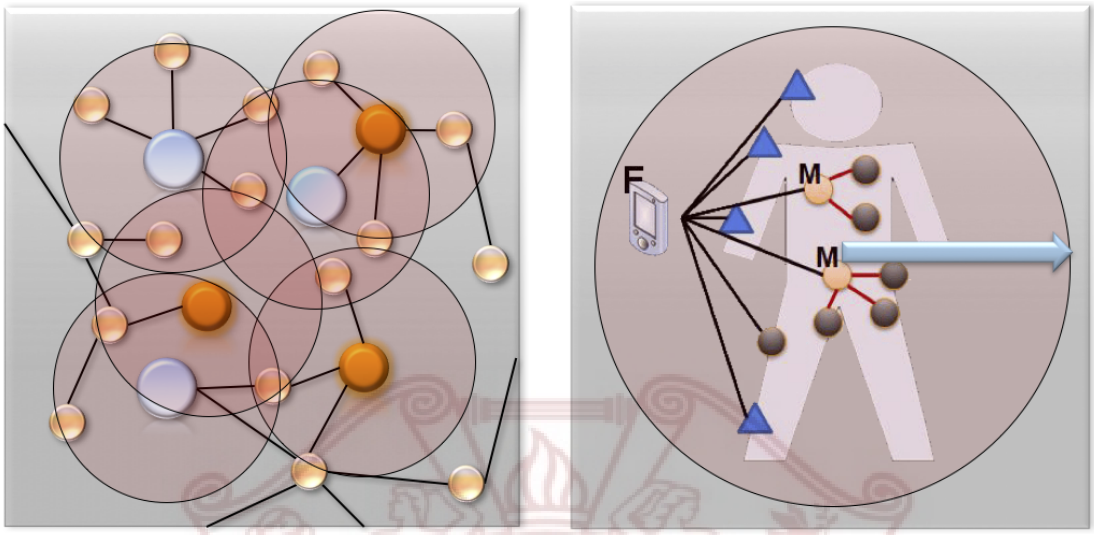
Channel Access for Single-channel WBAN

In this chapter, the thesis explains an aspect of contention complexity under coexistence environment. To solve the contention complexity problem, the thesis illustrates the proposed channel access algorithm which provides a priority-based adaptive channel access algorithm based on classified traffic priorities and four different sub-access phases.

3.1 Overview

As mentioned in chapter 2.2, WBAN MAC protocol exploits two different channel access methods: time referenced allocation and contention-based access. In general, time referenced allocation method is similar to fundamental TDMA which allocates time slots to each member nodes. Because time referenced allocation method assumes that reserved time slots are not contaminated from external interference However, its performance is highly sensitive to interference from other coexisting WBANs. On the contrary, contention-based access method is relatively less vulnerable to interference or collision due to the fact that it provides opportunistic channel access with CSMA/CA or slotted-Aloha. However, when many nodes are densely deployed in narrow region, contention complexity can increase quantities of collisions and amount of power consumption. Therefore, reducing contention complexity among coexisting WBANs is one of the most important issues to satisfy requirements of WBANs.

Meanwhile, the IEEE 802.15.6 classifies traffic into eight different types and gives



(a) Density of sensor nodes in WSNs (b) Density of sensor nodes in WBANs

Figure 3.1: A different aspect according to type of network and density.

priority for each traffic types to provide prioritized channel access for contention-based access mode. However, as explained in chapter 2.1, a WBAN should accommodate up to 256 sensor nodes, and up to 10 coexisting WBAN have to normally work in $6 \times 6 \times 6m^3$ area with fair bandwidth sharing. In this sense, density of sensor nodes in a WBAN is relatively higher than traditional wireless sensor networks as illustrated in Figure 3.1. Therefore, priority-based channel access policy in the IEEE 802.15.6 cannot resolve fundamental problems generated from high contention complexity.

The thesis proposes a priority-based adaptive channel access scheme for contention-based channel access mode of single-channel MAC protocol in WBANs. The proposed scheme categorizes traffic priority into four levels according to traffic types defined in the IEEE 802.15.6 baseline document, and it provides four different sub-periods based on categorized traffic levels to disperse contention complexity.

3.2 Related work

In this section, the thesis introduces the IEEE 802.15.4 which is the fundamental low-power communication technology in WPAN to analyze aspects of coexisting situation on IEEE 802.15.4-based WBAN MAC protocol. In addition, the thesis explains existing IEEE 802.15.4-based coexistence mitigation schemes for WBANs and analyzes communication performance of WBAN MAC protocol under coexistence environment.

In the early stage of WBAN development, the IEEE 802.15.4 protocol, a typical low-power protocol for WPANs was considered for WBAN services. As shown in Figure 3.2, the IEEE 802.15.4 uses a superframe structure in a beacon-enable mode that is similar to beacon mode with superframes in the IEEE 802.15.6 [6]. Its active period is divided into 16 equal-sized slots and consists of a contention-free period and a contention-access period (CAP). In CAP, beacon frame is broadcasted by coordinator to announce the start of the superframe and the parameters of the superframe. After broadcasting beacon frame, each member node accesses channel to transmit its data or control messages with CSMA/CA. If a node is to use guaranteed time slots (GTSs), which is similar to MAP in the IEEE 802.15.6, it can request GTS allocation to the coordinator in CAP. When there are GTS requests, the coordinator sets GTS allocation information in beacon frame to configure CFP in TDMA manner. In inactive period which is the next period of active period, every node in the network goes to sleep mode to save their power.

Figure 3.3 shows an example of coexistence situation between two IEEE 802.15.4-based WBANs. In this scenario, both active periods of two WBANs are overlapped, and thus transmitted data frame from coexisting WBANs will collided due to interference from each other. In general, communication reliability in CAP is barely influenced by interference from neighboring WBANs because it operates based on CSMA/CA acknowledge (ACK) message and retransmission. As described in chapter 2.1 and 2.3, however, sensor nodes in a WBAN are densely deployed in 3–5m range, and WBANs are also densely deployed in a populated area. In addition, the IEEE 802.15.4 was designed without considering

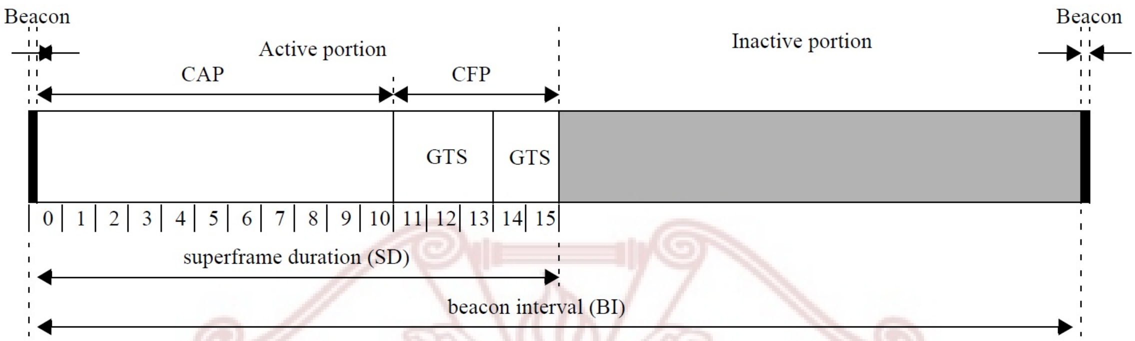


Figure 3.2: Superframe structure of the IEEE 802.15.4.

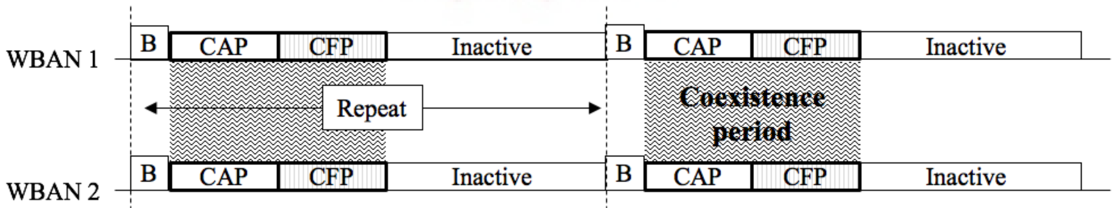


Figure 3.3: Coexistence period of IEEE 802.15.4-based WBAN.

coexistence problems. Therefore, a WBAN may suffer from coexistence problem although it uses contention-based channel access methods such as CSMA/CA.

Meanwhile, there are some studies to analyze coexistence problem in IEEE 802.15.4-based WBANs which analyze performance of IEEE 802.15.4-based WBAN MAC protocol in coexistence environments [7, 8]. Both studies show that communication performances for different channel access modes (CSMA/CA and CFP) with different parameters are dramatically decreased when the number of sensors or traffic load are increased.

To mitigate coexistence problem in IEEE 802.15.4-based WBAN, a number of studies are attempted [9, 10, 11, 12, 13]. J. Mahapatro *et al.* proposed an interference mitigation scheme for TDMA-based WBANs [9]. In this scheme, coexisting WBANs share common TDMA schedules to mitigate interference. This work considers that all WBANs operate in TDMA manner, and this scheme takes an advantage that coexisting WBANs efficiently use time slots through exchanging time schedule. However, data processing overhead of this scheme exists because coordinator manages scheduling information of its neighborhoods as the number of coexisting WBANs.

Meanwhile, M. Deylami proposed a dynamic coexistence management (DCM) mechanism to avoid interferences or collisions when IEEE 802.15.4-based WBANs detect coexistence situation [10]. In this scheme, when coexistence is detected, the coordinator scans the current channel during its beacon interval to get complete information of the current channel. Based on collected information, the coordinator reschedules its beacon transmission time. If coordinator cannot find the minimum length of its own active period between active periods of the coexisting WBANs, it scans a candidate channel for a possible channel switch and hops to the candidate channel. Through beacon rescheduling and channel switching, the proposed mechanism can significantly improve the reliability of the WBANs in the dynamic coexistence situation. However, this mechanism consumes large amount of power because it should monitor channel state for long time whenever WBAN detects coexistence.

Y. Kim *et al.* proposed an adaptive load control algorithm for IEEE 802.15.4-based WBAN/IEEE 802.11 coexistence environment [11]. In this scheme, WBAN coordinator has both IEEE 802.15.4 and IEEE 802.11 radio module, and thus it can cooperate with IEEE 802.11 AP to mitigate coexistence problem on IEEE 802.15.4-based WBAN. To guarantee the delay requirement which depends on interference from the IEEE 802.11, WBAN coordinator monitors the channel to observe the current channel utilization and the received signal strength from each IEEE 802.11-based node, and obtains the maximum allowable IEEE 802.11 channel utilization based on the maximum allowable channel utilization in the IEEE 802.11 network for IEEE 802.15.4-based WBAN node to decide the state of the current channel to 'Busy' or 'Idle'. If the state of the current channel state is 'Busy', WBAN coordinator informs channel utilization information and channel state, and requests controlling traffic load from IEEE 802.11 nodes. However, this algorithm cannot be directly applied to coexisting WBANs because it only focuses on IEEE 802.11 traffic and does not consider other communication technologies which share the same frequency bands with the IEEE 802.15.4. In addition, the performance of this algorithm may decrease in real communication environments because the authors does not consider operational characteristics of medium access mechanisms and they assume that PER (Packet Error Ratio) depends only on signal strength, BER (Bit Error Rate), and SINR (Signal and Interference to Noise Ratio).

To recognize unknown dynamics in coexisting WBANs and handle coexistence problem in WBAN, S. Movassaghi *et al.* proposed a decentralized coexistence prediction algorithm for inter-WBAN communication using the smart channel assignment technique [12]. this scheme captures the unknown dynamics and provides feedback to the coordinator of each WBAN and immediate updates of channel assignment based on the recent changes in the network. There is an attempt to apply game theory for coexistence problem in WBAN [13]. To study WBAN coexistence, the authors formulate a flexible game theoretic framework which allows the study of two coexisting heterogeneous WBANs. In

Table 3.1: Existing coexistence mitigation schemes in WBANs.

Ref. No.	Target coexistence environment	Channel access mode	Coexistence mitigation technique
[9]	Heterogenous WBANs	TDMA	Time-slot scheduling
[10]	Heterogenous WBANs	Probabilisitic access	Beacon shifting
[11]	IEEE 802.11 and WBAN	-	Coorporative traffic load control
[12]	Heterogenous WBANs	TDMA	Coexistence prediction, Time-slot scheduling
[13]	Heterogenous WBANs	TDMA	Game theory, Estimation method for games

addition, they also propose an estimation method to model games involving more than two players because the complexity in utility calculation and simulations grows greatly when the number of WBANs increases in a game. However, these schemes assume that WBAN operates based on TDMA-based channel access without interference from different communication technologies. Therefore, they are not suitable for practical coexisting WBAN environment.

3.3 Proposed priority-based channel access

As mentioned earlier, both traditional channel access modes (contention-free and contention-based) cannot guarantee various and different requirements of WBANs in coexistence environment. To handle a fundamental problem of contention complexity which is a major reason of coexistence problem on single channel environment, the thesis focuses on the way to disperse contention complexity. The detailed algorithm of the proposed scheme are as follows.

As shown in Table 3.2, the proposed channel access algorithm categorizes traffic priority into four different levels which is mapped with traffic priority in the IEEE 802.15.6 standard. Based on these categorized traffic levels and collected delay information during a previous superframe, coordinator obtains average delay, D^l_{avg}, defined as

$$D^l_{avg} = \frac{(\sum D^l_k)}{N^l}, \tag{3.1}$$

where N^l is a count of each categorized traffic level, D^l_k is a delay of each packet on level l.

After obtaining average delay, coordinator compares the pre-defined delay threshold with average delay for each level and divides contention access period into sub-phases as the number of exceeded average delay. The pre-defined delay threshold can be illustrated as follow:

- τ^3 and τ^2: thresholds for CE services ($\leq 250ms$)
- τ^1 and τ^0: thresholds for medical services ($\leq 125ms$)

Table 3.2: Priority mapping and CW values in proposed algorithm.

Traffic level	WBAN services	Data priotiry	Traffic type	Contention window	
				MinCW	MaxCW
3	Non-medical services	0	Backgournd (BK)	16	64
		1	Best effort (BE)	16	32
		2	Excellent effort (EE)	8	32
2	Real-time non-medical services	3	Video (VI)	4	16
		4	Voice (VO)	4	16
1	Fundamental healthcare services	5	Medical data or network control	4	8
0	Highest priority medical services	6	High-priority medical data or network control	2	8
		7	Emergency or medical implant event report	1	4

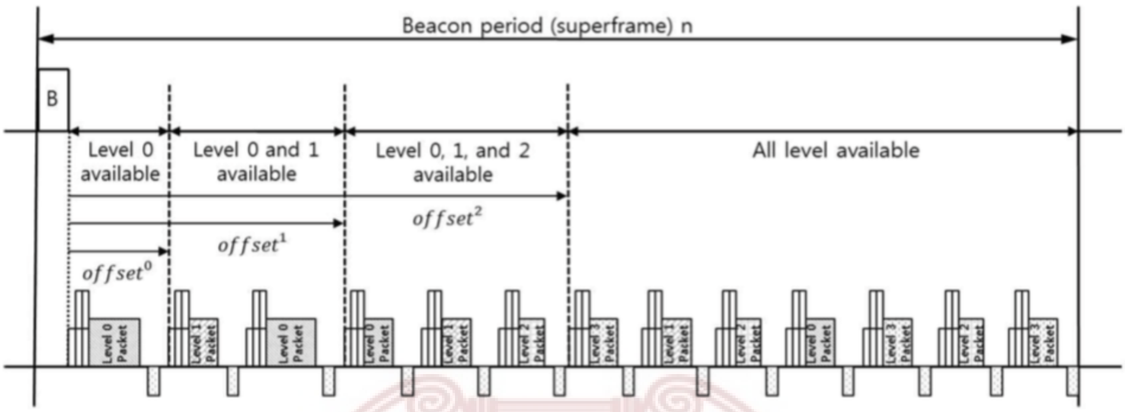


Figure 3.4: An example of proposed algorithm.

