Doctoral Thesis
博士論文

Proposal Methods for Performance Analysis of WBANs Based on CSMA/CA
CSMA/CA に基づいたワイヤレスボディエリアネットワークの理論性能解析に関する研究

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Abstract

The world population has been increasing, leading to a number of problems to society and economics of many countries around the world. In which, a increase of life expectancy is likely to age population, that requires higher health care costs. Wireless Body Area Networks (WBANs) appear as a potential candidate to solve this matter because of providing a dynamic, efficient and high quality e-health care.

In 2012, IEEE set up the standard for WBANs, IEEE.802.15.6, that has been considered as a breakthrough in development process of e-health care and information communication technology in general. To develop better technologies, protocols and to realize WBANs in commercial area are continuous works of researchers and engineers. The trend of research on WBANs can be clarified as follows, doing survey and overviewing on WBANs, developing technic for WBANs as coding or modulation scheme, improving medium access control (MAC) protocol for WBANs, implementing and designing hardware for WBANs, modeling the propagation channel in which WBANs working on, finally analyzing performance of WBANs in order to optimize parameters to achieve higher performance. This thesis belongs to the final trend.

A dependable and efficient MAC protocol is really important with WBANs when they are applied for medicine or even though for non-medicine. Better MAC protocol can produce low energy consumption or at least can guarantee the timely delivery of emergency traffic. Therefore, beside of improving MAC protocol, correctly analyzing it is necessary. There have been many works on performance analysis of IEEE 802.15.6, especially based on carrier sense multiple access with collision avoidance (CSMA/CA) scheme. The performance analysis on WBANs MAC layer can be clarified into two groups, using Markov chain model to simulate the state of sensor in WBANs and non-Markov chain model approach.

By employing discrete time Markov chain (DTMC) model, many previous works can illustrate the state of all sensor in WBANs or simulate how sensors working and affecting together in the system. As a result, previous works can calculate the access probability of all sensors and then calculate throughput and energy consumption or delay and consider these as final results. After reviewing carefully previous works, the authors of the thesis found out limitations as frequent assuming that channel is ideal and finishing such at analyzing, not optimizing or proposing any new technology, protocol or system. In order to overcome these limitations, the thesis developed discrete time Markov chain (MCMC) method to analyze performance of WBANs under non-ideal channel by taking into account bit error rate (BER) and packet error rate (PER). The MCMC method can be considered as development or adjustment of the DTMC method with key idea is to find the access probability approximately.

On the other hand, the DTMC method consists of method limitations as using assumption like saturation condition and non-saturation condition, and not taking into account remained packets. The saturation condition in this thesis can be explained as if a sensor in WBANs always has a packet to send or in its user priority (UP) queue there is always a packet waiting to be served, the sensor is saturated. In fact, saturation condition is likely to be relative with high traffic. The remained packets are the packets transmitted unsuccessfully due to collision or error. As a result, there are some previous works on MAC layer for WBANs not using the DTMC method. However, these works have limitations as consideration system having only a sensor node and a coordinator, or system with many sensors but only single UP, consequently, the effect each other of sensors in the same UP or different UPs is not taken into account. From these points, the thesis proposed dynamic statistical method for performance analysis

WBANs on MAC layer, taking into account remained packets and analyzing system performance changing following operation time and due to variable packet arrival rate, the number of sensors, payload size, retry limit and UP levels. The proposal method has been expected to be more flexible and precise.

Moreover, not finishing at analyzing performance, the thesis propose adaptive Bose-Chaudhuri-Hocquenghem (BCH) code rates for WBANs and the thesis also proved that this adaptive code can produce significantly higher throughput for WBANs.

In conclusion, the thesis produced three main results, proposing two methods, the MCMC and dynamic statistical method, for performance analysis of WBANs, and then proposing the adaptive BCH code rates for WBANs with higher throughput, which was already proved. The thesis still contains drawbacks or unsolved problems. Firstly, the proposal adaptive BCH code may cause system to become more complex and this is not solved yet in the thesis. Secondly, with the proposal dynamic statistical method in this thesis is only finished at algorithm. For the future work of this thesis, the authors hope to apply the MCMC method to other coding schemes with deep analysis of changing the complexity and energy consumption of system when adaptive coding scheme is employed. With the proposal dynamic statistical method, authors need to develop simulation program to produce the throughput or energy consumption of system and compare these with outstanding previous work results to prove the proposal method. Moreover, the second method should be extended to the real channel under noise and interference condition with deeper analysis of adaptive real change of channel because of noise and interference, employing cross layer with coding in order to optimize parameters of system and then proposing adaptive coding schemes with comparison of these.

あらまし

世界の総人口が増加することにより多くの社会的，経済的な問題が世界各国で引き起こされている．これによる平均余命の増加は人口の高齢化を招く可能性があり，高額な医療費が必要となる．ワイヤレスボディエリアネットワーク（WBAN）は，効率的で高品質な医療システムやヘルスケアを提供することによりこれらの問題を解決する技術として注目されている．

2012年，IEEEは，情報通信に基づく医療およびヘルスケアへ向けたWBANの国際標準規格としてIEEE802.15.6を策定した．WBANにおけるより優れた技術やプロトコルの開発，さらに実用化，商品化のためには研究者や技術者の継続的な活動が不可欠である．近年のWBAN関連研究の動向としてはWBANを取り巻く環境の調査と俯瞰，WBANにおける符号化技術や変調方式の開発，メディアアクセス制御（MAC）プロトコルの改善，ハードウェア設計と実装や，電波伝搬モデルや環境モデル分析に基づいた最適化などがあげられるが，本論文はこの中で環境モデル分析によるパラメータ最適化に関する研究に属する．

高信頼で且つ効率的なMACプロトコルはWBANが非医療のみならず医療用途に応用される場合に特に重要である．より良いMACプロトコルは電力消費が小さく，また通信遅延時間の最低限保障がなされる必要がある．したがってこれらを評価するためにMACプロトコルそのものの改善に加え，正確な分析手法の確立が必要となる．特にキャリア検出多重アクセスによる衝突回避方式（CSMA/CA）プロトコルを用いたIEEE802.15.6によるWBANの解析のためには多くの研究が発表されている．WBANのMAC層の性能解析手法としてはマルコフ連鎖モデルを用いて各センサーノードの状態をシミュレートする手法と．非マルコフ連鎖モデルに基づくものの2つにおおきく分類される．

離散時間マルコフ連鎖（DTMC）モデルを利用することにより，WBAN内のすべてのセンサの状態を示し，またはセンサ同士がシステム内でどのように相互に

作用しあっているかをシミュレーションにより解析することができる．その結果，先行研究において，すべてのセンサーの接続成功確率を計算することでスループットと電力消費または伝送遅延時間を計算し，これらを最終結果とみなしている．先行研究の慎重な調査を通し本論文の著者は，多くの先行研究における解析が伝送路環境が理想的であると仮定した解析，最適化または新技術やプロトコル，システムの提案に基づいていることに着目し，これらの限界を克服するために符号誤り確率（BER）とパケット誤り確率（PER）を考慮した非理想チャネル下での WBAN の性能を解析する離散時間マルコフ連鎖（MCMC）法を開発した．MCMC 法は，DTMC 法のより現実的な改良と見なすことができる．キーアイデアとしては，アクセス確率を近似的に求める点である．

一方，DTMC 法は，飽和条件や非飽和条件のような仮定に基づき，残ったパケットを考慮しないという手法による制約を含んでいる．この論文の飽和条件は，WBAN のセンサが常に送信パケットを保持しているか，またはユーザ優先度（UP）のキューに常に送信されるのを待っているパケットがあるかのように説明でき，センサは常に飽和しています．実際には，飽和状態はトラフィックが多いほど相対的に増加する可能性がある．残りのパケットは，衝突または符号誤りのために正常に送信されなかったパケットを意味している．その結果，DTMC 方式を使用しない WBAN のための MAC 層に関するいくつかの以前の研究が存在するが，これらの研究は，センサノードとコーディネータのみを有する対等システム，または多数のセンサを有するが単一の UP のみを有するシステムとして解析される制約があり，その結果，同じ UP または異なる UP 内のセンサの互い相互影響は考慮されていない．これらの点から，本論文では動的環境における WBAN の MAC 層性能解析のための統計的手法を提案し，パケットの残量や動作時間の変化，パケット到着率の変動，センサ数，ペイロードサイズ，リトライ回数ユーザー優先度レベルまで考慮した解析を可能とする．提案手法は，より柔軟で詳細な解析を可能とすることが期待されている．

さらに，性能解析に加え本論文では誤り訂正符号としての可変符号化率 BCH 符号による WBAN を提案し，適応的な符号化率を有する BCH 符号を用いることでスループットを大幅に改善できることを示す．