The length of each sub-phase is determined by calculating offset for starting point of each sub-phase, $offset^l$, and it can be obtained as

$$offset^l = \sum_{n=0}^{l-1} offset^n + L_{CAP}\left(\frac{N^l}{N_{total}}\right), \tag{3.2}$$

where L_{CAP} is a total length of contention access period in a superframe, N^l is the number of received frames for traffic level l, and N_{total} is the total number of received frames during a superframe. After calculating all $offset^l$, coordinator transmits beacon message with obtained $offset^l$ values to inform the starting time of each sub-phase. Each node which receives beacon message decides starting time to access its communication channel when transmit its data frame according to informed starting time and traffic level of its data frame.

To disperse contention complexity, coordinator sorts all sub-phase ordering traffic level, and each sub-phase allows access of specific traffic level. Figure 3.4 shows an example of the proposed algorithm, and Figure 3.5 and Figure 3.6 illustrate psuedo code of the proposed algorithm for both coordinator and sensor nodes. When all average delay exceed pre-defined threshold, contention access period may divided into four sub-phases.

Algorithm on Coordinator

```
Start of Pre-defined Period

P ← Period of superframe; l ← Level of packet
D[] ← Sum of delay on each level
N[] ← Count of received packet on each level
N_T ← Total count of received packet
T[] ← Delay threshold of each level

loop
  k = 0

  while(time()%P != 0)
    if(ReceiveType() == Packet)
      D[l] += Packet.Delay
      N[l]++
    endif
  end of while

  for(l=0;l<3;l++)
    if(D[l]/N[l] >= T[l])
       if(l!=0)
         offset[l] = offset[l-1] + L_CAP*(N[i]/N_T)
       else
         offset[l] = L_CAP*(N[i]/N_T)
      end of if
    end of if
  end of for

  insert offset[l] into Beacon message
  broadcast Beacon message
end of loop
```

Figure 3.5: Pseudo code of the proposed channel access algorithm for coordinator.

```
Algorithm on Node
Start of Pre-defined Period

Queue[] ← Queue for packet of each level

loop
  if(ReceiveType() == Beacon)
    for(l=0;l<3;l++)
      Queue[l+1].delay(Packet.offset[l])
    end of for
  end of if

  operate contention based channel access
end of loop
```

Figure 3.6: Pseudo code of the proposed channel access algorithm for sensor nodes.

In the first sub-phase, only sensor nodes which have frame categorized traffic level 0 can access to channel. The second sub-phase allows accessing both traffic level 0 and 1, and the third sub-phase permits accessing traffic level 0, 1, and 2. In the last sub-phase, all sensor nodes can access to channel.

3.4 Performance evaluation

In this section, the thesis describes the simulation model to evaluate performance of the proposed channel access algorithm. The performance of the proposed channel access algorithm is validated through extensive simulations comparing with channel access algorithm of the IEEE 802.15.4 and the IEEE 802.15.6.

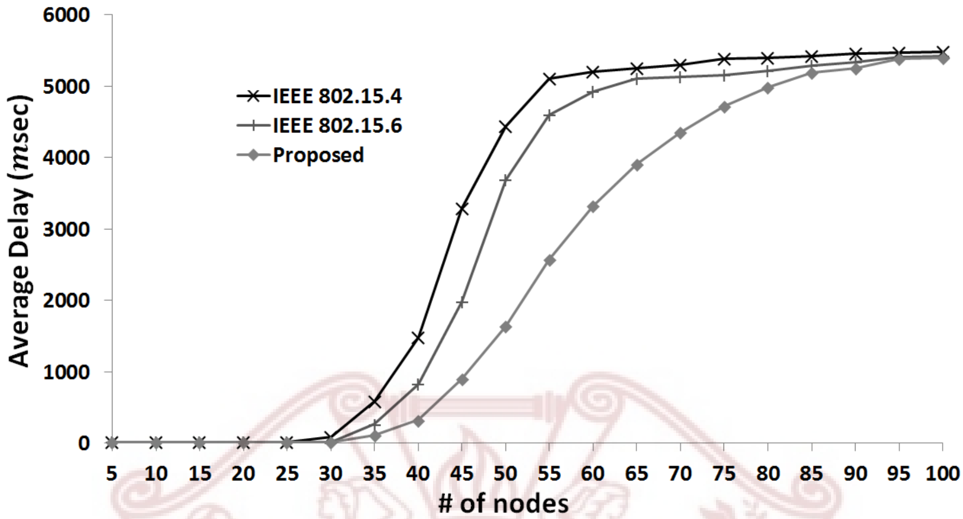


Figure 3.7: Simulation result: Latency.

3.4.1 Simulation model

To achieve fairness of comparison, the thesis assumes that all PHY model is based on the IEEE 802.15.4. All the IEEE 802.15.4, the IEEE 802.15.6, and the proposed channel access algorithm operate based on beacon-enable superframe mode, and the superframe has only contention access period (its length is 245.76 ms).

The thesis defines specific traffic model based on practical WBAN service scenario [14]. All sensor nodes probabilistically generate 250 bytes of data frames which randomly have traffic level 2 and 3 with random interval (10 ms – 500 ms), and 20% of sensor nodes generate 40 bytes of medical data frames which have traffic level 1 with different interval (20 ms, 40 ms, 80 ms, 100 ms, 1000 ms). In addition, all nodes also intermittently generate emergency data frame that 1% of traffic level 1 are mapped to traffic level 0. Based on PHY and traffic model, the thesis performs 5 times of simulation with 1,000,000 seconds of simulation time and obtains the final result by using average of all simulations.

The above simulation model has been implemented in SMPL library [15].

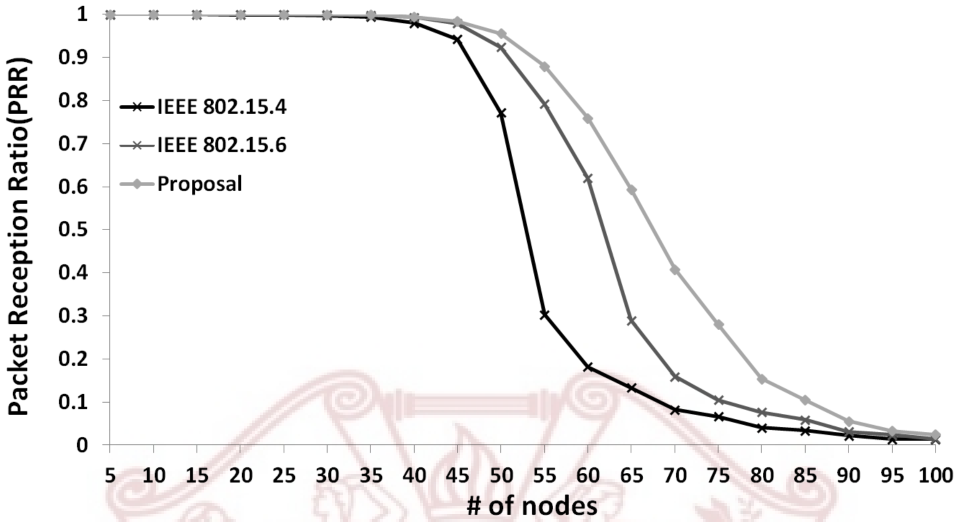


Figure 3.8: Simulation result: Packet Reception Ratio (PRR).

3.4.2 Simulation results

In this simulation, the thesis evaluates the performance of the proposed scheme in terms of latency, packet reception ratio (PRR), collision ratio, and power consumption.

Figure 3.7 represents the average latency. In the overall result, average delay values of all channel access algorithm converge 5,500 *ms* when the number of sensor nodes is more than 85. It means that contention complexity may increase when all sensor nodes try to access to channel. On the contrary, all channel access algorithm can satisfy latency requirements of WBANs when the number of sensor nodes is less than 30. More specifically, average latency values of both the IEEE 802.15.4 and the IEEE 802.15.6 dramatically increase when the number of sensor nodes is more than 35. On the other hand, the proposed channel access algorithm can guarantee low latency when the number of sensor nodes is less than 40 and it can be determined that the proposed channel access algorithm helps to reduce channel complexity.

In terms of PRR, the proposed channel access algorithm also outperforms both the

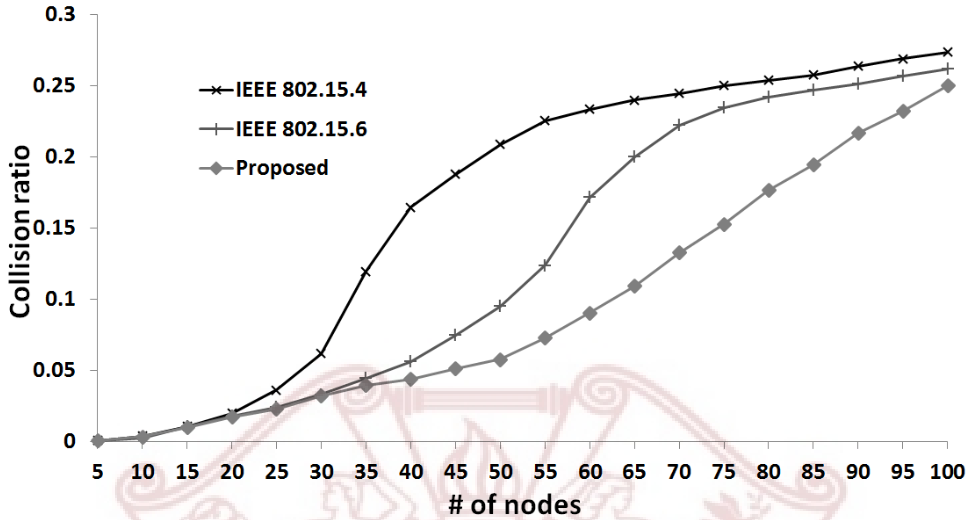


Figure 3.9: Simulation result: Collision ratio.

IEEE 802.15.4 and the IEEE 802.15.6 as shown in Figure 3.8. When the number of sensor nodes is more than 35, PRR of the IEEE 802.15.4 is sharply decreased because it does not have a contention complexity dispersion policy. Similarly, Priority-based channel access algorithm of the IEEE 802.15.6 cannot solve fundamental reason of contention complexity even though the IEEE 802.15.6 classifies traffic into eight different types and provides different the minimum/maximum value of contention window. On the contrary, the proposed channel access algorithm can provide gradually decreased PRR value.

Figure 3.9 shows the ratio of collision. In general, collisions can occur when more than two overlapped nodes transmit data simultaneously. Therefore, collision ratio may increase when a WBAN contains large number of nodes. In detail, The IEEE 802.15.4 shows higher PRR than other channel access algorithms, respectively. Especially, when a network contains 30 nodes, collision ratio sharply increases because slotted-CSMA/CA without prioritized policy does not solve fundamental contention complexity problem. On the other hand, collision ratio of the IEEE 802.15.6 and proposed algorithm is lower than

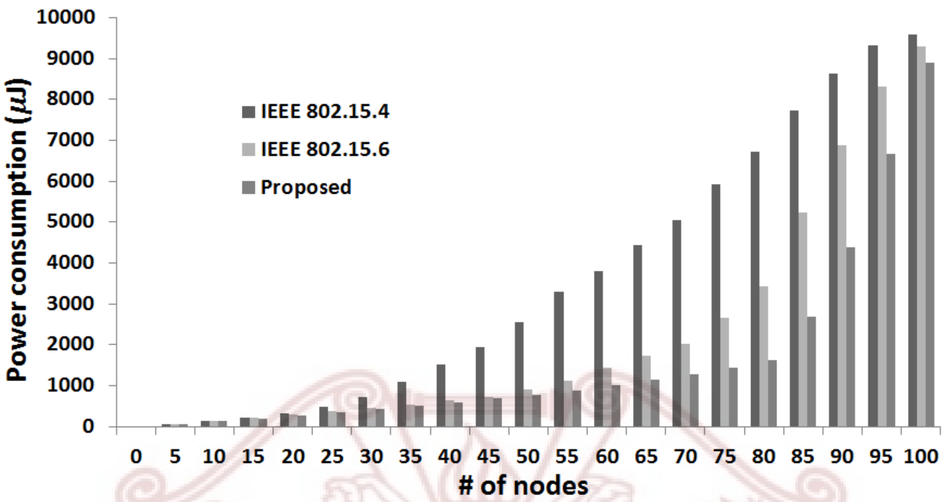


Figure 3.10: Simulation result: Power consumption.

the IEEE 802.15.4 because of their prioritized channel access policies. When a network contains 50 nodes, however, collision ratio of the IEEE 802.15.6 sharply increase. On the contrary, the proposed algorithm provides the lowest ratio of collision because it can disperse contention complexity.

The simulation result of power consumption is shown in Figure 3.10. Actually, power consumption is closely related to the number of collisions because collisions cause a number of retransmissions. Therefore, the result of power consumption is similar to the ratio of collision. In detail, the IEEE 802.15.4 shows high power consumption because all nodes contend with same contention policy. Moreover, high contention complexity causes increase collisions and it makes a large number of retransmission. Therefore, power consumption of the IEEE 802.15.4 MAC protocol increases sharply. Contrastively, the IEEE 802.15.6 and the proposed algorithm are less power-consuming. The reasons of results of the IEEE 802.15.6 and the proposed algorithm are that they provide prioritized channel access with differentiated contention window for each traffic types. Moreover, the proposed algorithm can disperse channel complexity and reduce contention complexity, and it helps to reduce a number of collision and retransmission. As a result, our proposed algorithm shows the lowest power consumption by comparison with the IEEE 802.15.4 and the IEEE 802.15.6 baseline MAC protocol.

3.5 Summary

In coexistence environment of WBANs, it is difficult to satisfy requirements of WBANs due to high contention complexity which causes a number of collisions and interference. More specifically, communication performance of contention-based channel access algorithm may decrease although contention-based channel access provides opportunistic channel access and retransmission policy. To solve fundamental problem of contention complexity, the thesis proposes a priority-based adaptive channel access algorithm for contention-based MAC protocol in WBANs. The proposed algorithm categorizes traffic types into 4-levels and divides contention access period into sub-phases throught predefined threshold. In addition, it allocates access permission for each sub-periods and it can disperse contention complexity and reduce power consumption. To evaluate the performance of the proposed algorithm, extensive simulations are performed by comparing with the IEEE 802.15.4 and the IEEE 802.15.6. The simulation results show that the proposed algorithm can solve fundamental problem of contention complexity in terms of latency, PRR, collision ratio, and power consumption.

Chapter 4

Channel Selection for Multi-channel WBAN

In this chapter, the thesis represents a channel selection method to mitigate coexistence problem in multi-channel WBANs. The proposed method includes an adaptive channel estimation and selection algorithm, and it guarantees reliable communication in multi-channel coexisting WBANs.

4.1 Overview

In general, sensor nodes of WBANs have been adopted the IEEE 802.15.6 standard to provide both medical and CE services simultaneously. In various WBANs applications, sensor nodes are deployed with high density, and it results in physical bandwidth limitations and heavy collisions on a single channel. In addition, WBANs share their communication bands with heterogeneous communication technologies, and thus density of communication devices may increase. This phenomenon can be defined as the *coexistence problem* which can cause degradation of communication performance [16, 17]. Especially, communication performance of a WBAN is significantly degraded when it coexists with IEEE 802.11-based devices [18, 19].

In order to solve the coexistence problem in WBANs, the IEEE 802.15.6 classifies coexistence environment into three different conditions (dynamic, semi-dynamic, and static), and also provides three different coexistence mitigation schemes (beacon shifting, channel hopping, and active superframe interleaving) to handle different coexistence conditions. However, the IEEE 802.15.6 does not define detailed algorithms for these schemes. Moreover, MAC protocol in the IEEE 802.15.6 uses single channel usage which results in physical bandwidth limitations and heavy collisions.