結論として，本論文では以下の3つの主要な結果を示した．WBANのMAC層性能解析のためのMCMC法を提案し，さらに先行研究において解析されている結果よりも高いスループットを実現する可変符号化率BDH符号化を提案し，加えてWBANのパフォーマンス分析のための動的な統計的方法を提案した．本論文の手法にはいくつかのドローバックや未解決な課題が残されており，まず提案手法である適応符号化率BCH符号による，システムの複雑化は本論文では議論されていない．第二に，この論文で提案された動的統計的方法は，アルゴリズムの提案にとどまっており，より詳細な解析を要する．本論文の今後の課題として，MCMC法を適応符号化方式を採用した場合のシステムの複雑さやエネルギー消費の変化についてより深く解析しするとともに，本論文において用いたBCH以外の符号化方式にも適用した場合について解析を行う予定である．また動的統計手法の提案では，システムのスループットやエネルギー消費量を算出するためのシミュレーションプログラムを開発し，これまでの解析結果と比較することで提案手法を証明する必要がある．また，2つ目の提案手法については，雑音と干渉を含み且つ動的に変化する現実的な伝送路についてより深く解析し，符号化を含む物理層とのクロスレイヤ解析に基づいてシステムのパラメータの最適化，最適な適応符号化手法の提案と従来手法との比較検討を将来の課題としている．

Chapter 1

Introduction

According to [1,2], the world population estimated in August 2016 was at 7.4 billion and the global population was expected increasingly to reach between 8.3 and 10.9 billion by 2050. While in some developed countries as Japan, Germany and Russia having low birth rate, the elderly people rate is really high. The increasing and aging population has been requiring essential health care in order to guarantee welfare for all people around the world. To develop efficiency health care system is a significantly important issue of all nations, medical organizations and researchers. In order to solve this problem, e-health care system is expected as a potential solution in which wireless body area networks (WBANs) can be considered as a breakthrough.

In 2012, The Institute of Electrical and Electronics Engineers (IEEE) set up the first version IEEE 802.15.6 standard for the WBANs after revising, combining and covering a number of initial research results. In general, the WBANs can be considered as wireless sensor networks (WSNs) in which sensors are distributed through human body to collect vital signal and then transmit to coordinator or center node which combines received signal to transmit to public networks as hospital network, Internet and mobile network. Since producing vital signal, the WBANs produce a wide range application for both medical and non-medical. There are a high number of researches on the WBANs covering overview of the WBANs [6,7,8] and the WBANs standard [4,5], developing MAC protocol for the WBANs [9,10,$\cdots$,14], developing technology for the WBANs as coding or modulation [15,16,17,18], analyzing propagation model of channel where the

WBANs working in [19,20,21,22], implementing the WBANs with the hope of realizing the WBANs sooner in commercial market [23,24,25,26] and analyzing performance of the WBANs and then optimizing parameters to improve the system performance [27,28,$\cdots$,38].

In the final way, there are also many previous works. In order to analyze performance for the WBANs on medium access control (MAC) layer previous works can be clarified into two methods, Markov approach that uses discrete time Markov chain (DTMC) [27,28,$\cdots$,35] and non-Markov approach [36,37,38]. By developing Markov chain to simulate the star topology WBANs, Markov method can analyze MAC protocol of the WBANs obviously and clearly as system working in the real. However, there are some limitations on this approach as most previous works considered system working in the ideal condition with no noise or noise free and no interference. Moreover, previous works usually finished at analyzing performance of system and considered that to evaluate correctly system performance as final target and result.

While previous researches analyzed performance of system on MAC layer, they usually set assumption that the channel is ideal. That seems like normal approach when evaluating MAC layer, the channel should be ideal, meaning that all effects of noise and interference of channel is assumed to be solved or mitigated totally in physical (PHY) layer. In fact, this assumption is not true in the real system. The effects of noise and interference can be mitigated or decreased mainly at PHY layer, however, there is no technique as modulation scheme and coding scheme can solve or mitigate totally the noise and interference, leading to evaluate system on MAC layer with ideal channel obviously produce not correct result. Different from previous work, in this PhD thesis the system performance of the WBANs is analyzed with consideration of non-ideal channel. The thesis analyzed performance of the WBANs on MAC layer, however, considering channel as a real channel with noise and interference and setting bit error rate (BER) or packet error rate (PER) as additional parameters when evaluating system on MAC layer. The thesis method can be considered as cross layer approach and potentially the thesis method can produce more correct result.

However, when non-ideal channel or BER and PER parameters were added in performance analysis on MAC layer, the conventional DTMC method becomes much more complex. In order to solve this problem, the thesis developed Markov chain Monte Carlo (MCMC) method to overcome complexity due to the additional BER and PER parameters, being presented in Chapter 4. In fact, the proposal MCMC method can be considered as development and adjustment of the conventional DTMC method with the key issue is to calculate the access probability approximately.

On the other hand, in the previous works on IEEE 802.15.6, the performance was frequently analyzed by using the access probability to calculate system throughput system and the Markov chain model was proposed to calculate the access probability in saturation or non-saturation conditions. The term saturation means that in this condition sensors always have at least a packet to send and this condition may be relative with really high traffic and packet generation rate while non-saturation condition is relative to low traffic and packet generation rate. Nevertheless, in both saturation and non-saturation conditions, the access probability or packet arrival rate defined as the number of generated packets per second were assumed likely to be fixed or the same for all user priority (UP). Moreover, the effect of remained packets, which are not transmitted because of busy channel or collision, was not considered adequately. These could make previous works meeting with limitations. In order to overcome these limitations, in this thesis, instead of Markov chain model, saturation and non-saturation conditions, the authors used statistical mathematics to calculate the successful probability and the throughput of system, being presented detail in Chapter 5. The proposal method still can give correct result under the time-saturation condition, which can be defined as the connecting condition or the condition takes places between saturation and non-conditions, whereas conventional method could find hard to give correct result. In addition, by taking into account remained packets and analyzing system performance changing following operation time and due to variable packet arrival rate, the number of sensors, payload size, retry limit and user priority levels, the proposal method has been expected to be more flexible and precise.

Moreover, because of considering system on MAC layer under non-ideal channel with BER and PER, the coding scheme is employed. Since the thesis developed cross layer method, after analyzing performance of system, the thesis could optimize Bose-Chaudhuri-Hocquenghem (BCH) code rates and then proposed adaptive BCH code rates for the WBANs, being presented in Chapter 6. The result of thesis states that adaptive BCH code rates can produce significant higher performance for the WBANs. The idea about adaptive code rate is not new. However, there are many previous works on adaptive code rate for other application as in [39,40] focusing on the adaptive BCH code rates for Bluetooth and data compression applications, respectively. The paper [17] proposed the adaptive Reed-Solomon (RS) code rates for the WBANs but in IEEE 802.15.6 this code is not used. The thesis is the really early work proposing adaptive BCH code rates for the WBANs and also proving the higher throughput for the WBANs when this code is employed. Finally, this thesis uses BCH code as an example and the proposal method can be extended potentially for other coding scheme.

In conclusion, the thesis produced three main results, proposing two methods, the MCMC and dynamic statistical method, for performance analysis of the WBANs, and then proposing the adaptive BCH code rates for the WBANs with higher throughput, which was already proved. The thesis still contains drawbacks or unsolved problems. Firstly, the proposal adaptive BCH code may cause system become more complex and how to estimate the condition of channel, and these are not solved yet in the thesis. Secondly, with the proposal dynamic statistical method in this thesis is only finished at algorithm. For the future work of this thesis, the authors hope to apply the MCMC method to other coding schemes with deep analysis of changing the complexity and energy consumption of system when adaptive coding scheme is employed. With the proposal dynamic statistical method, authors need to develop simulation program to produce the throughput or energy consumption of system and compare these with outstanding previous work results to prove the proposal method and then extend the proposal method in the case of real channel under noise and interference condition with deep analysis of these, employing cross layer with coding in order to optimize parameters of system.

The thesis is organized as follows, Fig1.1. Chapter 1 will introduce general view about thesis. Chapter 2 reviews the WBANs with information about structure, application, outstanding technical requirements and review of relative research on the WBANs. Chapter 3 describers shortly about Std. IEEE 802.15.6 in which related standards will be illustrated more detail. Chapter 4 will propose MCMC method for performance analysis of the WBANs in which the conventional methods will be described shortly and the proposal method is expected to overcome limitations of the previous methods. Chapter 5 will propose dynamic statistical method for performance analysis of the WBANs with really new idea about this work on the WBANs MAC layer based on statistical mathematics in which the proposal method is expected to open new algorithm for performance analysis of systems based on carrier sense multiple access with collision avoidance (CSMA/CA). Chapter 6 will propose adaptive BCH code rates for the WBANs that can be considered as a fundamental result of the thesis. Finally, Chapter 7 will conclude the thesis.