There are some works in the literature with the purpose of channel selection for multi-channel environments in WSNs [20, 21, 22, 23, 24, 25, 26, 27]. However, they assume that each node randomly selects communication channel, and they do not consider frequently changed channel conditions.

Meanwhile, there have been a number of attempts to solve the coexistence problem in WBANs [28, 29]. These studies mostly consider multi-channel usage by maintaining a list of available channels and selecting one channel from the list to avoid congested channels. However, these methods are based on simple channel selection schemes that do not consider the conditions of available channels. In addition, these studies cannot be directly applied to WBAN environments because they do not consider aforementioned characteristics of coexistence environment of WBANs and its requirements.

In this chapter, the thesis proposes a channel selection method for multi-channel usage. The proposed method maintains a history table and predicts the conditions of available channels based on two-state Markov chain with an exponentially controlled channel history, which can control the sensitivity of prediction.

4.2 Related work

This section discusses impacts of coexistence problem on ISM band which are used for the IEEE 802.11, the IEEE 802.15.4, and the IEEE 802.15.6. In addition, this section discusses the related work on solving the coexistence problems in WBAN that utilizes multi-channels.

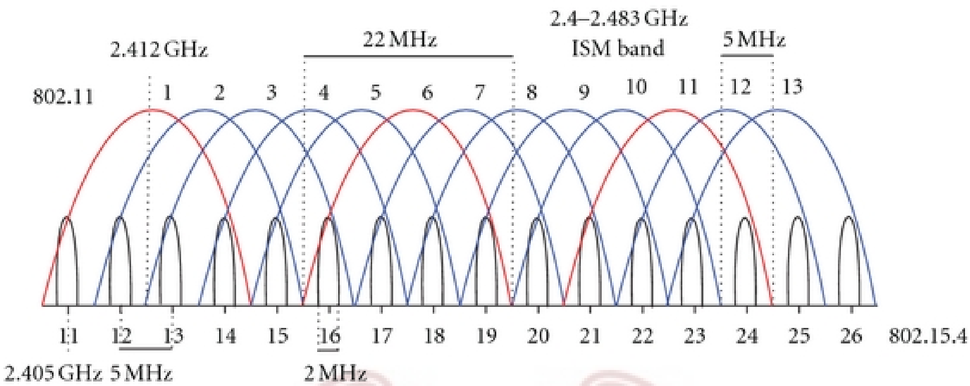


Figure 4.1: Channel composition of the IEEE 802.11 and the IEEE 802.15.4.

4.2.1 Interference between IEEE 802.11 and IEEE 802.15.4

In general, both IEEE 802.11 and IEEE 802.15.4 share 2.4GHz ISM band. As shown in Figure 4.1, frequency usage of IEEE 802.11 consists of 13 channels which are totally overlapped with 16 non-overlapped channels of IEEE 802.15.4. In addition, the transmission power of IEEE 802.11 is larger than IEEE 802.15.4. For instance, commercial available Atheros 802.11n AR5008 cards allow power setting between a minimum and maximum of 1 dBm and 15 dBm in step of 0.5 dBm [33]. However, CC2420 which is typically used for IEEE 802.15.4-based nodes provide transmission power from -25 dBm to 0 dBm [6, 34]. In this term, IEEE 802.15.4 network potentially experience interference from IEEE 802.11 traffic given that IEEE 802.11 transmissions usually occur at much higher power level although both protocols can transmit data through the overlapped channel.

Impacts of IEEE 802.11 interference on IEEE 802.15.4 networks was studied in [16, 17]. Wei *et al.* introduce two conditions that an IEEE 802.15.4 packet can be successfully received under IEEE 802.11b/g interference: power and timing [16]. They analyze co-existence situation between the IEEE 802.15.4 and the IEEE 802.11, and they conclude that interference from IEEE 802.11 significantly aspects to communication performance of the IEEE 802.15.4. Jun *et al.* measure the IEEE 802.15.4 and the IEEE 802.11 interference through empirical study [17]. From their measurement, they can classify the role of the IEEE 802.11 nodes as hidden, exposed, and blind terminal depending on how it interferes senders and receivers of the IEEE 802.15.4. Based on their experiment result, they also conclude that the performance degradation of IEEE 802.15.4 in the presence of blind IEEE 802.11 terminals is mainly caused by the heterogeneous PHY layer and power asymmetry. Similarly, Francisco *et al.* and Cho *et al.* try to identify aspects of coexistence problem between WLANs and WBANs [18, 19]. Both two works evaluate communication performance of WBANs which coexist with WLAN through performing extensive simulations and experiments, and they also conclude that communication performance of WBAN is significantly degraded due to interference from WLAN.

In summary, interference from IEEE 802.11 can cause performance degradation of IEEE 802.15.4 due to the fact that both of them have different transmission range, transmission power and sensitivity of channel assessment.

4.2.2 Existing multi-channel MAC protocols

One major solution for the coexistence problem is multi-channel MAC protocols, which allows simultaneous data transmission in a coexistence environment. There are some studies for multi-channel MAC protocols in WSNs, and they can be categorized into two different parts. The first part of multi-channel MAC protocols exploits multiple radio [20, 21, 22]. A sensor node within multiple radio can simultaneously communicate with other sensor nodes or the sink node due to the fact that it can exploits multiple channels. Therefore, multi-radio multi-channel MAC protocols can achieve extremely high communication performance, but they may consume more energy than other multi-channel MAC protocols which exploits only single radio. Based on above mentioned shortcoming, almost of protocols exploiting multiple channels generally use use single radio.

C. Li *et al.* proposed COM-MAC(Cluster On-demand Multi-channel MAC Protocol) which is a multi-channel MAC protocol for cluster-based WSNs [20]. This protocol aims to achieve low power consumption and high throughput. In this protocol, sensor nodes which organize target WSN can be categorized into three different layer. A sink node functions as the root and a relatively small number of aggregators has middle layer of the network topology with multiple radio and infinite power. The leaf layer of the network topology consists of a set of sensor nodes which has only single radio. A role of Aggregators is similar to cluster head in cluster-based WSNs which manages communication resource for their member nodes in cluster and collects data from sensor nodes. Sensor nodes act as cluster member which extracts sensing data and communicates with the aggregator. If aggregators complete collecting work, they transmit their collected data to the sink node. Due to exploiting powerful aggregators, COM-MAC can provide high throughput. However, they assume that aggregators has infinite energy and exploits multiple radio, and it is not practical in WSN.

K. K. Chintalapudi *et al.* also proposed multi-radio multi-channel MAC protocol which name is T-MALOHA(Transmission pipelined Multi-channel ALOHA) [21]. To achieve low data latency and high throughput, this protocol attempts to apply convergence between of slotted ALOHA and FDMA. The sink node has multiple radio and collects sensing data from its member nodes which has only single-radio. Due to applying converged channel access, they divides its communication time into a small size of unit time which also divided into into fixed number of smaller time slots. In every unit time, sensor nodes which has collected data probabilistically access the channel based on the role of slotted ALOHA. To guarantee reliable communication, the sink node transmits ACK message att the end of the frame (ack-slot). If many nodes use the same channel and time slot, pipelining scheme is used. However, it also consumes huge power due to exploiting multiple radio which does not used for commercial sensor nodes.

Y. Wu *et al.* proposed tree-based multi-channel MAC protocol which name is

TMCP(Tree-based Multi-Channel Protocol) [22]. They assume that sink node has multi-radio and the other nodes has only single radio. At the start of this protocol, the sink node constructs tree topology. The branches are extended from the sink node, and each branch is named as 'subtree' and has unique channel. TMCP has three different modules such as CD(Channel Detection), CA(Channel Assignment) and DC(Data Communication). The CD module discovers available channels which is not used by any sensor nodes. The CA module categorizes network topology into k subtrees and assigns unique channel which is one of available channels to each subtree. The DC module is operated after channel assignment by the CA module, and it manages data collection through each subtree and their assigned channels. To achieve low latency and high throughput, they divided interference into three different types. The first is interference among different subtrees and the second inter-tree interference The last type is intra-tree interference which indicates interference within a subtree. Due to the CA module which assigns unique channel to each subtree can minimize the inter-tree interference. However, they does not solve intra-tree interference which can cause communication performance degradation. In addition, this protocol cannot provide energy balance of sensor nodes that means sensor nodes which is closely located to sink node consume amount of energy than other nodes.

In summary, these protocols improve communication performance such as network throughput, energy efficiency and reliability by exploiting multiple radios. However they are not feasible in current commercial sensor nodes which have only one transceiver.

The second part exploits single radio to perform multi-channel MAC protocols [23, 24, 25, 26, 27]. In these protocols, sensor nodes has only single-radio, that means they can communicate in half-duplex manner while they exploit multiple channels because they can use only one channel by using a single antenna. In addition, the single-radio multi-channel MAC protocols which can implemented in commercial sensor module are insufficient. Most of multi-channel MAC protocols in traditional WSNs maintain an available channel list and select a channel to use in a random manner. Therefore, these

MAC protocols cannot draw potential advantages of multi-channel MAC protocol which can improve communication performance, and thus they may result in high data latency and channel inefficiency.

To guarantee reliable communication with low latency,, S. C. Ergen *et al.* propose a single-radio multi-channel MAC protocol which name is PEDAMACS(Power Efficient and Delay Aware Medium Access Protocol for Sensor Networks) [23]. The authors assume that the sink node has powerful communication and computation resources such as higher transmission power without regarding power consumption and amount of storage, and the sensor nodes has limited resources. All sensor nodes try to construct network topology by recognizing their parent nodes, neighbors and external interferers by SINR(Signal to Interference plus Noise Ratio). After network topology construction is complete, the sink node schedules communication time for all sensor nodes and informs this scheduling information by broadcasting *Scheduling message* which may be directly transmitted due to assumption of the sink node. Based on these procedure, this protocol can provides reducing intervention and reliable data transmission. However, this protocol cannot be applied to practical environment because the authors do not external interference. In addition, they just assign communication channel which may not the best channel among available channels.

There is an attempt to converge TDMA and FDMA into single-radio multi-channel MAC protocol, HyMAC(Hybrid MAC) [24]. In this protocol, network is constructed with tree topology. To apply concepts of both TDMA and FDMA, the protocol divides whole communication time into two different access periods (contention-based and contention-free access period), and both of periods are also divided into fixed length time slot which has a number of mini-slot. At the start of whole communication period, the sink node schedules communication time and channel and broadcasts scheduling information to member nodes. In the contention period, the sink node receives joining request messages from new sensor nodes or time-slot request message from member nodes which want to use contention-free period. In the contention-free period, each sensor node transmits its data based on scheduling information which is received from the sink node. This protocol can guarantee reliable communication with low latency, but it may suffer from external interference because they does not consider external interference when the sink schedule the communication channel for the member nodes. In addition, a number of exchanging control message may cause huge power consumption.

To provide energy efficiency by using converge case and channel hopping, J. Borms *et al.* proposed MuChMAC(Multi-Channel MAC) which is a single-radio multi-channel MAC protocol for traditional WSNs [25]. The authors first provide *'convergecast'* mechanism which provides contention-free channel access. In this protocol, sensor nodes generate time drift when they are used for a long time. When the time drift is intensified, the sink node broadcast *'synchronization message'* by on-demand manner. In addition, the sink node changes its communication channel when the current channel is congest. By synchronizing time drift between the sink and sensor nodes with on-demand manner, this protocol can provide low power consumption. However, there are some communication overhead such as frequent channel hopping and duplicated data transmission, and these can cause degradation of communication performance.

Zhang and Li proposed MMSN, which is a well-known multi-channel MAC protocol for WSNs [26]. This protocol selects the least chosen channel from an available channel list, and it also randomly selects a channel when multiple least chosen channels exist.

Abdeddaim et al. proposed MCCT (Multi-Channel Cluster Tree), which considers similar network structure to WBAN [27]. This scheme also randomly selects a channel in order to reduce the complexity of channel selection. However, their channel scanning is performed in sequential manner which causes huge overheads. In practical point of view, actually, duration of channel scanning should be at least 8 symbol periods (128 μs) to measure RSSI value [6, 34]. As a result, total scanning time can be calculated as the number of channel times a channel scanning time and it may result huge performance degradation. In addition, channel condition is dynamically changed due to high-density deployment and network-level mobility of WBANs.

Meanwhile, there have been few attempts to improve the performance of WBANs by using multi-channel MAC protocol [28, 29]. Lee et al. proposed an efficient multi-channel management protocol for WBANs to provide communications between in-body devices and out-body devices [28]. This protocol reserves the channel using a one-to-one mapping between the beacon slot and the data channel. In addition, it also performs channel aggregation that allocates indiscrete channels to an in-body device to be used as a single wide channel. However, they only focus on improving performance of a single WBAN, and do not consider coexistence environment in WBANs. In addition, their method does not provide a way to select a channel to communicate, which is an important issue to maintain stable performance in coexisting WBAN environments.

Ivanov et al. proposed a cooperative wireless sensor environments to support WBANs [29]. To improve communication performance, this scheme builds a virtual topology and allocates channel through redundant channel blocking. This scheme also extends the cooperation at the MAC layer to a cross-layered gradient based routing solution, which is determined in order to ensure data delivery from WBANs to a distant gateway. However, they also do not consider various factors of the coexistence problem such as a channel condition. Thus, properly selecting the best channel is necessary to not only improve the performance multi-channel MAC protocols but also to solve the coexistence problem.

Table 4.1 illustrates summary of existing multi-channel MAC protocols and their channel selection schemes.

4.3 Proposed channel selection

The goals of the proposed channel selection method is to mitigate the coexistence problem and improve performance by using calculating criterion of channel selection. The detail

Table 4.1: Existing multi-channel MAC protocols and their channel selection schemes.

Reference No.	Target network	The number of radio	Goal				Channel management	
			Latency	Power	Reliability	Coexistence	Channel selection	Target
[20]	Cluster-based WSN	Multiple	○	×	○	×	-	Cluster
[21]	Large scale WSN	Multiple	○	×	○	×	-	Node
[22]	Tree-based WSN	Multiple	○	×	○	×	-	Sub-tree
[23]	Tree-based WSN	Single	×	×	○	×	None	Branch link
[24]	Tree-based WSN	Single	○	×	○	×	None	Branch link
[25]	Large scale WSN	Single	×	○	×	×	Random	Node
[26]	Large scale WSN	Single	○	×	×	×	Random	Node
[27]	Small scale WSN	Single	○	○	×	○	Random	Sub-tree
[28]	Single WBAN	Single	○	×	○	×	None	Node
[29]	Multiple WBANs	Single	○	×	○	×	None	Single topology

Table 4.2: History table (HT)

Channel ID	TI	History of Channel States				
		$N-(HW_{max}-1)$	$N-(HW_{max}-2)$	...	N-1	N
1	3	I	B	...	I	I
2	4	B	B	...	B	I
3	2	I	B	...	I	B
4	6	I	I	...	B	B
...	...	...	...	...	...	...

of the proposed channel selection algorithm is described below.

First, a coordinator maintains a *History table*, which stores the history of channel states for all the channels as shown in Table 4.2. The history table contains Channel ID, Transition Index (TI), and *History of Channel States* for all channels. *TI*, a criterion for channel stability, is used to control the size of the *History Window (HW)* for adaptively estimating channel condition. *History of Channel States*, HW_{max}, is the maximum length of HW representing the list of channel states for the latest HW_{max} times.

To adaptively control the sensitivity of channel prediction, the coordinator adjusts TI based on the latest channel state transitions within the range 1 to TI_{max}, where TI_{max} represents the maximum value of TI. For example, if the next channel state of channel 3 in Table 4.2 transitions to a different state (e.g., Busy → Idle) indicating that the next channel state of channel 3 will be probably changed to different state, the proposed scheme regards channel 3 is unstable channel. In this case, recent channel transitions of channel 3 should be considered to provide higher prediction sensitivity for channel 3. Therefore, TI is set to 2 for decreasing HW of channel 3 in half. On the other hand, if the next channel state of channel 3 stays at Busy indicating that the next channel state of channel 3 will be probably stay in the same state, the proposed scheme regards channel 3 is stable channel. In this case, a greater number of channel transitions should be considered to improve prediction accuracy. Therefore, TI is set to 4 to double HW of channel 3.

After obtaining TI, the History Window for the i^{th} channel, HW^i, can be calculated as

$$HW^i = 2^{TI^i - 1} \times HW_{min}, \tag{4.1}$$

where TI^i represents the transition index of the i^{th} channel, and HW_{min} denotes the minimum value of HW. In this stage, the coordinator can give different channel sensitive rate to each channel. In other words, the length of target history length is controlled by last channel state change rate which reflects durability of channel.

Based on HW obtained from History table, the coordinator applies a two-state Markov model to adaptively predict channel conditions of the all channels as shown in Figure 4.2. The two-state Markov model consists of *Idle* (I) state, *Busy* (B) state, and transition probabilities p and q. The state I and state B denote the channel conditions, and p is the transition probability from state I to state B. In contrast, q represents the transition probability from State B to State I.

Based on Equation 4.3, the coordinator counts all the possible state transitions for all the channels within the range of $(N - (HW^i - 1))^{th}$ channel condition to N^{th} channel condition. The counts of all possible state transitions for the i^{th} channel are defined as

$$\begin{aligned} \alpha^i &= \# \text{ of transitions from state } I^i \text{ to state } I^i, \\ \beta^i &= \# \text{ of transitions from state } B^i \text{ to state } I^i, \\ \gamma^i &= \# \text{ of transitions from state } I^i \text{ to state } B^i, \\ \delta^i &= \# \text{ of transitions from state } B^i \text{ to state } B^i. \end{aligned} \tag{4.2}$$

From Equation (4.2), transition probabilities of the i^{th} channel, p^i and q^i, can be

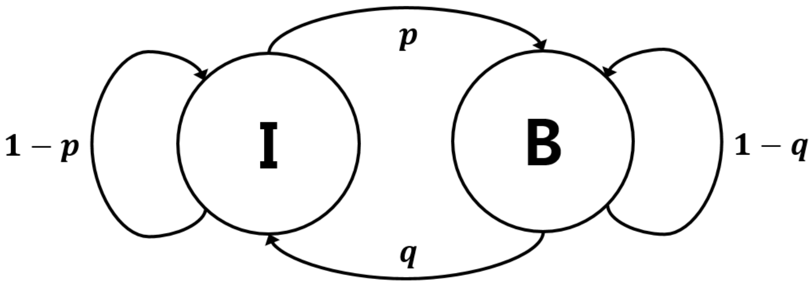


Figure 4.2: Two-state Markov model in the proposed scheme.

expressed as

$$\begin{aligned} p^i &= P[X_N^i = Busy \mid X_{N-1}^i = Idle] = \frac{\gamma^i}{\alpha^i + \gamma^i}, \\ q^i &= P[X_N^i = Idle \mid X_{N-1}^i = Busy] = \frac{\beta^i}{\beta^i + \delta^i}. \end{aligned} \tag{4.3}$$

According to Geometric stochastic process, the stationary probability of State I for the i^{th} channel, ρ^i, can be obtained as

$$\rho^i = P[X_N^i = Idle] = \frac{q^i}{p^i + q^i}. \tag{4.4}$$

Based on Equation (4.4), the coordinator can select the best channel, which has the highest ρ^i. Since HW^i exponentially increases or decreases based on recent channel transitions, the proposed scheme simultaneously considers both stability of channel state and estimated channel condition. Figure 4.3 illustrates the pseudo code of the proposed channel selection algorithm.

4.4 Performance evaluation

4.4.1 Simulation model

Performance evaluation of the proposed channel selection method was performed using a simulator written in C++. The simulation models has a WBAN consisting of a coordi-

Channel Selection Algorithm

```
/*Notation*/
SUP_DUR ← Superframe duration
N       ← The number of channels
HW      ← History Window
HW_max  ← The maximum value of History Window
HW_min  ← The minimum value of History Window
BestCH  ← The best channel

struct _ChannelInfo {
   CHID           // Channel ID
   TI             // Transition Index
   HCH[HW_max]    // History of channel states
   St_Prob        // Stationay probability of State IDLE
} CHInfo[N]  ← History table

/*Algorithm*/
CollectCHInfo() {
   for(i=0;i<N;i++) {
      CHInfo[i] = scanCH(i);
      CHInfo[i].HCH[HW_max-1] != CHInfo[i].HCH[HW_max-2] ?
         CHInfo[i].TI = (CHInfo[i].TI-1)%TI_max :
         CHInfo[i].TI = (CHInfo[i].TI+1)%TI_max;
   }
}

CHSelection() {
   while(time()% == SUP_DUR) {
      CollectCHInfo();
      for(i=0;i<N;i++) {
         if(CHInfo[i].HCH[HW_max-1] == IDLE) {
            HW = 2^(CHInfo[i].TI-1)*HW_min;
            BestCH = CHEstimation(HW);
         }
      }
      hopCH(BestCH);
   }
}
```

Figure 4.3: Pseudo code of the proposed channel selection algorithm.

Table 4.3: Simulation parameters

Parameters	Values
Simulation time	10000 *sec*
Channel Scanning Interval	5 *sec*
Channel Selection Interval	100 *ms*
Transmission period	10 *ms*
Packet size	20 *bytes*
per	0.01
p	$\mu(0.7, 0.9)$ for Good,$\mu(0.1, 0.3)$ for Bad
q	$\mu(0.2, 0.4)$ for Good,$\mu(0.6, 0.8)$ for Bad
Initial TI	1
TI_{max}	5
HW_{min}	5
HW_{max}	80

nator and 20 in-body sensor nodes that periodically transmit data through the selected channel of the MICS band, and the coordinator performs the proposed method at every 100 ms. The energy consumption model of LEACH [52] is used to simulate energy consumption of the sensor nodes.

The proposed method was compared against both single channel scheme in the IEEE 802.15.6 [3] and random channel selection scheme [26, 27], the traditional channel selection scheme for multi-channel MAC protocol, in terms of Packet Reception Rate (PRR) and throughput.

To model wireless channel, we exploit two-state Markov model which is generally used to model wireless channel [30, 31, 32]. The two-state Markov model shown in Figure 4.2 is used to model the wireless channel condition, and this model is performed in every *Channel Interval* period. In this model, the stationary probability of each state, $P[X = Good]$

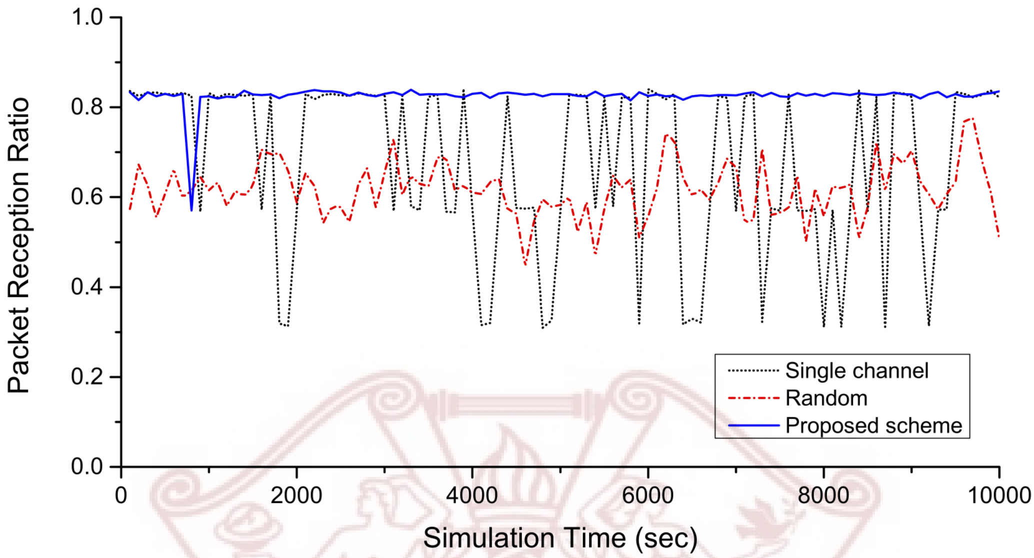


Figure 4.4: Simulation results: Packet Reception Radio (PRR).

and $P[X = Bad]$, is defined as

$$P[X = Good] = \frac{q}{p+q}, \quad P[X = Bad] = \frac{p}{p+q}. \tag{4.5}$$

From Equation (4.5), the probability of successful data transmission, P_s, can be also calculated as

$$P_s = (1 - per)P[X = Good], \tag{4.6}$$

where *per* denotes Packet Error Rate (PER), which is required to be at most 1% for IEEE 802.15.6 [3].

The parameter used for the simulation study are shown in Table 4.3.

4.4.2 Simulation results

Figure 4.4 shows PRRs for the single channel scheme for IEEE 802.15.6, random channel selection, and the proposed method. Due to absence of dynamically changing chan-

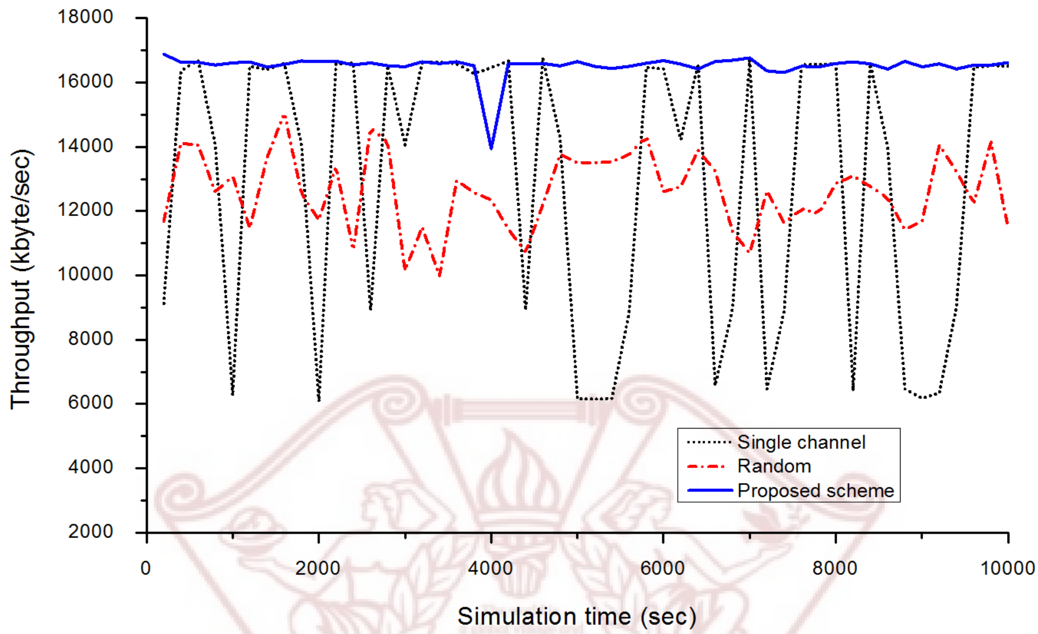


Figure 4.5: Simulation results: Throughput.

nel state, both the single channel scheme and the random channel selection scheme are unstable and result in low PRR. The single channel scheme in particular shows more drastic changes in PRR because it does not provide channel switching function. On the other hand, PRR for the random channel selection is more stable than the single channel scheme because the random channel selection probably mitigate congested channel by channel switching. However, the random channel selection exhibits lower PRR than the proposed scheme because it switches channel without considering expected channel states. In contrast, the proposed channel selection method shows more stable PRR than the other two schemes, which indicates that the proposed channel estimation model helps in selecting the best channel.

Figure 4.5 illustrates throughput for all schemes in the simulation. Similarly to the result of PRRs, the result of the single channel scheme present greater deviation of throughput. This means that channel quality can be frequently changed in coexistence environ-

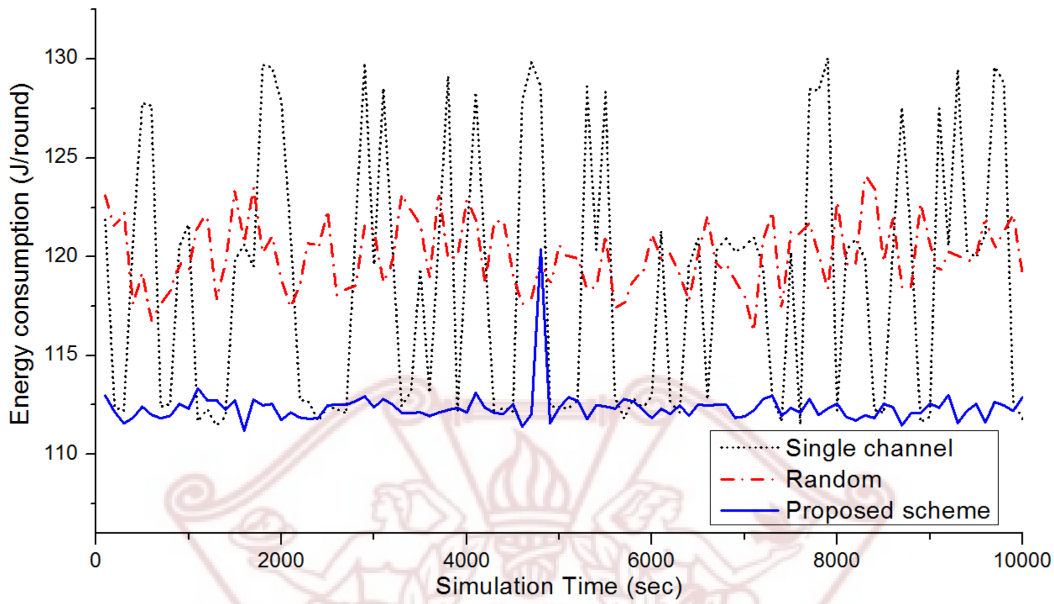


Figure 4.6: Simulation results: Power consumption.

ment and it does not change its communication channel, and thus the single channel scheme cannot guarantee the throughput requirement of WBAN. Meanwhile, the random channel selection can provide higher and stable throughput than the single channel scheme because it does not consider channel condition when the network changes its communication channel. In contrast, the proposed scheme can provide the highest throughput due to its adaptive channel estimation algorithm which helps to select the best channel.

In general, nodes try to reliably transmit their packets to receiver through the ARQ (Automatic Repeat reQuest) mechanism which attempts to retransmit a failed packet up to three times. Therefore, the number of retransmission may increase when channel condition is not good or unstable. This point of view, we also product result of power consumption per round as shown in Figure 4.6. In Figure 4.6, the single channel scheme shows that the power consumption is rapidly changed and the average power consumption of the single channel scheme is larger than the proposed scheme, because it does not change its communication channel which may suffer from external interference. The random channel selection scheme shows more stable power consumption than the single channel due to channel switching. However, it shows larger power consumption than the proposed scheme because it does not consider any factors when select channel. On the contrary, the proposed shows lowest power consumption because it selects the best channel which is stably good in every round. It means that the number of retransmission in the proposed scheme is less than others due to channel condition.

4.5 Summary

In this chapter, the thesis proposed a channel access method for coexistence mitigation in WBANs. The proposed method maintains history table and predicts states of available channels based on 2-state Markov chain with an exponentially controlled channel history which can control sensitivity of prediction. Since estimation of channel conditions based on dynamically controlled channel history, the proposed method can help to select the best channel among available channels. Our simulation study shows that the proposed method provides significant higher PRR compared to existing studies that does not consider channel conditions.

Chapter 5

Relay Node Selection for Two-hop Communication in WBAN

This chapter presents an Analytical Hierarchy Process (AHP)-based flexible relay node selection scheme that considers a multitude of decision factors, such as average SNR, remaining energy ratio, and traffic load. Moreover, the proposed scheme can adaptively satisfy the requirements of WBAN in various scenarios.