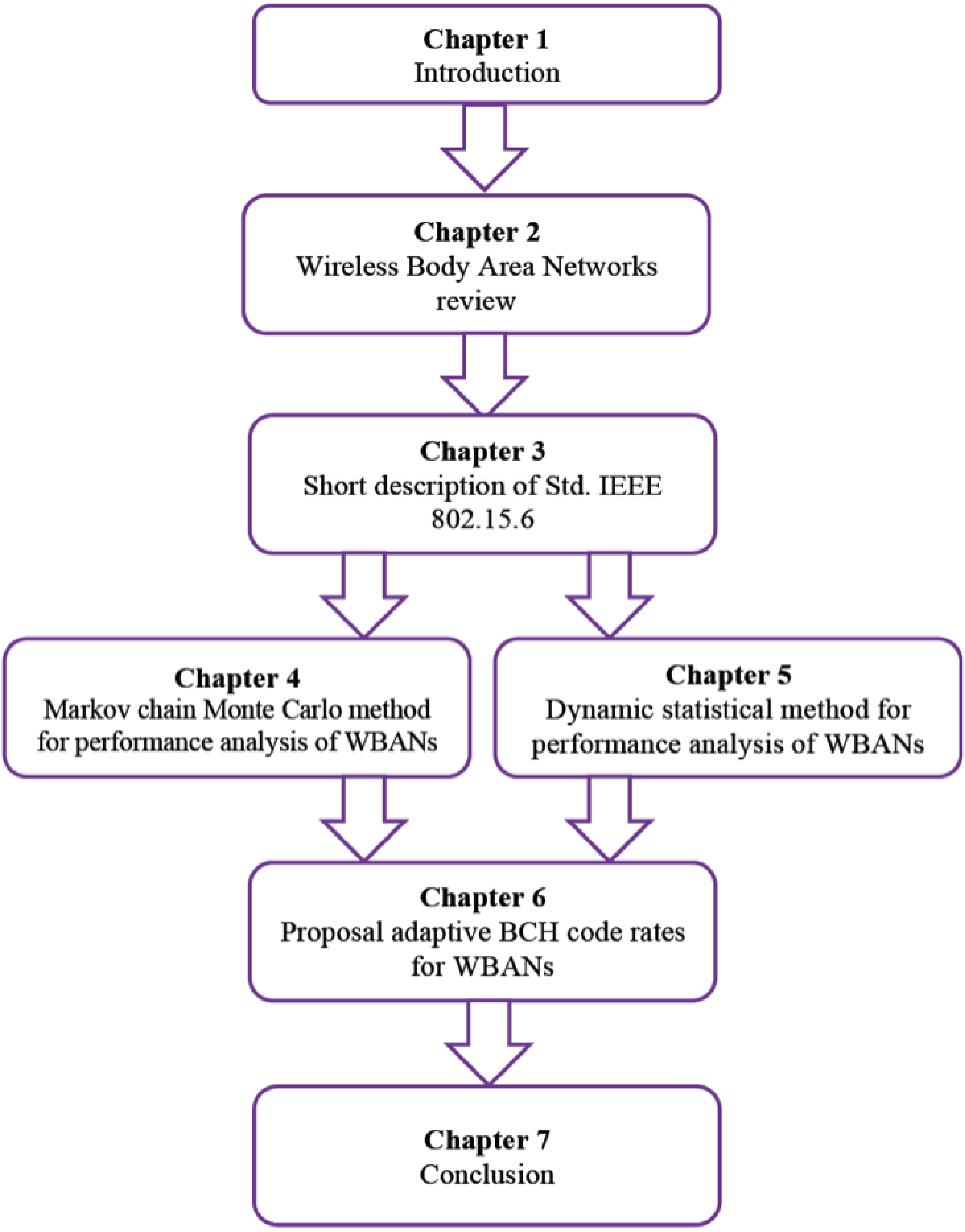

Figure 1.1 The flow chart of this thesis

Chapter 2

Wireless Body Area Networks review

2.1 Structure of WBANs

In fact, the WBANs can be considered as WSNs. The general architecture of the WBAN network has three tiers: Intra-WBAN, inter-WBAN and beyond-WBAN as in Fig. 2.1. Each tier responds for typical tasks, however, when we develop the real WBAN systems we can combine or optimize all devices in the tier for the oriented application WBANs. For example, we can develop a WBAN to collect information about electroencephalography (EEG), electrocardiography (ECG), temperature, peripheral capillary oxygen saturation (SpO2) and blood pressure and then transmit to mobile phone network to emergency, private doctor and family. As a result, we can optimize not only device but also technology as coding scheme, modulation scheme and protocol for the oriented application WBAN.

Firstly, the intra-WBAN communications responds for two types of communications. The first type is the communication between some sensors in the case of multiple hoping as defined in IEEE 802.15.6 maximum multiple hoping is two. The second type is the communication between sensors distributed through body and a portable personal server or device (PS/PD), also called body control unit (BCU), body gateway (BC), central node or coordinator usually set at the center of body. The sensors can be on, near or implanted in the body, and these

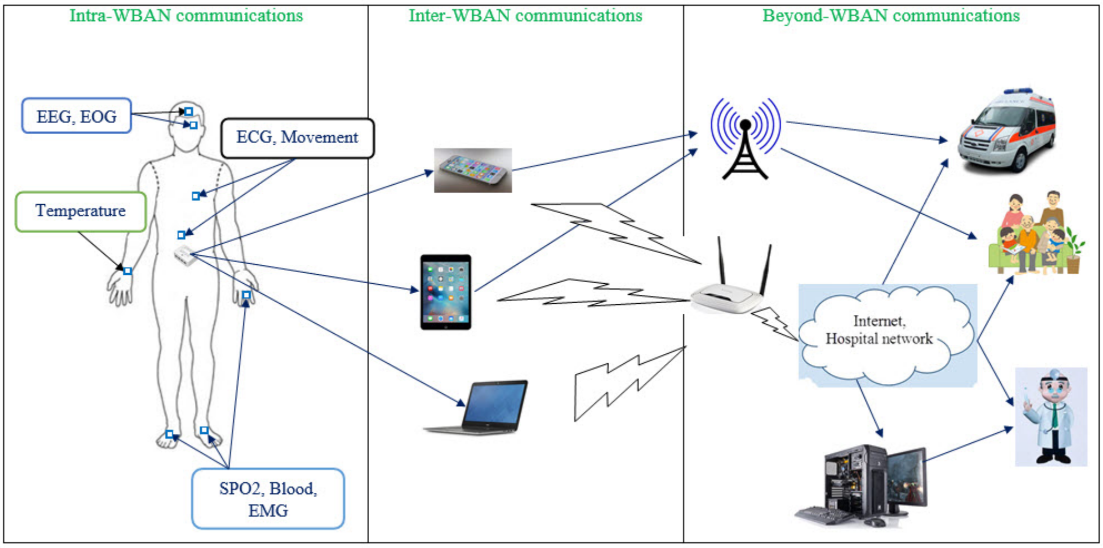

Figure 2.1 Structure of WBANs.

define two types of WBANs, wearable and implantable. There are also two communication directions in this tier, some of sensors only collect data and then process and report the information wirelessly to the portable PD while others not only collect data to transmit to the coordinator but also receive data from the coordinator in order to perform medicine administration based on the information received from other sensors in the same network, through interaction with the user or from professional doctor or emergency. The transmission direction from the coordinator to sensor node may let the WBANs can be applied directly for treatment in medical application.

Secondly, the inter-WBAN communications responds for the communication from the PD to access point or base station. After collecting data from sensors, the coordinator will send this information some devices as mobile, tablet or computer and then this information will be retransmitted to access point or base station to public networks as Internet, hospital network or mobile network.

Finally, the data from the public networks will be sent to emergency center, doctor, family, or medical sever or database. This communications belongs to beyond-WBAN communications. The final tier may be developed basically based on the application and in this tier the private issue is essential due to that the personal information of user is frequently processed and analyzed by human being.

2.2 Application

In this section, the thesis will shortly illustrate many potential applications of the WBANs. The WBANs applications span a wide area such as military, ubiquitous health care, sport, entertainment, solving disaster and many other areas. In the IEEE 802.15.6, the WBANs applications can be categorized into medical and non-medical as can be seen in Table 2.1 [3,7]. In which some implantable and wearable WBANs applications, remote control medical devices and non-medical applications are also defined in this table. Depending on the applications, main characteristics as data rate, power consumption, quality of service (QoS) and privacy are also required, Table 2.2 [3,7].

2.2.1 Medical Applications

As can be seen from Fig.2.2 and Fig.2.3 the WBANs can produce a huge potential to revolutionize the future of health care monitoring by diagnosing a number of life threatening diseases, providing real time patient monitoring and also contributing directly to treatment. According to [1,2], it is predicted that the worldwide population over 65 will have doubled in 2025 to 761 million from the 1990 population of 357 million. As a result, it is true that by 2050 medical aged care will become an essential issue. Moreover, in many dangerous diseases, one of the leading causes of death is related to cardiovascular disease, which is estimated to be as much as 30 percent of deaths worldwide [1,2,7]. In order to solve these, based on advanced information communication technology, the deployment and servicing of health care services will be fundamentally changed and modernized.