5.1 Overview

The two major requirements of WBAN are as follows: First, a WBAN has to provide reliable communication because medical services are directly related to the safety of human lives. However, network conditions frequently change due to the variability of WBAN environments. For example, sensor nodes in a WBAN exhibit mobility due to postural body movement, which can cause link loss between the coordinator and sensor nodes. Frequent link losses decrease network stability and lead to network partitioning. In addition, in-body sensor nodes communicate through the human body medium, which has different characteristics than the air medium, such as higher signal attenuation and link loss.

Second, sensor nodes in a WBAN need to operate using battery power in order to provide mobility. Due to this requirement, low power consumption for WBAN devices is one of the most important research issues. In particular, it is difficult to replace or recharge batteries of in-body sensors. To satisfy this requirement, technical requirement document (TRD) defines low duty cycle (i.e., sampling rate) to reduce the average transmission power consumption [5].

The aforementioned variabilities in WBANs increase packet drop rate, retransmission rate, and power consumption. In addition, the communication power of each device, which increases as a function of distance between nodes, is typically higher than the processing power. Therefore, using relay nodes in WBANs is an efficient way to reduce power consumption.

To tackle these issues, the IEEE 802.15 TG6 defines a two-hop star topology extension to help establish a new link [3]. This is illustrated in Figure 5.1, where a node (e.g., Node 4, 5, or 6) and the coordinator can use a two-hop communication to exchange frames through another node referred as a *relay node* (i.e., Node 1 or 2). In order to establish a relayed communication, either the coordinator or the node initiates the two-hop communication by sending a control message. The relay node also directly sends its own frames to the coordinator just as in a one-hop star network. However, the two-hop star topology extension of IEEE 802.15.6 does not specify how a relay node should be selected. The standard also does not consider a variety of requirements for different service applications and network conditions that change frequently.

Recently, numerous studies have focused on how to select relay nodes in ad-hoc networks, cooperative communications, cognitive radios, and wireless sensor networks (WSNs) [35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. Most of these studies, however, assume that nodes are deployed in a large-scale geographical region, and they support more than two-hop transmissions. Furthermore, these studies assume each node has abundant resources, such as GPS, battery, and computation power, which allow for more complex schemes to be applied to solve the aforementioned problems. In contrast, a WBAN does not support more than two-hop transmission because nodes are deployed within a short range of at most 3 m with small battery capacity, and the communication range of each

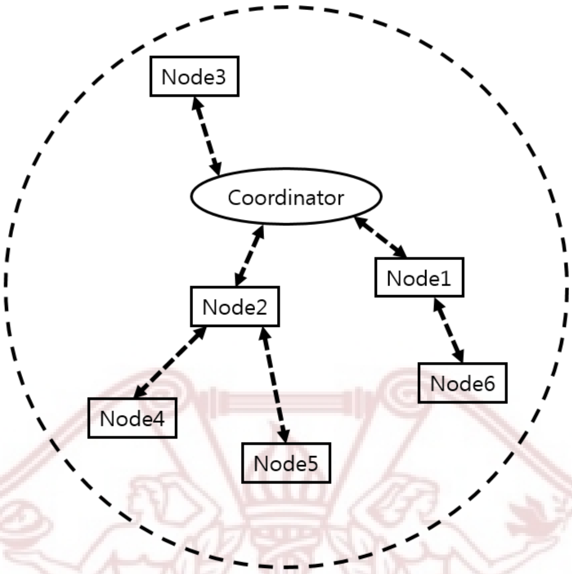


Figure 5.1: Two-hop star topology defined in the IEEE 802.15.6 standard.

node can cover all the other nodes in the network.

There are some existing work with the purpose of increasing network lifetime of WBANs using relay nodes [45, 46, 47]. However, these studies assume fixed network topologies, and thus, dynamic network changes caused by postural body movements are not taken into account. In addition, since they assume multi-hop transmission (usually more than two hops), these methods are not compliant with the two-hop extension of the IEEE 802.15.6 standard. The authors in [48] modified the two-hop star topology extension of IEEE 802.15.6 to reduce the number of exchanged messages and to prolong network lifetime. This scheme assumes that the coordinator is capable of transmitting data directly to all of the nodes in the network without involving intermediate relay nodes. However, the wireless link between the coordinator and sensor nodes can be disconnected due to the characteristics of human body medium and postural body movements regardless of the transmission power of the coordinator or the sensitivity of receiver nodes. Moreover, their work does not try to find the optimal relay node.

In order to overcome the shortcomings of the existing methods, the thesis proposes an *Analytical Hierarchy Process (AHP) based Flexible Relay Node Selection Scheme* for WBANs. The specific contributions of this paper are as follows:

- To overcome the problem of frequently and dynamically changing network conditions, the proposed method applies AHP to provide a *flexible* decision making process for relay node selection by considering various factors, such as high reliability and low power consumption.
- Unlike existing relay node selection schemes, the proposed scheme is compatible with the two-hop star topology extension of IEEE 802.15.6.
- The performance of the proposed scheme is compared with the IEEE 802.15.6 standard in terms of packet reception ratio (PRR), power consumption, delay, and network life time. Our simulation results show that the proposed scheme outperforms IEEE 802.15.6 and can be flexibly applied to various applications of WBAN with different requirements and scenarios.

5.2 Related work

A number of studies exist on relay node selection and routing schemes for ad-hoc networks [35, 36, 37]. Yaozhou *et al.* proposed a flexible relay node selection scheme and a routing protocol based on Analytical Hierarchy Process-Gray Relational Analysis (AHP-GRA), which considers the number of message copies over the network, the expected path length, and the priority of messages [35]. They assumed that the network requires only communication reliability in a mobile environment without consideration of latency and energy consumption, and this assumption is similar to ones used in the Delay Tolerant Network (DTN) scenario. Adaptive rate-and-relay selection with Greedy Perimeter

Stateless Routing (GPSR) was considered in [36], where a throughput product metric function is determined based on node location and SNR to improve network throughput. To provide adaptability to the IEEE 802.11 standard, the authors developed a scheme based on Distributed Coordination Function (DCF). J. Kim *et al.* proposed an Opportunistic Network Coding (OPNC) with relay node selection for wireless communications [37]. They consider a system model that includes multiple relay nodes and multiple sink nodes. Based on the system model, they propose a relay selection scheme which considers the channel state between relays and destination nodes, and they combine the proposed relay selection model with network coding to improve average system throughput. These schemes focused on improving network performance, but energy efficiency was not considered. Moreover, they assumed that nodes are deployed in a large-scale area and can transmit data to the destination using more than two-hops, which is not supported in WBANs. Consequently, these schemes cannot be directly applied to WBANs.

Relay node selection is an important issue in both cooperative communication and cognitive radio research communities [38, 39, 40, 41, 42]. Tao *et al.* employed the optimal stopping theory to take into account the time required to scan for candidate relay nodes before stopping at a suitable one with good channel quality in a cognitive radio environment [38]. Their scheme guarantees that such a relay node will be found within a short observation/scan time. I. Krikidis *et al.* investigated a relay selection scheme for a finite buffer-aided decode-and-forward cooperative wireless network [39]. In order to maximize the achieved diversity gain, the proposed scheme fully exploits the buffering capability at relays and provides transmission scheduling for available channel links. To evaluate performance of the proposed scheme, the authors perform extensive simulations and verify the performance of the proposed scheme in terms of outage probability and diversity gain by providing a significant coding gain for small buffer size. S. Zhang *et al.* proposed a low overhead multi-relay selection protocol to support multi-stream cooperative communications for multi-stream cooperative Multiple Input Multiple Output

(MIMO) systems with multiple relay nodes [40]. At high Signal-to-Noise Ratio (SNR) value, the proposed protocol obtains good trade-offs between diversity and multiplexing or throughput and reliability when using lower outage probability value. L. Song *et al.* considered a simple suboptimal min-max criterion for relay selection, called 'Relay Selection Amplify-and-Forward (RS-AF)', which selects a single relay that minimizes the maximum symbol error rate between two sources [41]. To improve the system performance, the authors determine the optimal power allocation (OPA) between the sources and the relay based on asymptotic symbol error rate. Theoretical analysis and simulation indicate that their RS-AF with OPA achieves the full diversity for multiple relays scenario. Elrabiei *et al.* proposed an energy-efficient cooperative multicasting scheme that selects relay nodes based on their location, channel condition, and coverage [42]. They considered Worldwide Interoperability for Microwave Access (WiMAX) single frequency networks, and simulated a nearest neighbor protocol and transmission radius Relay Agent (RA) selection algorithm, including two further optimized versions of them based on the transmission range of relay node and the instantaneous channel state information. These schemes assumed a mobile environment and a relay infrastructure that have plentiful resources. Moreover, most of these studies focused only on improving performance of relaying transmissions in terms of latency and throughput, but did not consider both transmission reliability and power consumption. In contrast, a WBAN consists of nodes that have limited resources and requires low overhead and low power consumption on relay nodes.

In general, nodes in WSNs have limited resources. To overcome this problem, there are a number solutions on relay node selection and routing protocol for WSNs. Tuah *et al.* proposed a relay node selection scheme to minimize power consumption and extend network lifetime in cluster-based WSNs with heterogeneous sensor nodes [43]. They assumed that the placement of relay nodes in the network is important when each node has different capacity. To achieve energy efficiency, the authors proposed a three layered architecture and two algorithms called Highest Energy Levels Relay Selection' and Minimum Energy Over Distance Rate Relay Selection. These algorithms first select cluster heads and then select a relay node from the selected cluster heads. M. de Graaf intoruced an analytical model to maximize network lifetime for various clustering algorithms, which is related to the research on hierarchical routing protocols for wireless sensor network [44]. The author constructs a general power consumption model and performs numerical analysis for two different cases (fixed and uniformly distributed power case, and geometrical power case). However, due to the different requirements of a WBAN, such as rapid channel variation due to postural body movement, more constrained energy consumption requirement, and small-scale high-density network, existing schemes for WSNs cannot satisfy the requirements of WBANs.

A number studies have been done to extend the network lifetime of WBANs using relay nodes [45, 46, 47, 48]. Ehyaie *et al.* proposed a method that employs optimal power allocation with the constraint of targeted outage probability to minimize energy consumption [45]. The method considers two strategies – power allocation with and without posture state information. An on-body packet routing algorithm for WBAN was considered in [46]. To avoid packet loss due to frequent postural network partitioning, the authors presented Relative LOCation based Forwarding (RLOCF), where network partitioning pattern was measured and analyzed based on experiments. Elias *et al.* investigated the effect of adding a relay network to the network of body sensors to reduce energy consumption [47]. The authors defined a relay node that only has relaying capacity without sensing capacity. In their method, when the network is initialized, a network topology is constructed based on the predetermined number of relay nodes and their locations. However, their study only focused on the initial locations of nodes and does not take into account frequent link loss due to human activity and postural movement. In an another perspective, a WBAN standard-based energy efficient two-hop star topology extension was proposed in [48]. This scheme assumes that the coordinator is capable of transmitting data directly to all of the sensor nodes without relay nodes, which will increase power consumption and the cost of nodes. Moreover, they did not consider how to efficiently select relay nodes.

As mention above, existing relay node selection and routing schemes cannot be directly apply to WBANs due to different communication environment and requirements. Therefore, a relay node selection scheme that satisfies the requirements and characteristics of WBAN is necessary. To provide reliable communication with low delay, a relay node selection method for WBANs should consider various factors for different scenarios, such as dynamic link losses due to intra-network mobility. Table 5.1 indicates summary of above related works.

5.3 Proposed relay node selection

Our proposed method focuses on adaptively satisfying the requirements of WBANs to prolong the network lifetime and improve reliability in situations where signal attenuation and link loss occur frequently due to dynamic node mobility.

Figure 5.2 illustrates the proposed AHP-based Flexible Relay Node Selection scheme. First, when a node looses its direct link to the coordinator, the discovery of relay candidates is initiated by a simple control message exchange. Second, among the available relay candidates, the node decides on a relay node using AHP and establishes a relay link with the selected relay node. Finally, the recovery of the direct link between the coordinator and the node, if possible, is carried out.

The proposed method is implemented using the following three modules: *Relay Candidates Discovery*, *AHP-based Relay Node Decision*, and *Direct Link Recovery*. The following subsections provide detailed discussions of the three modules.

Table 5.1: Existing relay node selection schemes

Ref. No.	Target network	Distribution	Goal				Relay selection factor	Allowed hop count
			Throughput	Power	Reliability	Coexistence		
[35]	Ad-hoc network	Large scale	×	×	○	×	# of message exchange, path length, message priority	$\geq$ 3 hop
[36]	Ad-hoc network	Large scale	○	×	×	×	Node location, SNR	$\geq$ 3 hop
[37]	Wireless mesh network	Large scale	○	×	○	×	Channel state	$\geq$ 3 hop
[38]	Cognitive network	Large scale	×	○	○	○	Channel state	$\geq$ 3 hop
[39]	Cooperative wireless network	Large scale	○	×	○	○	Channel state, buffering technique	$\geq$ 3 hop
[40]	Cooperative wireless network	Large scale	○	×	○	×	SNR, outage probability	$\geq$ 3 hop
[41]	Cooperative wireless network	Large scale	×	○	○	×	Power consumption, symbol error rate	$\geq$ 3 hop
[42]	Cognitive network	Large scale	○	○	○	×	Node location, channel state, communication coverage	$\geq$ 3 hop
[43]	Cluster-based WSN	Large scale	×	○	×	×	Remaining energy	$\geq$ 3 hop
[45]	WBAN	Extended star-topology	×	○	○	×	Remaining energy, postural state info.	$\geq$ 3 hop
[46]	WBAN	Extended star-topology	×	×	○	×	Postural state info	$\geq$ 3 hop
[47]	WBAN	Extended star-topology	×	○	×	×	# of relay node, remaining energy	$\geq$ 3 hop
[48]	WBAN	Extended star-topology	○	×	○	○	-	$\leq$ 2 hop

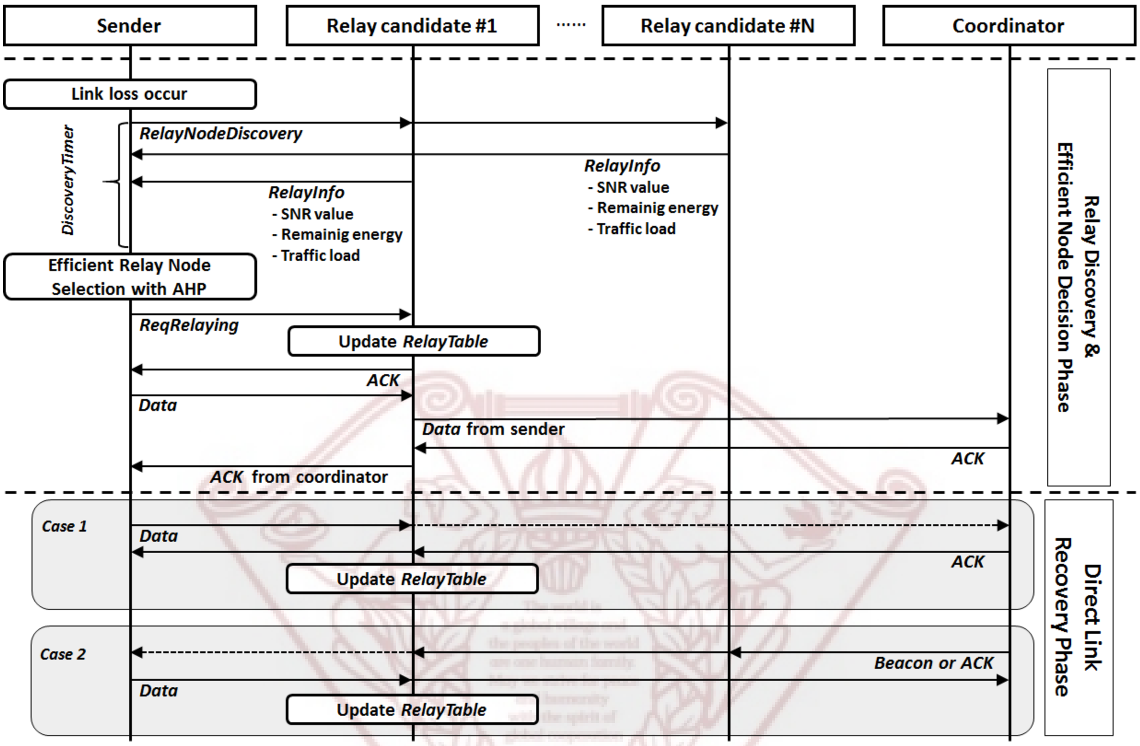


Figure 5.2: Overall sequence of the proposed scheme.

5.3.1 Relay candidates discovery

Relay Candidates Discovery is performed using a control message called *RelayNodeDiscovery*. If the node does not receive a *BEACON* or an *ACK* message, it broadcasts a *RelayNodeDiscovery* message to neighboring nodes and sets the *DiscoveryTimer*. Our scheme only selects on/around-body devices as relay nodes. This is because in-body medical devices have small battery capacity and their replacement requires surgery, and thus it is impractical to use these devices as relay nodes.

When the relay candidates receive the *RelayNodeDiscovery* message, each relay candidate i sends a *RelayInfo* message, which contains average SNR value, total traffic load, and remaining energy ratio.

Average SNR for node i, $AvgSNR_i$, represents SNRs of the coordinator and the node relative to a relay candidate, and is given as

$$AvgSNR_i = \frac{SNR_{i \rightarrow cord} + SNR_{i \rightarrow node}}{SNR_{i \rightarrow cord} \times SNR_{i \rightarrow node}}, \tag{5.1}$$

where $SNR_{i \rightarrow cord}$ is the SNR from the coordinator to the relay candidate i and $SNR_{i \rightarrow node}$ is the SNR from the relay candidate i to the node.

The total traffic load of the relay candidate i, TL_i^{total}, is defined as

$$TL_i^{total} = \frac{1}{TL_i + \sum TL_{RelayingNode}}, \tag{5.2}$$

where TL_i denotes the relay candidate i's own traffic and $TL_{RelayingNode}$ denotes traffic load of the other nodes that communicate with the coordinator via relay candidate i.

The remaining energy ratio of node i, E_i^{Ratio}, is defined by the following equation:

$$E_i^{Ratio} = \frac{E_i^{Rest}}{E_i^{Init}}, \tag{5.3}$$

where E_i^{Rest} and E_i^{Init} represent the residual and initial energy of node i, respectively.

When the *DiscoveryTimer* expires, the node constructs a table of relay candidates based on received *RelayInfo* messages, and then selects a relay node using the AHP-based relay node decision model that will be explained in the next subsection.

5.3.2 AHP-based relay node decision

The AHP is a multiple criteria decision-making method that decomposes a complex problem into a hierarchy of simpler and more manageable sub-problems [49]. These sub-problems are referred to as *decision factors* or *criteria*, and each factor is given a *weight* according to its relative importance to the problem. Consequently, the importance of each factor to the problem is synthesized to find the best solution.

Our proposed method uses AHP to determine the weights of the relay candidates according to which next hop is selected when a relay link is established. Figure 5.3

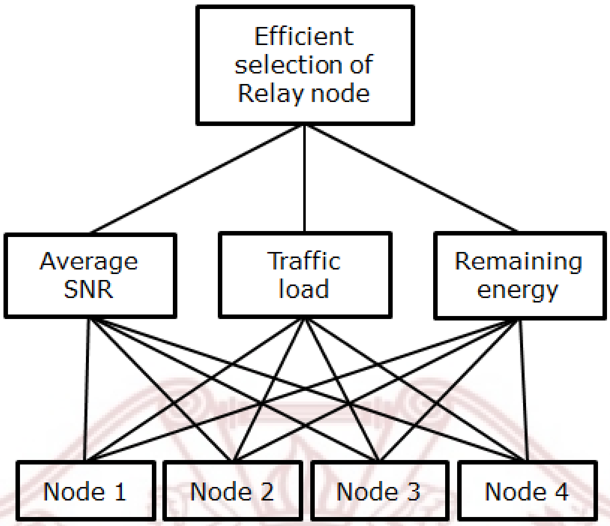


Figure 5.3: AHP hierarchy for relay node selection.

shows the AHP hierarchy model for the relay node selection. In the model, the goal of the decision "Efficient selection of relay node" is at the top of the hierarchy. The average SNR, traffic load of the relay candidate, and remaining energy ratio are taken into consideration as the decision factors, which are in the middle level of the hierarchy model. The bottom level consists of m alternative relay candidates to be evaluated. Based on the pre-constructed AHP hierarchy model, the *weight acquiring process* is carried out using the following three steps:

1. Collect information and formulate the relay node selection problem as a decision hierarchy of independent factors.

2. Decide and calculate the relative local weights of decision factors or alternatives of each level.

3. Synthesize the above results to determine the overall weight of each alternative nodes and choose the one with the largest weights as the appropriate relay node.

The local weights consist of two parts: The weight of each decision factor to the goal and the weight of each candidate to each decision factor. Both are calculated using the same procedure. Taking the former as an example, the following describes the procedure.

An evaluation matrix is developed using a pairwise comparison of each decision factor under the topmost goal. The comparison results are generated by asking questions, such as "Which is more important and by how much?", and are presented as a square matrix A given by

$$\mathbf{A} = (a_{ij})_{3\times 3} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, \tag{5.4}$$

where a_{ij} denotes the ratio of the i^{th} weight factor to the j^{th} weight factor, and n is the number of factors. Each weight factor is decided by the user or the service provider based on the fundamental 1 to 9 scale, which can be used to rank the judgments as shown in Table I. The smaller weight in a pair is chosen as a unit and the larger weight is estimated as a multiple of that unit, and then a number is assigned based on the perceived importance. Similarly, the reciprocals of these numbers can also be used to show the inverted comparison results. Thus, a reciprocal matrix can be obtained where the entries are symmetric with respect to the diagonal.

For the matrix A, its eigenvalue is calculated based on the equation $AW = \lambda_{max} W$, where W is a non-zero vector called eigenvector, and λ_{max} is a scalar value called eigenvalue. After normalizing the eigenvector W, the elements of W are regarded as the approximate local weights of the decision factors expressed as

$$W_j^T = (w_\alpha, w_\beta, w_\gamma), \tag{5.5}$$

where w_α, w_β, and w_γ are approximate local weights for the average SNR, traffic load of the relay candidate, and remaining energy ratio, respectively.

Table 5.2: A fundamental 1 to 9 scale

Number Rating	Verbal Judgment of Preferences
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred

Table 5.3: Consistency index

n	1.2	3	4	5	6	7	8	...
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	...

If every element in Eq. 5.4 satisfies the equations $a_{ij} \times a_{ji} = 1$ and $a_{ik} \times a_{kj} = a_{ij}$, the matrix A becomes a consistency matrix. Unfortunately, the evaluation matrices are often not perfectly consistent due to people's random judgments. These judgment errors can be detected by a consistency ratio (CR), which is defined as the ratio of consistency index (CI) to random index (RI) as shown below.

$$CR = CI/RI, \tag{5.6}$$

where RI is given in Table 5.3[49], and CI is defined as

$$CI = (\lambda_{max} - n)/(n - 1), \tag{5.7}$$

where

$$\lambda_{max} = (1/n)\sum_{i=1}^{n}(AW)_i/W_i. \tag{5.8}$$

When $CR \leq 0.1$, the judgment errors are considered to be tolerable, and the weight coefficients of the global weight W_j becomes the weights of decision factors under the topmost goal. Otherwise, pairwise comparisons need to be adjusted until matrix A satisfies the consistency check.

From the above steps, not only the weights of decision factor from W_j towards the topmost goal can be obtained, but also the weights of the candidate nodes towards each factor. As an example, suppose a node has four neighbors in a WBAN. Then, the weights of four alternatives under the three factors result in a 3×4 matrix, denoted as w_{n_ij}, shown below.

$$w_{n_ij} = \begin{array}{c} \\ \\ n_1 \\ n_2 \\ n_3 \\ n_4 \end{array} \begin{array}{c} \begin{array}{ccc} Average & Traffic & Remaining \\ SNR & Load & Energy \end{array} \\ \begin{pmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \\ w_{41} & w_{42} & w_{43} \end{pmatrix} \end{array} \tag{5.9}$$

where n_1, n_2, n_3, and n_4 denote the candidate relay nodes.

The global weight of each sensor node can be derived by multiplying the local weight to its corresponding parent. As a result, the final weight matrix w_{n_i} is calculated as

$$w_{n_i} = w_{n_ij} \cdot w_j, \tag{5.10}$$

where each alternative neighbor's final weight is calculated as

$$w_{n_i} = \sum_{j=1}^{3} w_{n_ij} \cdot w_j. \tag{5.11}$$

The larger the final weight of the neighbor node, the higher the importance it has towards enhancing the performance of network lifetime or reliability. Thus, the neighbor with the largest weight is selected as the relay node.

The following example illustrates the AHP process, where the matrix A is determined according to Eq. (5.4) and shown below:

$$\mathbf{A} = \begin{array}{c} \\ \\ \alpha \\ \beta \\ \gamma \end{array} \begin{array}{ccc} Average & Traffic & Remaining \\ SNR(\alpha) & Load(\beta) & Energy(\gamma) \\ 1 & 1/2 & 1/4 \\ 2 & 1 & 1/2 \\ 4 & 2 & 1 \end{array} \tag{5.12}$$

where the three criteria are denoted by α, β, and γ.

In this example, the service provider regards energy consumption as the most significant criterion, traffic load as the second important criterion, and the average SNR as the third important criterion, and their overall relative importance α:β:γ is given as 4:2:1. Therefore, relative importances of the three possible pairs of criteria α:β, β:γ, and γ:α are 1:2, 1:2, and 4:1. Based on this assumption, the eigenvector can be calculated as $W = (0.142857, 0.285714, 0.571429)$, which indicates the local weights of the average SNR, traffic load, and remaining energy, respectively. Based on this, it is clear that the remaining energy is the most important criterion, and the average SNR is the least important. According to Eq. (5.8), the eigenvalue is $\lambda_{max} = 3.0$. Consequently, consistency ratio can be calculated as $CR = 0.0 < 0.1$, thus matrix A satisfies the consistency check.

Information of each relay candidate determines the weight matrixes of alternatives under the three factors, and then global weight is obtained based on its specific situation. Finally, its eligibility as a relay node can be decided by the AHP hierarchy model.

Afterwards, the node sends a *ReqRelaying* message to the selected relay node, and the relay node inserts the node's information into its *RelayTable*. Then, the relay node can pass on *BEACON*, *DATA*, and *ACK* message between the coordinator and the node.

5.3.3 Direct link recovery

Since the network conditions continuously change, the disconnected link between the coordinator and the node may be recovered. If no attempt is made to recover the direct link even when it is possible, the relay node will consume unnecessary energy and transmission latency will increase. For this reason, the Direct Link Recovery algorithm is proposed.

Figure 5.4 shows the details of the Direct Link Recovery algorithm. The first case represents the direct link recovery process from the perspective of the coordinator. If the coordinator overhears a *DATA* frame from the node to the relay node, it designates the node as the destination for an *ACK* frame. After the node receives the *ACK* frame, it checks the information in the received frame and directly communicates to the coordinator. The second case represents the direct link recovery process from the perspective of the node. If the node can overhear a *BEACON* or an *ACK* frame from the coordinator, then the node recovers the direct link to the coordinator. Meanwhile, the relay node releases the node's information in the *RelayTable* when it overhears a *BEACON*, an *ACK*, or a *DATA* frame.

5.4 Performance evaluation

This section discusses the performance evaluation of our scheme through simulation using various scenarios. As mentioned in Section 5.2, network environments of existing relay node selection schemes and routing protocols for ad-hoc, cooperative communication, cognitive radio, and WSN [35, 36, 38, 42, 43, 37, 44, 39, 40, 41] are different from WBAN. Moreover, requirements of WBAN is more strict than existing works. Therefore, they are not suitable to be directly applied to WBAN environment. In addition, relay selection schemes for WBAN [45, 46, 47, 48] also cannot be considered as subjects of a comparison

```
PROCEDURE OF Direct LINK RECOVERY
When COORDINATOR attempts Direct Link Recovery:
    COORDINATOR:
    if((RcvPkt→DestAddr != COORDINATOR) && RcvPkt→type == DATA)) {
            set DestAddr to Rcv→SrcAddr
            send ACK message
    }

    NODE:
    if((RcvPkt→DestAddr == this→Addr)
        && (RcvPkt→type == ACK) && (this→useRN == TRUE)) {
            set DestAddr to COORDINATOR
    }

When NODE attempts Direct Link Recovery:
    NODE:
    if((RcvPkt→DestAddr == this→RNAddr) &&
        (RcvPkt→isRN == TRUE) && (RcvPkt→type == BEACON || ACK)) {
            set DestAddr to COORDINATOR
            if(isEmpty(this→queue) == FALSE) {
                    send DATA
            }
    }

Operation of RELAY NODE
after COORDINATOR or NODE performs Direct Link Recovery:
    cnt = 0
    if(RcvPkt→isRN == FALSE) {
            while(cnt != RelayTableLength) {
                    if(RcvPkt→SrcAddr == RelayTable[cnt]→Addr) {
                            release(RelayTable[cnt])
                            break
                    }
                    cnt++
            }
    }
```

Figure 5.4: Pseudo-code algorithm for Direct Link Recovery.

for the simulation due to their strong assumptions. By these reasons, we compared with the two-hop star topology extension scheme in the IEEE 802.15.6 standard. The proposed method is implemented with OMNeT++ [51].

5.4.1 Simulation model

In our simulation, sensor nodes are randomly deployed in a circular area with a radius of 3 m. The coordinator is placed at the center of the network, and the number of sensor nodes is 20. The transmission range of the sensor nodes is 3 m and each has 1 mJ as the initial energy. The default network is a one-hop star topology and the sensor nodes periodically generate 240 bytes of data. Link loss occurs uniformly on every link in the network with a percentage. Note that we consider 10–90% of link loss rate in order to reflect relatively critical problem in coexisting WBANs, but 80–90% of link loss rate is not applicable to real communication environment. The PHY layers of the proposed method and the IEEE 802.15.6 standard are identical to those of IEEE 802.15.4 [6], and each link state is decided based on randomly changing SNR values based on the percentage of link loss. The energy consumption model of LEACH [52] is used to simulate energy consumption of the sensor nodes. The *DiscoveryTimer* for the Relay Candidates Discovery module of the proposed method is set to 1 ms, and the maximum retransmission count is 3.

To evaluate the flexibility and adaptability of the proposed scheme, the following four scenarios that reflect various real situations in WBANs are defined: *Normal Medical Service*, *Low Battery*, *Critical Medical Service*, and *Emergency*. In these scenarios, the average SNR, remaining energy ratio, and traffic load of the relay candidates are set as the first, second, and third weight factors, respectively, for the following priority matrixes. Details of these scenarios are discussed below.