Table 2.1 Applications of WBANs.

The WBANs Applications	**Medical**	**Wearable WBANs**	Assessing Soldier Fatigue and Battle Readiness
			Aiding Professional and Sport Training
			Sleep Staging
			Asthma
			Wearable Health Monitoring
		Implantable WBANs	Cardiovascular Diseases
			Cancer Detection
		Remote Control of Medical Devices	Ambient Assisted Living
			Patient Monitoring
			Tele-medicine Systems
	Non-medical		Real Time Streaming
			Entertainment Applications
			Emergency

The use of the WBANs is expected to produce e-health care systems to enable more effective management and detection of diseases, and reaction to crisis rather than just wellness. It is expected that by employing medical applications of the WBANs, we can design the real e-health care systems allowing for continuous monitoring of one ’ s physiological attributes such as EEG, ECG, SpO2, blood pressure, heartbeat and body temperature. For example, in cases where abnormal conditions are detected, this information will be collected by the sensors and then the sensors will send to coordinator, after that the coordinator will transmit this data to mobile phone, tablet or computer and then these devices may retransmit to the public networks as mobile network, Internet or hospital network. Finally, doctor, emergency or family will receive this information and then the intermediate suitable action can be taken. In addition, the WBANs will become a key approach in early diagnosis, monitoring and treatment of patients with possibly fatal diseases of many diseases as diabetes, hypertension, cardio-

Table 2.2 Characteristics of application

Application Type	Sensor Type	Data Rate	Duty Cycle	Power Consumption	QoS	Privacy
Implantable Application	Glucose Sensor	Few Kbps	< 1%	Extremely low	Yes	High
	Pacemaker	Few Kbps	< 1%	Low	Yes	High
	Endoscope Capsule	> 2 Mbps	< 50%	Low	Yes	Medium
Wearable Medical Application	ECG	3 Kbps	< 10%	Low	Yes	High
	SpO2	32 Kbps	< 1%	Low	Yes	High
	Blood Pressure	< 10 bps	< 1%	High	Yes	Medium
Wearable Non-medical Application	Music for Headsets	1.4 Mbps	High	Relatively High	Yes	Low
	Forgotten Things Monitor	256 Kbps	Medium	Low	Yes	Low
	Social Networking	< 200 Kbps	< 1%	Low	Yes	High

vascular related diseases and so on. The medical applications of the WBANs can be further classified into three subcategories as follows.

A. Wearable WBAN applications

Wearable medical applications of the WBANs can further be classified into the following two subcategories as disability assistance and human performance management. Some of these applications are mentioned bellows.

Assessing Soldier Fatigue and Battle Readiness The military field is absolutely special and hard. It is essential if the commander know exactly all activities of his soldiers in the battlefield, which can be monitored and analyzed more clearly by the WBANs. For example, the real typical WBAN systems consisting of cameras, vital sensors, GPS (Global Positioning System) connected with wireless network producing communication between soldiers to other soldiers and head quarter. As a result, the commander will know where his soldiers are and how they are, leading to planning or adjusting campaign more efficiently to achieve victory. However, in order to prevent ambushes, a secure communication channel should exist among the soldiers and the security of the system should be guarantee at really higher level to avoid enemy catching this information. Moreover, the WBANs can be used in harsh environments as for policemen, fire-fighters or solving disaster staff, reducing the probability of injury while providing improved monitoring and care in case of injury in order to make a timely support decision.

Aiding Professional Sport Training The combination of technology and sport may improve the performance of many sports. The training schedules of athletes can easily be tuned via the WBANs as they provide monitoring parameters, motion capture and rehabilitation, producing data to analyze to make adjustment for higher result and performance. Moreover, sport scientists can use the real-time feedback data provided from exercise of the athletes to analyze and allow for performance improvement and prevents injuries related to incorrect training.

Sleep Staging It is obvious that sleep is an important behavior and regular physiological function, and one human being usually spends one-third of everyday life for sleeping. In fact, according to many medical reports, there is large population, an average of 27% of the world population, especially with elderly and staff working in pressure environment, suffering from sleep disorders. A good sleep is essential for all people and at least it can refresh our brain. Such disorders may cause quite severe and lead to cardiovascular diseases, sleepiness at work place and drowsy driving. As a result, sleep monitoring appears as a burning issue and takes the great interest of many sleeping researchers in the recent years. The sleep disorders can be realized through a sleep study test, which requires analysis of a number of bio-potentials and data recorded over night. If we use such system requiring a lot of cables that run from the head to a box connected to the patient ’ s belt and interrupt the patient from falling sleep or the received data may not so correct due to the patient suffered by this system. Moreover, the system also disturbs the motion of patient and initiates artifacts, reducing the signal quality. It is clear that the WBANs can produce an excellent solution to overcome these limitations. In stead of many cables, the WBANs will reduce the effect of device to the patient at lowest level.

Asthma Asthma is a chronic disease involving the airways or bronchial tubes in the lungs, which allow air to come in and out of the lungs. If people have asthma their airways are always inflamed and they become even more swollen and the muscles around the airways can tighten when something triggers symptoms, making difficulty for air to move in and out of the lungs, causing symptoms such as coughing, wheezing, shortness of breath and chest tightness. The WBANs can produce dynamic monitoring allergic agents in the air and providing real time feedback to doctor and family, which can help millions of patients suffering from asthma around the world.

Wearable Health Monitoring It is clear that the WBANs can provide real time health monitoring. For instance, a WBAN with glucose sensor can be used for diabetes patients. The data from such the sensor may be stored or sent to a doctor for analysis to produce efficiency treatment. With high blood pressure patients, it is absolutely dangerous when such the disease acts while the patients are staying alone. If the WBANs are employed, the timely report will be sent to doctors or relatives to support them to ban unwanted results.

B. Implant WBANs

Not only are the WBANs applied for medical monitoring, but they also can be used directly for treatment of some diseases as diabetes, cardiovascular and cancer diseases. This class of applications is base on the implantable WBANs in which sensors are implanted in the body or under skin of human body. For example, the thesis will illustrate how the WBANs can be applied for monitoring and treatment for diabetes disease, which is one type of metabolic diseases in which there are high blood sugar levels over a prolonged period. The symptoms of this disease include frequent urination, increased thirst, and increased hunger. If left untreated, diabetes can cause many complications. According to some medical reports, as of 2015, an estimated 415 million people had diabetes in the world, representing 8.3% of the adult population with equal rates in both women and men. By 2014, it is suggested that the rate would continue to rise, at least doubling a person's risk of early death. From 2012 to 2015, approximately 1.5 to 5.0 million deaths each year resulted from diabetes. In fact, this disease does not cause death directly and fast, however, it brings many uncomfortable and anxious things to patients and they will be no longer happy with meal. Consequently, the global economic cost of diabetes in 2014 was estimated to be $612 billion.

When diabetes patients use the WBAN systems, they will be monitored dynamically all the time. The data from patients will be used to analyze to adjust treatment approach. Moreover, we also can develop some typical sensors implanted in the patient body, which can inject directly insulin to the body based on the received and analyzed information from the patient. In addition with cardiovascular disease and cancer, the implantable WBANs can produce dynamic timely data for doctors to analyze and find out the best treatment solution.

C. Remote Control of Medical Devices

One other class of the WBANs applications is the remote control of medical devices. With the ubiquitous mobile network and Internet connectivity of WBANs allows for networking of the devices and services in home care, which is known as Ambient Assisted Living (AAL) in which the WBANs wirelessly communicates with a back-end medical network. The AAL system aims to pro-

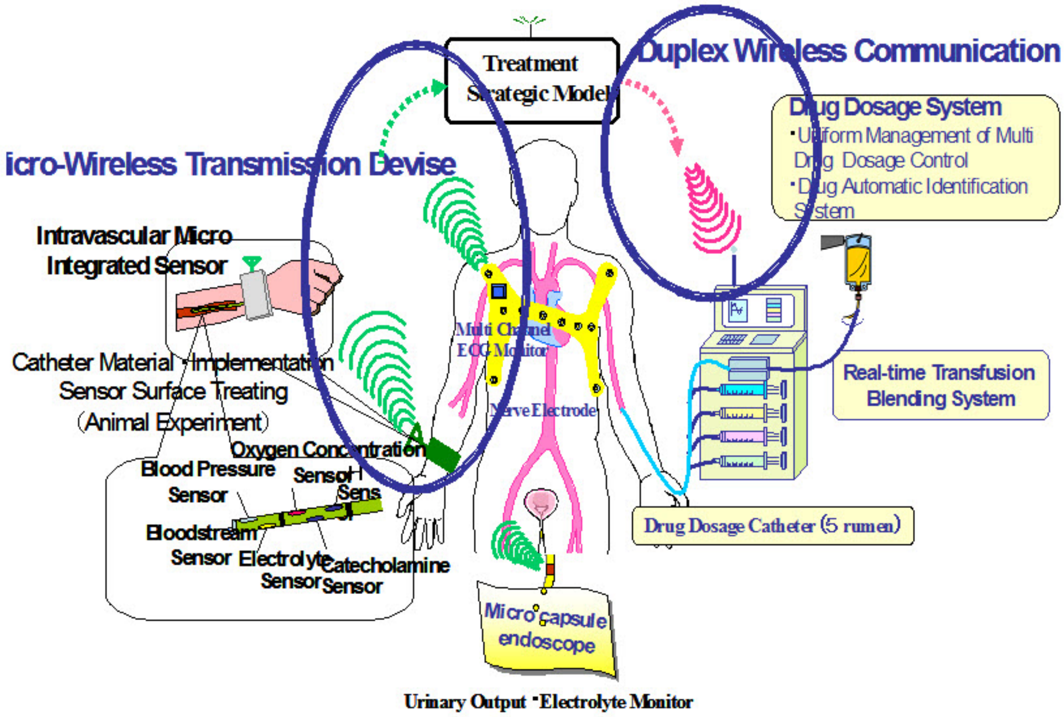

Figure 2.2 Structure and application of WBANs

duce the self-conducted care of patients that are assisted in their home, resulting in minimizing the dependency on intensive personal care, increasing welfare and quality of life, and may decreasing health care costs. In fact, the AAL system is expected to become an efficient e-healthcare system and will replace the conventional and traditional heath care system, which is very expensive and requires many doctors and medical staff. The thesis will shortly illustrate two applications of this class of remote control of medical devices application as patient monitoring and telemedicine systems.

Patient monitoring can be considered as one key application of the WBANs, monitoring vital signals, as well as providing real time feedback and information on the recovery process in health monitoring applications. For example, when the WBANs are employed, many vital signals such as heart rate, body temperature, respiration rate, blood pressure, SpO2, EEG, ECG and so on will be collected and transmit to doctors, hospital and family. The WBANs are

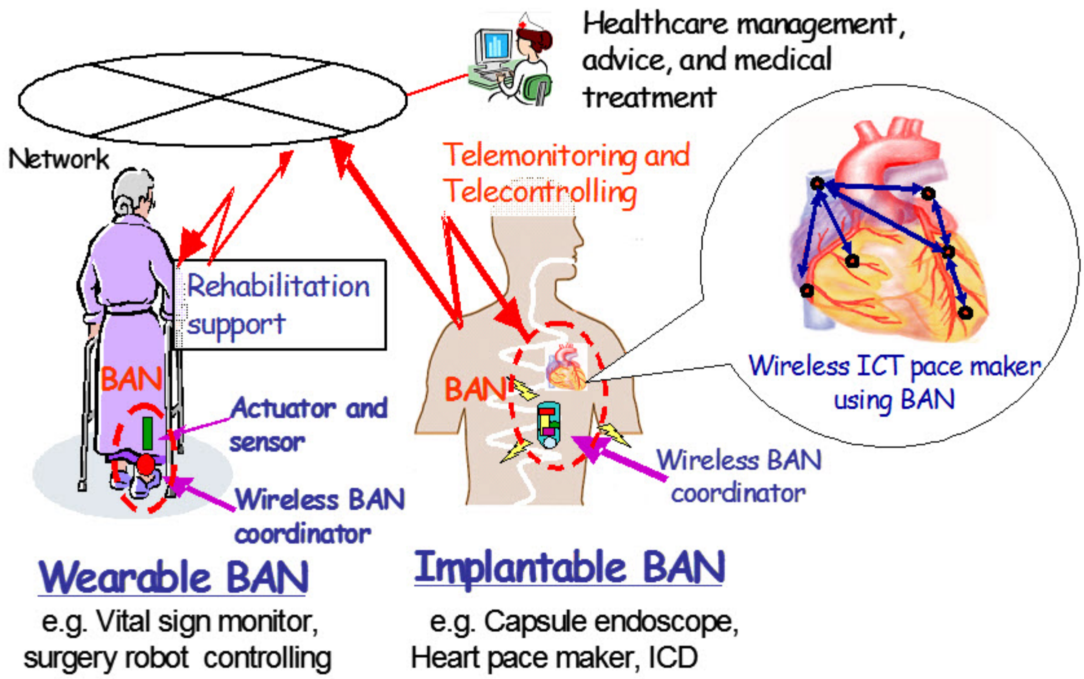

Figure 2.3 Wearable and Implantable WBANs

also used for administration of drugs in hospitals because of bringing remotely monitoring of human physiological data, aid rehabilitation and providing an interface for diagnostics. It is clear that continuous patient monitoring and providing necessary medication when required are considered as an important development field for the WBANs. Because of the WBANs providing an interconnection amongst various devices in, on or around the body such as hearing aids and digital spectacles, we can develop many their applications for patient monitoring, post-treatment follow-up, pharmaceutical research, trauma care, remote assistance in accidents and research in chronic diseases [7,8].

In addition, telemedicine systems either use a power demanding protocol like Bluetooth, however, this is open to interference from other devices working in the same frequency band, or defined wireless channels with own distributed frequency band for transferring information to remote stations. As a result, the systems restrict prolonged monitoring. Whereas integrating WBANs in a telemedicine system allows for long periods of unobtrusive ambulatory health monitoring. In the near future, if we can develop recharging WBAN sensors, which can be made by wireless energy transmission technology or energy harvesting devices that collect energy from various sources, external to the sensors such as inertial energy harvesting devices and thermo-electric devices, the e-telemedicine system will become more efficient and competitive than conventional system.

2.2.2 Non-Medical Applications

A. Real Time Streaming

Not only are the WBANs applied for medical, they are also can be applied for non-medical, real time streaming, entertainment, emergency, emotion detection, and secure authentication. Firstly, class of real time streaming applications consists of video streaming such as capturing a video clip by the camera in a mobile phone, trading shows for sport goods along with the latest fashion designs and three dimensions (3D) video. The WBANs also can produce audio streaming possible through voice communication for headsets for instance listening to explanation of art at the museum and speed in some events or listening to the bus schedule information on the bus stop, multicasting for conference calls, browsing music samples in a music compact disk (CD) store and so on. Moreover, this type of applications also includes stream transfer, which is used for remote control of entertainment devices, body gesture recognition or motion capture for designing some games [7,8].

B. Entertainment Applications

This category consists of gaming applications and social networking. Appliances such as microphones, MP3-players, cameras, head-mounted displays and advanced computer appliances can be used as devices integrated in the WBANs, which produce information from game center or computer center to players while other sensors or devices will illustrate how players are by collecting dynamic data from players to transmit to center. As a result, because of illustrating the real action and motion of players, the WBANs can be used in virtual reality and gaming purposes such as game control with hand gesture, mobile body motion game and virtual world game, personal item tracking, exchanging digital profile, business card and consumer electronics, producing more actual feeling for gamers. For this type of application, the requirement about high data capacity is an essential issue [7,8].

C. Emergency

We also can integrate typical off-body sensors in the WBANs or set up some sensors in the house, which can communicate with the WBANs, are capable of detecting a non-medical emergency such as fire in the home or flammable and poisonous gas in the house and must urgently communicate this data to wearable devices to warn the wearer of the emergency condition. The fire fighters also can use these WBANs to alarm and detect dangers when they solve disasters, which is job and action in really hard and dangerous environment in order to prevent possible accidents.

D. Emotion Detection

By analyzing speed and visual data, recent research has shown the effective realization of human emotions. For example, wearable WBANs have enabled emotion detection through the induction of physical action or the human body, leading to the production of signals to be measured via simple vital sensors. For more detail, by collecting and analyzing many physiological signals as ECG, EEG, electro dermal activity (EAD) and body temperature via the WBANs, the emotion status of a person can be detected and monitored dynamically all the time at anywhere. As a result, a number of applications are proposed.

Firstly, emotion detection provide the data for psychology science by analyzing how humans show universal consistency in recognizing emotions but also show a great deal of variability between individuals in their abilities. Moreover, emotion recognition is used for other variety of reasons, for instance, Affectiva is an emotion measurement technology company using it to help advertisers and content creators to sell their products more effectively and Eyeris is an emotion recognition company that works with embedded system manufacturers including car makers and social robotic companies on integrating its face analytics and emotion recognition software.

E. Secure Authentication

This application of the WBANs relates to utilizing both physiological and behavioral biometrics such as iris recognition, fingerprints and facial patterns. Because of produce absolutely private and outstanding information of a human being, it is easy to detect correctly people when the WBANs are employed. This application may become interesting applications of WBANs due to duplicability and forgery, which has motivated the use of new behaviors and physical characteristics of the human body, in essence multi-modal biometric, gait and EEG. However, when we develop this application, the accompanied privacy issue should be guaranteed.

2.3 Outstanding technical requirements of WBANs

To develop and realize the WBANs in the real world is a challenging and really complex task because of the broad range of requirements accompanied by the applications described above. The most essential requirements, as recommended by the IEEE 802.15.6 standard, are illustrated in this section.