Scenario 1 - Normal medical service: This scenario assumes that a WBAN consists of typical medical devices, which have enough energy capacity and the same priority for frames. In this scenario, there are no exceptional situations such as emergency, low battery, etc., and thus, the relative weights of all the criteria is the same and the priority matrix A_{Normal} is set as shown below:

$$\mathbf{A_{Normal}} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \tag{5.13}$$

Scenario 2 - Low battery: This scenario assumes that the remaining energy in the network is low. Therefore, low power consumption is more important than Scenario 1, and the relative weight for the remaining energy should be higher than other criteria. Thus, the priority matrix $A_{LowEnergy}$ is set as follows:

$$\mathbf{A_{LowEnergy}} = \begin{pmatrix} 1 & 1 & 1/5 \\ 1 & 1 & 1/5 \\ 5 & 5 & 1 \end{pmatrix} \tag{5.14}$$

Scenario 3 - Critical medical service: This scenario considers some medical devices that are critical to a user's health, referred to as *Critical Medical Devices*, and require reliable communication. Therefore, this scenario rates the communication reliability as a top priority, and the priority matrix $A_{Critical}$ is defined to guarantee high reliability of critical medical data. The priority matrix $A_{Critical}$ is expressed as follows:

$$\mathbf{A_{Critical}} = \begin{pmatrix} 1 & 5 & 5 \\ 1/5 & 1 & 1 \\ 1/5 & 1 & 1 \end{pmatrix} \tag{5.15}$$

Scenario 4 - Emergency: In this scenario, a WBAN must be able to guarantee prompt and reliable transmission during an emergency situation. A WBAN should immediately handle situations when devices sense irregular data during monitoring of vital signals. Otherwise, user's critical requests may not be delivered. Based on this, the priority matrix $A_{Emergency}$ shown below reflects the importance of link quality and traffic load:

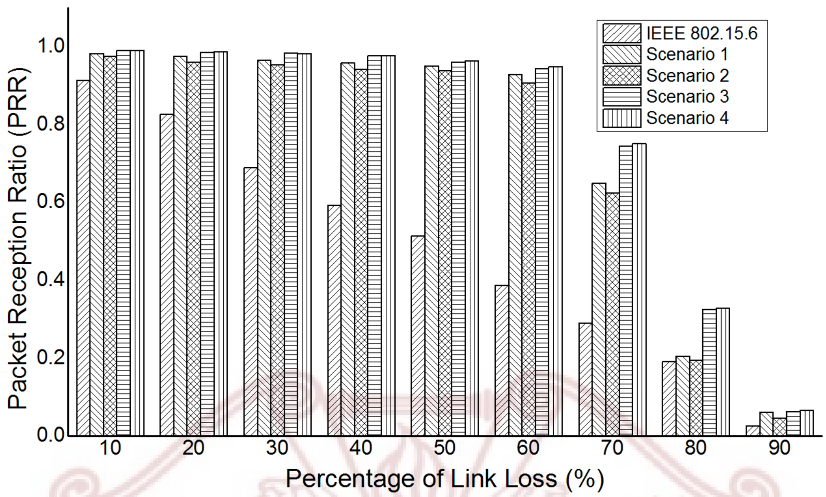


Figure 5.5: Packet Reception Ratio (PRR) vs. percentage of link loss.

$$\mathbf{A}_{\mathbf{Emergency}} = \begin{pmatrix} 1 & 1 & 5 \\ 1 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{pmatrix} \tag{5.16}$$

5.4.2 Simulation results

Figure 5.5 compares the PRR values of the proposed scheme and IEEE 802.15.6 as a function of the percentage of link loss for the four scenarios. In general, Scenarios 3 and 4 outperform other scenarios since their priority matrices reflect the fact that reliability is more important than energy consumption. On the other hand, Scenario 2 shows the lowest PRR for the proposed scheme. However, since the proposed scheme reflects both average SNR and traffic load into the selection of relay nodes using AHP for all the scenarios, it can provide PRR of up to 90% until the percentage of link loss falls below 60%. In contrast, PRR of IEEE 802.15.6 decreases linearly as the percentage of link loss increases, which is due to the fact that link states are not considered in IEEE 802.15.6.

Figure 5.6 shows the average power consumption of the proposed scheme and IEEE

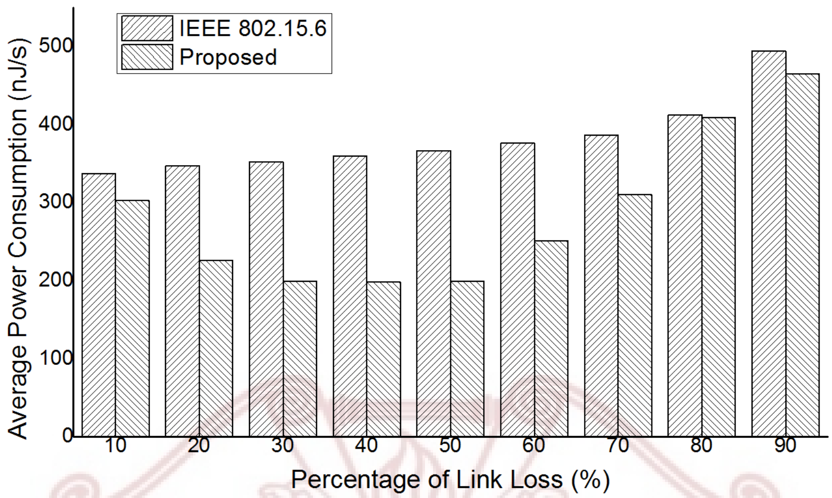


Figure 5.6: Average power consumption vs. percentage of link loss.

802.15.6 for Scenario 1 as a function of the percentage of link loss. The average power consumption for the proposed scheme decreases until the link loss reaches 40%, but increases afterwards. The decrease in the first half occurs because the proposed scheme dynamically selects relay nodes when link losses occur, and this leads to reduction in the number of retransmissions. In addition, the number of additional control messages exchanged decreases as the link loss ratio increases because the number of available links decreases. Based on this, the average power consumption of the proposed scheme decreases when link loss increases. However, the average power consumption of the proposed scheme drastically increases when link loss is more than 40%. This can be explained by the fact that the number of retransmissions rapidly increases in situations where link loss is frequent. On the other hand, the average power consumption of IEEE 802.15.6 increases linearly as the percentage of link loss increases, and it is always higher than the proposed scheme. This indicates that proposed scheme can achieve better energy efficiency than IEEE 802.15.6 despite the overhead due to control message exchanges.

Figure 5.7 tracks the number of live nodes as simulation progresses when the percent-

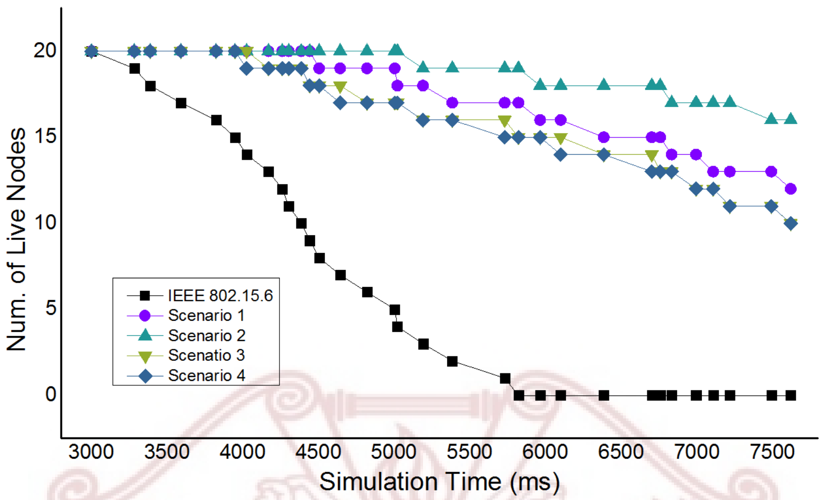


Figure 5.7: Number of live nodes vs. time.

age of link loss is 40%. The number of retransmissions for IEEE 802.15.6 is larger than the proposed scheme since it cannot dynamically handle link loss among the coordinator, relay nodes, and nodes. Therefore, the proposed scheme maintains a higher survivable rate of nodes by considering the remaining energy. In particular, the results of Scenario 2 show the longest network life time since remaining energy has a higher weight than average SNR or traffic load. Since IEEE 802.15.6 does not consider the remaining energy of relay nodes, the energy consumption increases resulting in shorter network lifetime.

The average delay of the proposed scheme and IEEE 802.15.6 as a function of the percentage of link loss is shown in Figure 5.8. The proposed scheme shows lower delay compared to IEEE 802.15.6 due to the fact that it considers traffic load as a link quality. Both Scenarios 3 and 4 give higher weight to the average SNR value, and this results in better performance. Scenario 4 assumes an emergency situation, which requires low delay and high reliability, and hence average SNR and traffic load are highly weighted. Consequently, this leads to the lowest delay for Scenario 4.

In summary, IEEE 802.15.6 shows the worst performance in terms of PRR, average

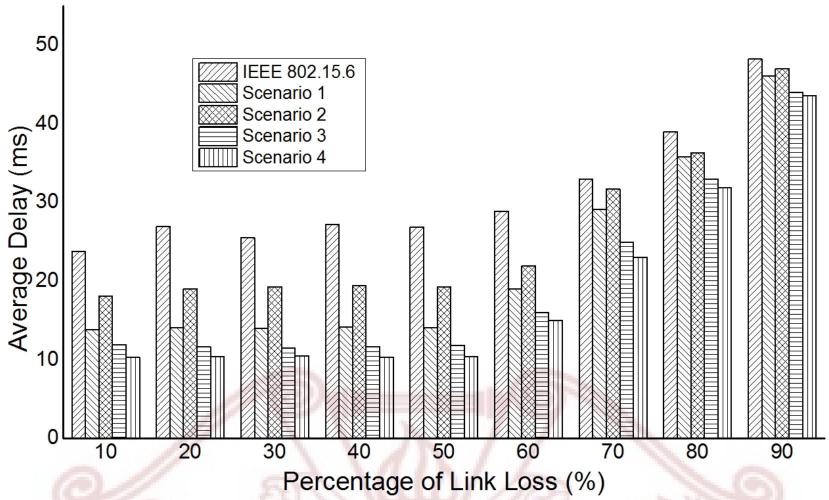


Figure 5.8: Average delay vs. percentage of link loss.

power consumption, network lifetime, and average delay since it does not consider how a relay node should be selected. In contrast, the proposed scheme dynamically selects relay nodes using AHP, which considers average SNR, traffic load, and remaining energy, and thus guarantees high reliability, low power consumption, and low delay. As a result, the proposed scheme can flexibly satisfy various requirements for different scenarios in WBANs.

5.5 Summary

WBANs need to provide ultra-low power consumption and reliable communication between the coordinator and sensor nodes. However, due to characteristics of the body medium and postural body movements in a WBAN, link loss frequently occurs causing additional energy consumption and unreliable communication. To cope with these issues, this paper proposed an AHP-based Flexible Relay Node Selection scheme for WBANs, which can be adaptively applied to various situations leading to lower power consumption and delay as well as more reliable data transmission. Our simulation results verify that the proposed scheme significantly improves the power consumption and the reliability of the system compared with the conventional IEEE 802.15.6 scheme.

Chapter 6

Conclusions and Future work

In this chapter, we conclude from the research results presented in this thesis and suggest few directions for future work.

6.1 Conclusions

Generally, WBANs are densely deployed in the popular area, and each WBAN has two different types of mobility due to characteristics of WBAN operations. In this situation, WBAN dynamically coexists with a number of WBANs, and they may suffer from interference which causes significant performance degradation, referred to as the *Coexistence problem*. To efficiently solve the coexistence problem in WBANs and to satisfy requirements of WBANs, the thesis has proposed coexistence mitigation schemes which focus on MAC protocol in WBANs considering synergy among them. This thesis consists of three different gradationally approached coexistence mitigation schemes: '*a priority-based channel access scheme for single channel*', '*an adaptive channel selection scheme for multiple channel*', and '*an AHP-based relay node selection scheme*'.

The purpose of the first part is identifying aspects of the coexistence problems in WBANs which exploit single channel usage and reducing contention complexity on single channel. Based on analyzing result of aspects of the coexistence problems in WBANs, the thesis concludes contention complexity in contention-based channel access is a major issue of single channel coexisting WBAN, and the thesis also sets up the purpose of reducing contention complexity. To achieve the purpose, the thesis proposes a priority-based channel access scheme for contention-based channel access on single channel. The proposed scheme divides a contention-based channel access period into the maximum four sub-phases according to pre-defined traffic levels and threshold values for latency. Through performing extensive simulations, the thesis evaluates the performance of the first scheme that can reduce contention complexity and can improve the communication performance on single channel communication of coexisting WBANs.

The second part of the thesis propose a channel selection scheme based on adaptive channel estimation algorithm for multiple channel communication of coexisting WBANs. The proposed channel selection scheme provides an accurate channel estimation algorithm which performs two-state Markov model based on exponentially controlled channel history table. By exploiting the second scheme, a WBAN can use different communication channel from neighbor WBANs, and thus coexisting WBANs efficiently mitigate interference from each other.

According to the first and the second scheme in the thesis, coexistence problem for both single and multiple channel communication can be solved. However, channel conditions of WBANs frequently change due to postural body movement, and it causes frequent link losses. To solve these problems, the third part of the thesis proposes a relay node selection scheme based on AHP. The proposed relay node selection scheme can provide a choosing method considering a multitude of decision factors, such as average SNR, remaining energy, and traffic load. In addition, the proposed scheme can adaptively satisfy the requirements of WBAN in various scenarios.

Based on these three different interference mitigation schemes for coexistence problem in WBANs, the thesis proposes an interference mitigation framework for WBAN MAC protocol considering with organic operation among them, which may create synergy effects for handling coexistence problem in WBANs. Figure 6.1 illustrates the proposed interference mitigation framework for WBAN MAC protocol.

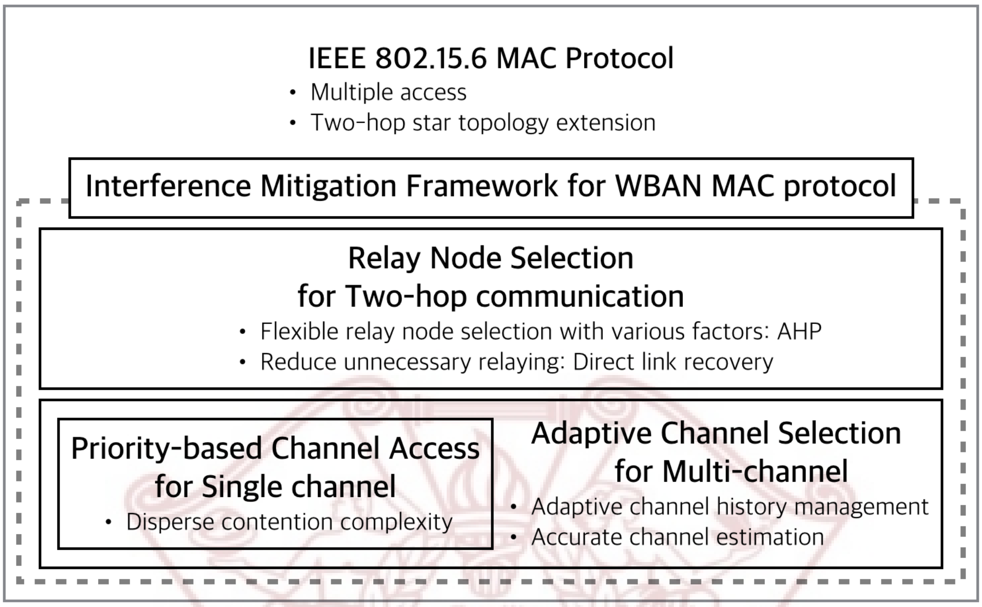


Figure 6.1: The proposed interference mitigation framework for coexisting WBANs.

6.2 Future work

This thesis aims to mitigate the coexistence problem in WBANs from the perspective of MAC protocol, and the proposed schemes in the thesis make a synergy effect against the coexistence problem in WBANs. Although the proposed schemes can solve the coexistence problem and can improve communication performance of coexisting WBANs, however, the requirements of IoT-based healthcare systems are changing because a number of novel services are created and these services require exploiting a number of different communication technologies.