2.3.1 Bit rate and Quality of Service

Depending on the applications and on the type of data to be transmitted, the bit rate, delay and BER requirements change on a very broad range. With bit rate requirement, it goes from less than 1 kbps (Glucose level monitor) to 10 Mbps (Video streaming). This can be explained as, for some applications

Table 2.3 Requirements for applications.

Application	Bit rate	Delay	BER
Deep brain stimulation	< 320 kbps	< 250 ms	$< 10^{-10}$
Drug delivery	< 16 kbps	< 250 ms	$< 10^{-10}$
Capsule endoscope	1 Mbps	< 250 ms	$< 10^{-10}$
ECG	192 kbps	< 250 ms	$< 10^{-10}$
EEG	86.4 kbps	< 250 ms	$< 10^{-10}$
EMG	1.536 Mbps	< 250 ms	$< 10^{-10}$
Glucose level monitor	< 1 kbps	< 250 ms	$< 10^{-10}$
Audio streaming	1 Mbps	< 20 ms	$< 10^{-15}$
Video streaming	< 10 Mbps	< 100 ms	$< 10^{-3}$
Voice	50 - 100 kbps	< 100 ms	$< 10^{-3}$

such as glucose level monitor or drug delivery, there is few information while for some applications as video streaming game high data capability is a key issue. About, delay requirement, the entertainment applications such as audio streaming, video streaming and voice are likely to require low delay, under 100ms, while medical applications allow higher delay, under 250ms. On the other hand, the BER requirement is different from delay requirement. With medical applications such as deep brain simulation, drug delivery, capsule endoscope, glucose level monitor, ECG, EEG and EMG require absolutely low BER, under 10^{-10}, while entertainment applications as audio streaming, video streaming and voice require higher BER, under 10^{-5}. It is obvious that medical applications require extremely low BER due to it affects directly to human health and disease treatment. Table 2.3 [8] reports a list of requirements for the different WBAN applications.

2.3.2 Power Consumption

The power consumption requirement is a fundamental issue of the real WBANs. For the real WBAN systems, the sensors, which are distributed through or implanted in the body of human being, should be absolutely thin and they should work for long time, at least few years. Consequently, these sensors have to consume as low as possible power while they have to guarantee enough SNR for coordinator can detect signal. Moreover, if the sensors consume lower power, the effect of signal to the body will lower, meaning that it is safer for user. In order to reduce power consumption, there are some solutions.

Firstly, we should design ultra-low power transceivers and receivers as well [23,24]. In addition, many proposal MAC protocols [9,⋯,14] and many technologies as coding scheme and modulations scheme [15,16,17,18] with key ideal is low power consumption were developed. In short, ultra-low power design for radio transceivers and power-wise MAC protocol design is fundamental. A potential technique for power-wise MAC protocol at the expense of end-to-end delay is lowering the duty cycle, allowing devices to be in sleep mode for most of the time. This approach may be efficient for applications requiring infrequent transmissions, however, there is a trade-off between delay and power consumption, meaning that with this approach power consumption is reduced but delay may increase.

2.3.3 Safety

Since the WBANs consist of many sensors that are worn or implanted in the body of human being, they should be very safe for user. It is clear that these sensors will affect to human tissues including heating effect. As a result, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) specifies general restrictions and limits that the WBANs have to guarantee health safety when the user is exposed to dynamic electromagnetic fields. For example, with frequency band from 100 kHz to 10 GHz such restrictions are established in terms of Specific Absorption Rate (SAR). The SAR is defined as a measure of the rate at which energy is absorbed by the human body when exposed to a radio frequency (RF) electromagnetic field. For detail, it is measured as the power absorbed per mass of tissue and has units of watts per kilogram (W/kg). For designing hardware such as transceiver or antenna for the WBANs, the SAR index is a fundamental requirement. As a result, there are some international or regional SAR regulations for the WBANs and other systems (such as those defined by the European Union for Europe and by the Federal Communications Commission (FCC) for USA).

2.3.4 Antenna and Propagation

Designing antenna for the real WBANs is a really hard task. The fundamental requirements for the WBANs antenna are small and safe for human while it have to guarantee enough SNR and transmit signal via unstable channel. In the WBANs scenarios diversity is really important, which is explained as that the continuously moving human body may shield or block a single channel of wave propagation. There are three types of diversity, which can be clarified as space diversity, pattern diversity and polarization diversity. Depending on the limited space on or around a human body, space diversity may be more difficult to implement in some cases. The WBANs usually require a low-power antenna, so a patch antenna or a horizontal dipole or monopole antenna with a reflector can be used to generate the two horizontal polarizations. As a result, some new designs for antenna were proposed [25,26]. Furthermore, a correct radio channel characterization is also mandatory in order to design an antenna able to provide the proper radiation properties. Many types of channel were defined in the IEEE 802.15.6 such as channel for communication from inside to on, from inside to inside and on to outside of the body. The impact of radio channel on network performance and the analysis of characterization of channel were explored in [19,20,21,22].

2.3.5 Coexistence

The coexistence is other important requirement of the WBANs. In fact, the WBANs were proposed recently and how these systems works with other conventional systems is essential. For example, some WBANs were designed to operate in the license-free of the industrial, scientific, and medical radio (ISM) band centered at 2.45 GHz. It is obviously that this band is an overcrowded radio band, in which there are some traditional systems as Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15.1), IEEE 802.15.4, ZigBee and others operating in this band. All WBAN medical applications require really high dependability and stability, especially when an emergency or alarm traffic has to be established, consequently, techniques to avoid, reduce or mitigate interference should be studied proposed and implemented.

2.3.6 Signal processing

In the WBAN systems, there are many types of sensors which collect many different types of signal such as EEG, ECG, SpO2, body temperature, heartbeat and so on. While the WBAN applications are power consumption limited and the radio circuits are often the power greedy part of the system, such many types of signal require more efficient signal processing techniques. In fact, efficient signal processing techniques can keep under control the power consumption related to the acquisition and analysis of the vital signals. For example, compressed sensing (CS) is a potential solution because it allows to sample sparse analogue signal at a sub-Nyquist rate, leading to save energy while keeping the information contained in it. The CS technique may be applied to some WBAN scenarios such as EEG, ECG and EMG, in which many previous research results stated that energy consumption is reduced by decreasing the amount of information transmitted using CS to compress data up to a factor. However, an efficient signal processing for the WBAN hardware does not mean as a complex signal processing technique, which may require more power consumption due to CPU has to perform more task. As a result, developing and proposing an efficient but simple signal processing technique is an essential work for researchers and engineers.

2.3.7 Security

Since the WBANs collect, process and transmit private information of user, the security issue should be guaranteed at high level. Especially, for some applications for army or military field, if the security is not performed totally and then the enemy may receive the transmitted data, the following consequence is unpredicted. Furthermore, developing high secure level encryption algorithms may conflict with many hard requirements of the WBANs in terms of power consumption, memory, communication rate and computational capability as well as inherent security vulnerabilities, resulting in the security specifications proposed for other networks and applications are not suitable with the WBANs. Some secure issues proposed for the WBANs are illustrated as follows [7,8].

Secure Management The protocol to provide and share key between coordinator and sensor nodes in the WBAN systems should be defined. The decryption and encryption operation requires secure management at the coordinator or center node in order to provide key distribution to the sensor nodes. In order to manage the key, the center node will add and remove the sensor nodes in a secure manner during association and disassociation.

Availability While we have to keep very high secure level, the availability of the patient ’ s information to the defined doctor needs to be ensured at all the time. This means that the defined received objects as doctor, emergency center and family can receive information from user at any time. If there is an attack towards availability in the WBANs could be capturing and disabling an ECG node, leading to unpredicted consequence or even though loss of life. From these points, the operation, maintenance and capability to change or switch to another WBAN in case of availability loss is required.

Data Authentication The data authentication is required for both medical and non-medical applications of the WBANs. In the WBAN systems, both the sensor nodes and the coordinator require verification that data which is transmitted from the trust center and not a false adversary. In order to perform this task, the sensor nodes and the coordinator will compute a message authentication code (MAC) for all data by sharing a secret key and then if the correct MAC is calculated, the coordinator will recognize that the received data is transmitted from the trust center.

2.4 Review of relative research on the WBANs

In recent years, the WBANs have appeared as a burning issue. The WBANs were proposed because of the necessity of monitoring health situations, and hence the standard IEEE 802.15.6 for the WBANs was established in Feb 2012. There are a high number of researches on the WBANs covering overview of the WBANs standard and the general WBANs overview [4,5,6,7,8], developing MAC protocol for the WBANs [9,10,$\cdots$,14], developing technology for the WBANs as coding or modulation [15,16,17,18], analyzing propagation model of channel where WBANs working in [19,20,21,22], implementing the WBANs with the hope of realizing the WBANs sooner in commercial market [23,24,25,26] and analyzing performance of the WBANs based on Markov chain [27,27,$\cdots$,35] or non-Markov chain [36,37,38]. In this thesis a survey of researches on the WBANs was conducted, especially, the closely relative researches were illustrated more detail to illustrate which remained problems are solved in this thesis.