From these reasons, I plan to extend my research issue into three different directions in the future. The first direction is closely related to an advanced study for the coexistence problem in WBAN. Actually, operating environment of WBANs is congested due to its mobility characteristics, and this phenomenon may be more complex through arriving IoT ages, the next generation communication paradigm. However, studies for coexistence

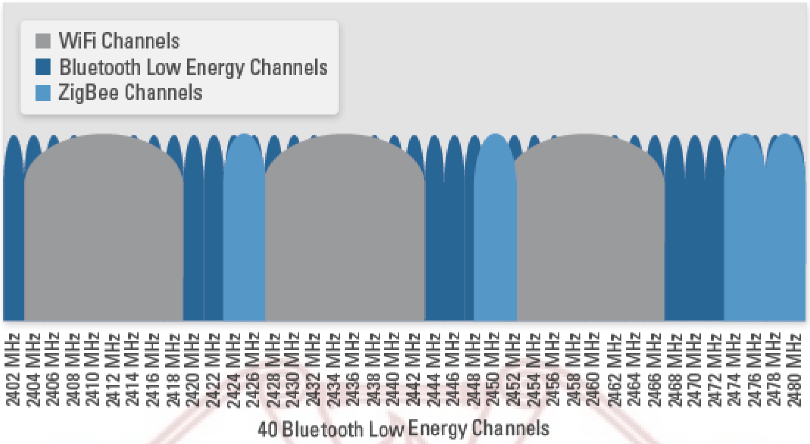


Figure 6.2: Frequency band usage of WiFi, BLE, and ZigBee.

mitigation techniques based on practical point of view are not existed because implementation works of radio frequency (RF) modules based on IEEE 802.15.6 are not completed yet. Therefore, I will focus on making new angles on the coexistence problem in WBANs and developing network techniques to improve performance of WBAN considering both expendability for IEEE 802.15.6-based RF module (developing work will be completed soon) and more complex coexistence environment which consists of heterogeneous communication technologies. In addition, I will study for coexistence estimating or recognizing schemes which may facilitate pre-handling for coexistence problem in WBANs.

The second research direction is coexistence problem mitigation for different wireless communication technologies for IoT. Actually, my research topic can be applied to new communication technologies to provide IoT services because coexistence problem in wireless communication is major reason of communication performance degradation. For example, BLE (Bluetooth Low Energy), which is a typical short range and low power communication technology for IoT, exploits 2.4 GHz ISM bands, all channels of BLE are shared with WiFi and ZigBee as shown in Figure 6.2. In another case, LoRaWAN, which is recently completed low power wide area network technologies for IoT, also exploits 800-

900 MHz bands and it may suffer from interference from other mobile communication technologies such as LTE-M and GSM. In addition, the IEEE standardization organization published the IEEE 802.19 Working Group (WG) to solve coexistence problem among homogeneous or heterogeneous networks in IoT. Based on these research trends, I will analyze new communication technologies for IoT (e.g., LoRaWAN, BLE), and I will try to adapt my coexistence mitigation schemes for them.

The last direction for my future work is about a network management technique to satisfy requirements from target applications. In my Ph.D. candidate period, focusing range of my research has been extended from WBAN to IoT, and I recognized that recent researches for networking techniques tend to be concentrated in narrow senses because important performance factors of access networks are closely related to requirements of target applications. However, not only that they cannot be combined in some conditions but also they cannot be applied commercial network services flexibly, and thus developing an integrated and flexible network management scheme for different applications are necessary. Therefore, I will track recent research trend such as IoT and CPS (Cyber Physical System), and I will attempt to apply varying decision-making or learning techniques based on raw network information, which can be naturally collected during basic communication procedure, to different network services.

Bibliography

[1] A. Milenkovic, C. Otto, and E. Jovanov, “Wireless Sensor Networks for Personal Health Monitoring: Issues and an implementation,” *Computer Communications*, 29, (13-14), pp. 2521-2533, Aug. 2006.

[2] IEEE 802.15 WPAN Task Group 6 (TG6) Body Area Networks: `http://www.ieee802.org/15/pub/TG6.html`

[3] “IEEE standard for local and metropolitan area networks - Part 15.6: Wireless body area networks," *IEEE Std 802.15.6-2012*, pp. 1–271, Feb. 2012.

[4] J. Choi, B. Kim, and J. Cho, “A Coexistence Mitigation Scheme in IEEE 802.15.4-based WBAN,” *Journal of Internet Computing and Services*, Vol. 16, No. 3, June 2015, pp. 1–11.

[5] B. Zhen, M. Patel, S. Lee, E. Won and A. Astrin, “TG6 Technical Requirements Document (TRD),” IEEE 802.15 Working Group Document, IEEE P802.15-08-0644-05-0006, Sept. 2008.

[6] “IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wire- less Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer," IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011), pp. 1–225, 2012.

[7] C. Li, H. Li, and R. Kohno, "Performance Evaluation of IEEE 802.15.4 for Wireless Body Area Network(WBAN)," *Proc. of IEEE International Conference on Communication Workshops (ICC Workshops 2009)*, June 2009, pp. 1–5.

[8] S. Ullah and K. Kwak, "Performance study of low-power MAC protocols for Wireless Body Area Networks," *Proc. of IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops 2010)*, Sept. 2010, pp. 112–116.

[9] J. Mahapatro, S. Misra, M. Manjunatha, and N. Islam, "Interference mitigation between WBAN equipped patients," *Proc. of International Conference on Wireless and Optical Communications Networks (WOCN 2012)*, Sept. 2012, pp. 1–5.

[10] M. Deylami, "A Distributed Scheme to Manage The Dynamic Coexistence of IEEE 802.15.4-Based Health Monitoring WBANs," *IEEE Journal of Biomedical and Health Informatics*, Vol. 18, No. 1, Aug. 2014, pp. 327–334.

[11] Y. Kim, S. Lee, and S. Lee, "Coexistence of ZigBee-Based WBAN and WiFi for Health Telemonitoring Systems," *IEEE Journal of Biomedical and Health Informations*, Vol. 20, No. 1, Jan. 2016, pp. 222–230.

[12] S. Movassaghi, A. Majidi, D. Smith, M. Abolhasan, and A. Jamalipour, "Exploiting Unknown Dynamics in Communications Amongst Coexisting Wireless Body Area Networks," *Proc. of IEEE Global Communication Conference 2015 (GLOBECOM 2015)*, Dec. 2015, pp.1–6.

[13] Y. Qiu, D. Haley, T. Chan, and L. Davis, "Game Theoretic Framework for Studying WBAN Coexistence: 2-Player Game Analysis and n-player Game Estimation," *Proc. of Australian Communications Theory Workshop 2016 (AusCTW 2016)*, Jan. 2016, pp. 53–58.

[14] D. Lewis, "802.15.6 Call for Applications - Response Summary," IEEE 802.15 Working Group Document, IEEE 802.15-08-0407-02, July 2008.

[15] M. MacDougall, "Simulating Computer Systems-Techniques and Tools," *MIT Press*, 1987.

[16] W. Yuan, X. Wang, and J. Linnartz, "A Coexistence Model of IEEE 802.15.4 and IEEE 802.11b/g," *Proc. of 14th IEEE Symposium on Communication and Vehicular Technology in the Benelux,* Nov. 2007, pp. 1–5.

[17] J. Huang, G. Xing, G. Zhou, and R. Zhou, "Beyond Co-existence: Exploiting WiFi White Space for ZigBee Performance Assurence," *Proc. of IEEE International Conference on Network Protocols*, Oct. 2010, pp. 305-314.

[18] R. de Francisco, L. Huang, and G. Dolmans, "Coexistence of WBAN and WLAN in Medical Environments," *Proc. of IEEE 70th Vehicular Technology Conference Fall (VTC 2009-Fall)*, Sept. 2009, pp. 1–5.

[19] B. M. Cho, K. J. Park, and E. C. Park, "Contention Window Adaptation for Coexistence WBAN and WLAN in Medical Environments," *Proc. of International Conference on Information and Communication Technology Convergence (ICTC 2014)*, Oct. 2014, pp. 945–946.

[20] C. Li, P. Wang, H. H. Chen, and M. Guizani, "A Cluster Based On-demand Multi-Channel MAC Protocol for Wireless Multimedia Sensor Networks," *Proc. of IEEE International Conference on Communications (ICC 2008)*, May 2008, pp. 2371–2376.

[21] K. K. Chintalapudi and L. Venkatraman, "On the Design of MAC protocols for Low Latency Hard Real-Time Discrete Control Applications Over 802.15.4 Hardware," *Proc. of 7th International Conference on Information Processing in Sensor Networks (IPSN 2008)*, April 2008, pp. 356–367.

[22] Y. Wu, J. A. Stankovic, T. He, and S. Lin, "Realistic and Efficient Multi-Channel Communications in Wireless Sensor Networks", *Proc. of 27th IEEE International Conference on Computer Communications (INFOCOM 2008)*, April 2008, pp. 1867–1875.

[23] S. C. Ergen and P. Varaiya "PEDAMACS: power efficient and delay aware medium access protocol for sensor networks," *IEEE Transactions on Mobile Computing*, Vol. 5, Iss. 7, July 2006, pp. 920–930.

[24] M. Salajegheh, H. Soroush, and A. Kalis, "HyMAC: Hybrid TDMA/FDMA Medium Access Control Protocol for Wireless Sensor Networks", *Proc. of 18th International Symposium on Indoor and Mobile Radio Communications (PIMRC 2007)*, Sept. 2007, pp. 1–5.

[25] J. Borms, K. Steenhaut, and B. Lemmens, "Low-Overhead Dynamic Multi-channel MAC for Wireless Sensor Networks," *Proc of 7th European Conference on Wireless Sensor Networks (EWSN 2010)*, Feb. 2010, 81-96.

[26] H. Zhang, and S. Li, "A Practical Design of Multi-channel MAC for Cluster-tree WSN," *Proc. of 6th IEEE International Forum on Strategic Technology (IFOST 2011)*, Aug. 2011, pp. 22–24.

[27] N. Abdeddaim, F. Theoleyre, F. Rousseau, and A. Duda, "Multi-Channel Cluster Tree for 802.15.4 Wireless Sensor Network," *Proc. of 23rd IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC 2012)*, Sept. 2012, pp. 590–595.

[28] W. Lee, S. H. Rhee, Y. Kim, and H. Lee, "An Efficient Multi-channel Management Protocol for Wireless Body Area Networks," *Proc. of IEEE International Conference on Information Networking (ICOIN 2009)*, Jan. 2009, pp. 1–5.

[29] S. Ivanov, D. Botvich, and S. Balasubramaniam, “Cooperative Wireless Sensor Environment Supporting Body Area Network,” *IEEE Transactions on Consumer Electronics*, Vol. 58, No. 2, May 2012, pp. 284–292.

[30] P. Sadeghi, R. A. Kennedy, P. G. Rapajic, and R. Shams, “Finite State Markov Modeling of Fading Channels,” *IEEE Signal Processing Magazine*, Sept. 2008, pp. 57–80.

[31] C. Pimentel, T. H. Falk, and L. Lisvoa, “Finite-State Markov Modeling of Correlated Rician-Fading Channels,” *IEEE Transactions on Vehicular Technology*, Vol. 53, No. 5, Sept. 2004, pp. 1491–1501.

[32] G. Hablinger and O. Hohlfeld, “The Gilbert-Elliott Model for Packet Loss in Real Time Services on the Internet,” *Proc. of 14th GI/ITG Conference on Measuring, Modeling and Evaluation of Computer and Communication Systems (MMB 2008)*, April 2008, pp. 1–15.

[33] Atheros Communications Press Release, Atheros Communications Expands Performance and Possibilities with First Draft 802.11n Wireless LAN Solutions, `http://www.atheros.com/news/xspan`

[34] Chipcon AS SmartRF, CC2420 Preliminary Datasheet (rev 1.2), June 2004.

[35] Y. Ma, R. Kibria, and A. Jamalipour, “Optimized Routing framework for Intermittently Connected Mobile Ad Hoc Networks," *Proc. of IEEE International Conference of Communication 2008 (ICC 2008)*, Beijing, China, pp. 3171-3175, May 2008.

[36] N. Mehta, A.Duel-Hallen, and W. Wang, “Enabling Adaptive Rate and Relay Selection for 802.11 Mobile Ad Hoc Networks," *Proc. of IEEE International Conference of Communication 2012 (ICC 2012)*, Ottawa, Canada, pp. 4150–4154, June 2012.

[37] J. Kim, and J. Lee, "Opportunistic wireless network coding with relay node selection," *EURASIP Journal on Wireless Communications and Networking 2011*, 2011:196, Dec. 2011.

[38] T. Jing, S. Zhu, H. Li, X. Cheng, and Y. Hou, "Cooperative Relay Selection in Cognitive Radio Networks," *Proc. of IEEE International Conference on Computer Communications 2013 (INFOCOM 2013)*, Turin, Italy, pp. 175–179, April 2013.

[39] I. Krikidis, T. Charalambous, and J. S. Thompson, "Buffer-Aided Relay Selection for Cooperative Diversity Systems without Delay Constraints," *IEEE Transactions on Wireless Communications*, 11, (5), pp. 1957–1967, May 2012.

[40] S. Zhang, and Vincent K. N. Lau, "Multi-Relay Selection Designed and Analysis for Multi-Stream Cooperative Communications," *IEEE Transactions on Wireless Communications*, 10, (4), pp. 1082–1088, April 2011.

[41] L. Song, "Relay Selection for Two-Way Relaying With Amplify-and-Forward Protocols," *IEEE Transactions on Vehicular Technology*, 60, (4), pp. 1954–1959, May 2011.

[42] S. M. Elrabiei, and M. H. Habaebi, "Energy Efficient Cooperative Communication in Single Frequency Networks," *Proc. of IEEE Annual International Symposium on Personal, Indoor, and Mobile Radio Communications 2010 (PIMRC 2010)*, Istanbul, Turkey, pp. 1719–1724, Sept. 2010.

[43] N. Tuah, and M. Ismail, "Extending Lifetime of Heterogeneous Wireless Sensor Network using Relay Node Selection," *Proc. International Conference on Information and Communication Technology 2013 (ICoICT 2013)*, Bali, Indonesia, pp. 17–21, March 2013.

[44] M. de Graaf, "Energy efficient networking via dynamic relay node selection in wireless networks," *Elsevier Ad Hoc Networks*, 11, (3), pp. 1193–1201, May 2013.

[45] A. Ehyaie, M. Stachyra, and P. Khadivi, “Using relay network to increase life time in wireless body area sensor networks," *Proc. of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2009 (WoWMoM 2009)*, Kos, Greece, pp. 1–6, June 2009.

[46] E. Reusens, W. Joseph, B. Latre, B. Braem, G.Vermeeren, E. Tanghe, L. Martens, I. Moerman, and C. Blondia, “Characterization of on-body communication channel and energy efficient topology design for wireless body area networks,”Ăİ *IEEE Transactions on Information Technology in Biomedicine*, 13, (6), pp. 933–945, Sept. 2009.

[47] J. Elias and A. Mehaoua, “Energy-aware Topology Design for Wireless Body Area Networks,” *Proc. of IEEE International Conference of Communication 2012 (ICC 2012)*, Ottawa, Canada, pp. 3409–3413, June 2012.

[48] C. Lin and P.Chuang, “Energy-efficient Tow-hop Extension Protocol for Wireless Body Area Networks,” *IET Wireless Sensor Systems*, 3, (1), pp. 37–56, June 2013.

[49] Saaty TL (2000) “Fundamentals of decision making and priority theory with the analytic hierarchy process,” *RWS Publications*, USA.

[50] Q. Y. Song and A. Jamalipour, “A network selection mechanism for next generation networks," *Proc. of IEEE International Conference of Communication 2005 (ICC2005)*, Seoul, Korea, pp. 1418–1422, May 2005.

[51] A. Varga, “The OMNeT++ discrete event simulation system," *In Proc. European Simulation Multiconference 2001 (ESM 2001)*, Prague, Czech, pp. 319–324, June 2001.

[52] W. R. Heinzelman, A. Chandrakasan, and H.Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks," *Proc. of Hawaii Interna-*

tional Conference on System Sciences 2000 (HICSS 2000), Maui, Hawaii, pp. 3005–3014, Jan. 2000.