A. Overview of the WBANs [4,5,6,7,8]

These previous works provide surveys on the WBANs in order to produce wide range information, including their applications and standard technologies, the main features and challenges in their design and the possible future research directions. After the definition of the WBANs standard, main applications and requirements, the standard solutions identified are illustrated and compared through the introduction of some case studies. Particular attention is paid to the IEEE 802.15.6 standard, being optimized for low power devices and operation on, in or around the human body. Moreover, the papers presents some insights with reference to the main issues identified above, by introducing other case studies, with the aim of showing the impact on the WBAN performance of some key factors to be addressed in the design, as the impact of the radio channel, the energy consumption and the coexistence with external interfering networks.

B. Developing MAC protocol for the WBANs [9,10,⋯,14]

In these works, the authors proposed some protocol in order to reduce power consumption, handoff delay. For example, in [9], all the sensors are in standby or sleep mode until the centrally assigned time slot to reduce energy consumption. When a sensor joins network, there is no possibility of collision within a cluster as all communication is initiated by the central node and is addressed uniquely to a slave node. For avoiding collisions with nearby transmitters, a clear channel assessment algorithm based on standard listen-before-transmit (LBT) is proposed. Moreover, to further reduce the handoff delay and signaling cost, an enhanced group mobility scheme is proposed in [12] to reduce the number of control messages, including router solicitation and router advertisement messages as opposed to the group-based proxy mobile IPv6 protocol.

C. Developing technology for the WBANs [15,16,17,18]

In these works, many modulation and coding schemes were proposed to improve the system performance. In the paper [15], an iterative demodulation and decoding receiver for M-ary differential chaos shift keying (DSCK) modulation is proposed over Additive White Gaussian Noise (AWGN) channel. The Log-Likelihood Ratios (LLRs) of coherent DCSK demodulator and decoder are derived assuming that its perfect carrier synchronization happened. In the paper [17], the RS coding scheme was proposed to avoid severe noise level surrounding the human body.

D. Analyzing propagation model of channel [19,20,21,22]

In these works, authors investigated deeply about the characteristic of channel where WBANs working in. For example, in [19] wave propagation in the WBANs is analytically modeled as a polarized point source close to an elliptic lossy dielectric cylinder. By employing the Fourier transform (FT) along the axes, the expansion in terms of Mathieu functions in cross section, and the impedance boundary condition (IBC) on surface, the field distribution outside the cylinder can be formulated. In [21] the propagation models for IEEE 802.15.6 of implant communication is analyzed and then proved by experiment.

E. Implementing the WBANs [23,24,25,26]

With the purpose realize the WBANs in the real world, many works focused on implementation for the WBANs. In this trend, researchers hoped to design low power consumption transmitters and receivers and antenna for the WBANs, which can be considered as the most difficult tasks of the real WBANs system.

F. Analyzing performance of the WBANs based on Markov chain [27,27,$\cdots$,35]

By employing DTMC model, many previous works can illustrate the state of all sensor in WBANs or simulate how sensors working and affecting together in the system. As a result, previous works can calculate the access probability of all sensors and then calculate throughput and energy consumption or delay and consider these as final results. After reviewing carefully previous works, the authors of the thesis found out limitations as frequent assuming that channel is ideal and finishing such at analyzing, not optimizing or proposing any new technology, protocol and system. In order to overcome these limitations, the thesis developed MCMC method to analyze performance of the WBANs under non-ideal channel by taking into account BER and PER. The MCMC method can be considered as development or adjustment of the DTMC method with key idea is to find the access probability approximately. Moreover, not finishing at analyzing performance, the thesis propose adaptive BCH code rates for the WBANs and the thesis also proved that this adaptive code can produce significantly higher throughput for the WBANs.

G. Analyzing performance of the WBANs based on non-Markov chain [36,37,38]

The DTMC method consists of method limitations as using assumption like saturation condition and non-saturation condition, and not taking into account remained packets. The saturation condition in this thesis can be explained as if a sensor in WBANs always has a packet to send or in its UP queue there is always a packet waiting to be served, the sensor is saturated. In fact, saturation condition is likely to be relative with high traffic. The remained packets are the packets transmitted unsuccessfully due to collision or error. As a result, there are some previous works on MAC layer for WBANs not using the DTMC method [36,37].

However, these works have limitations as consideration system having only a sensor node and a coordinator [36], or system with many sensors but only single UP, consequently, the effect each other of sensors in the same UP or different UPs is not taken into account. From these points, the thesis proposed dynamic statistical method for performance analysis WBANs on MAC layer [37], taking into account remained packets and analyzing system performance changing following operation time and due to variable packet arrival rate, the number of sensors, payload size, retry limit and user priority levels. The proposal method has been expected to be more flexible and precise.

Chapter 3

Short description of Std. IEEE 802.15.6

3.1 PHY layer

The physical layer is primarily responsible for establishing a reliable and physical link to transmit binary data. In simple terms, the physical layer protocol is an agreement between receiver and transmitter or other equipment. The IEEE802.15.6 standard [3] not only provides an international standard for the WBANs, but also gives an opportunity for the development of the WBANs. This section will work for the operation bands, channels, modulation and demodulation, structure of data units. And the three physical layers, Ultra Wideband (UWB), Human Body Communication (HBC) and Narrow Band (NB) are introduced respectively as follows. In which the relative standard as narrow NB and BCH code will be described more detail.

3.1.1 UWB PHY layer

The design and construction of the UWB PHY layer is not only in order to improve the robustness of the WBANs, but also provides opportunities for implementation of high performance, low complexity and low energy consumption. There are two different types of UWB technologies included in the UWB PHY defined in the IEEE 802.15.6, impulse radio UWB (IR-UWB) and ultra wideband frequency modulation (FM-UWB). The specification defines two modes of

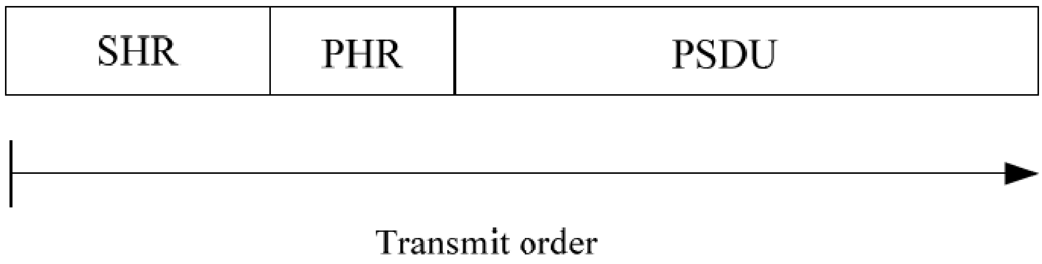

Figure 3.1 The structure of UWB PPDU

operation such as default mode and high quality of service (QoS) mode.

In the UWB PHY layer, the standard defines 11 channels, and the channels are numbered from 0 to 10, in which each channel bandwidth is 499.2 MHz. These channels are clarified into two frequency bands as low band and high band. The low frequency band consists of three channels (channel 0 - 2), whose center frequencies are 3494.4 MHz, 3993.6 MHz and4492.8 MHz. In addition, the channel 1 is mandatory while the other channels are optional. On the other hand, the high frequency band consists of eight channels(channel 3 - 10), whose center frequencies are 6489.6 MHz, 6988.8 MHz, 7488.0 MHz, 7987.2 MHz, 8486.4 MHz, 8985.6MHz, 9484.8 MHz and 9984.0 MHz, in which the channel 6 is mandatory and the others are optional.

The UWB PPDU is formed by combination of the preamble synchronization header (SHR), physical layer header (PHR) and physical layer service data unit (PSDU), which is illustrated as in Fig.31 [3]. In comparison with NB PHY layer, the length of the UWB PHY layer frame is 24 bits and it is added HARQ mechanism. Some parameters of the UWB PHY layer is represented as in Table 3.1 [3,4].

3.1.2 HBC PHY layer

Distributed at the lowest frequency band in PHY layer of the IEEE 802.15.6 is the HBC PHY. The HBC is also defined as Electric Field Communication (EFC) in many previous literatures, in which the EFC is the basic of physical

Table 3.1 Parameters of UWB PHY

Operation Modes	PHY	Data rate (kbps)	Modulation	Operation Band
Default	IR-UWB	487.5	On-off keying	Low band High band
	FM-UWB	250	CP-BFSK FM-UWB	High band
QoS	IR-UWB	487.5	DPSK	Low band High band

realization. Because of working with electric field not electromagnetic field, its transmitter is implemented with only digital circuits and needs one electrode, instead of antenna. The implementation and design of the receiver need none RF modules, which makes equipment easy to carry, leading to really low energy consumption.

In the standard, the band of operation is centered at 21MHz, data rates distributed in 164.1kbps, 328.1kbps, 656.3kbps, or 1312.5kbps respectively. The HBC PHY layer packet frame format is illustrated as in Fig. 3.2, which is composed of the PLCP Preamble, the Start Frame Delimiter (SFD), the PLCP Header and the PHY Payload (PSDU). The preamble and SFD that are transmitted before PSDU while SFD or rate indicator (RI) field is used as start frame delimiter (SFD) non-burst packet or is used as the RI for burst packet.

3.1.3 NB PHY layer

In the thesis, we analyze the WBAN systems based on NB PHY layer, so this type of PHY layer will be represented more detail. In the IEEE 802.15.6, the NB PHY layer is optional and responds for the following tasks such as activation and deactivation of the radio transceiver, clear channel assessment (CCA) within the current channel and data transmission and reception.

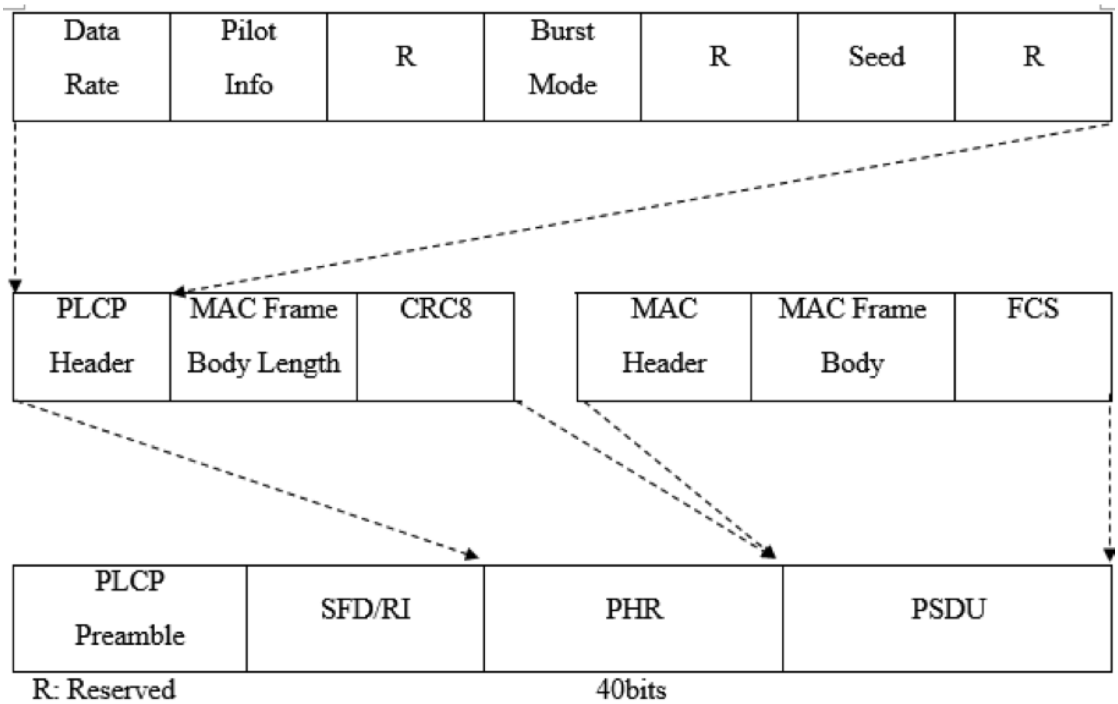

Figure 3.2 HBC PPDU structure

This NB PHY layer also provides an approach for transforming a physical-layer service data unit (PSDU) into a physical-layer protocol data unit (PPDU). In the transmission duration, the PSDU should be pre-appended with the physical layer preamble and the physical layer header in order to create the PPDU. After that, the physical layer preamble and physical layer header serve as aids in the demodulation, decoding and delivery of the PSDU at the receiver side. The PSDU, PPDU, physical layer convergence protocol (PLCP) preamble, PLCP header and PHY header will be illustrated detail in the following sections.

A. PPDU

Figure 3.3 [3] shows the format for the PPDU consisting of three main components such as the PLCP preamble, the PLCP header and the PSDU. These components are listed in the order of transmission.

Firstly, the PLCP preamble is the first component of the PPDU. The use of the preamble is to aid the receiver during timing synchronization and carrier-offset recovery.

Secondly, the PLCP header is the second main component of the PPDU. The use of the PLCP header is to convey the necessary information about the PHY parameters to aid in the decoding of the PSDU at the receiver side. Moreover, the PLCP header also can be further decomposed into the RATE, the LENGTH, the BURST MODE, the SCRAMBLER SEED, the reserved bits and the header check sequence (HCS), and BCH parity bits. Since the BCH parity bits are added, the robustness of the PLCP header is improved. The PLCP header will be transmitted depending on the given header data rate in the operating frequency band.

Finally, the PSDU is the last component of the PPDU. The PSDU is formed by combination of the MAC header with the MAC frame body and the frame check sequence (FCS). Before being scrambled, the PSDU may be encoded and spread or interleaved. The PSDU shall be transmitted depending on one of the data rates available in the operating frequency band as defined in the standard.

If the packet is transmitted, the first part, which is sent, is the PLCP preamble, followed by the PLCP header and finally the PSDU. All multiple octet fields shall be transmitted with least significant octet first and each octet shall be transmitted with the least significant bit (LSB) first.

In the PHY layer, a compliant device shall be available to support transmission and reception in at least one of the following frequency bands: 402 MHz to 405 MHz, 420 MHz to 450 MHz, 863 MHz to 870 MHz, 902 MHz to928 MHz, 950 MHz to 958 MHz, 2360 MHz to 2400 MHz, and 2400 MHz to 2483.5 MHz as shown in Table 3.2, Table 3.3 and Table 3.4 [3].

B. PLCP preamble

In order to aid the receiver in packet detection, timing synchronization and carrier-offset recovery, the PLCP preamble is added prior to the PLCP header. In the NB PHY layer, there are two unique preambles are defined in order to mitigate false alarms due to networks operating on adjacent channels. In the standard, each preamble is constructed by concatenating a length-63 m-sequence

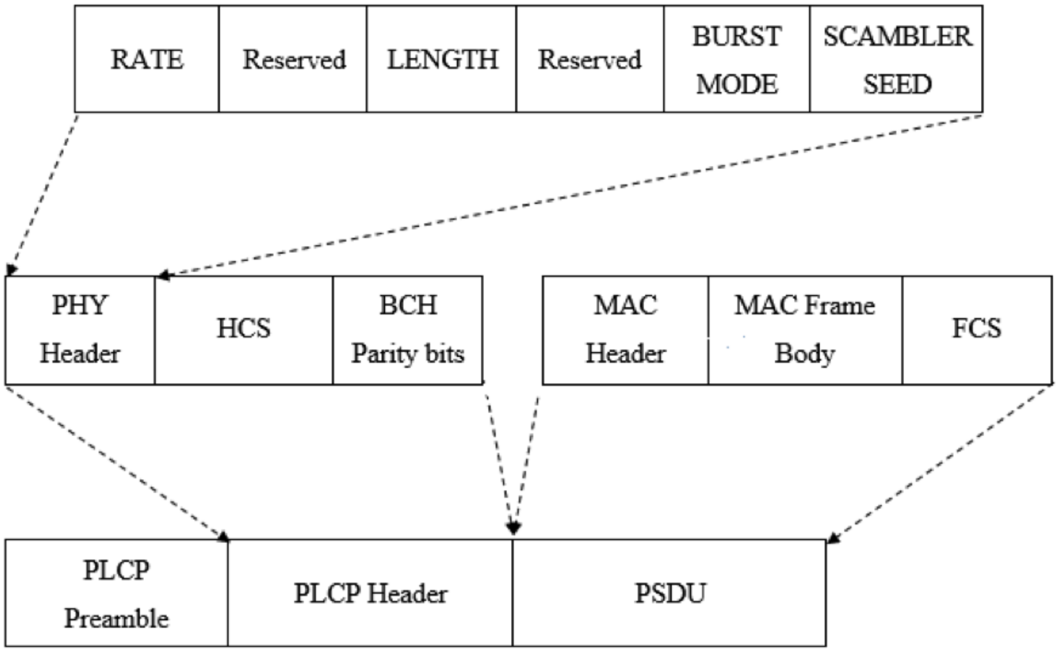

Figure 3.3 NB PHY layer PPDU

with a 0101010101011011011011011011 extension sequence, consequently, the length of the two preamble is the same as 90 bits. The preamble sequence #1 can be used to implement packet detection, coarse-timing synchronization, and carrier-offset recovery, while the preamble sequence #2 can be used to implement fine-timing synchronization.

The two preamble sequences are illustrated in Table 3.5 [3]. The preambles shall be transmitted at the symbol rate for the desired band of operation and shall be encoded using the same modulation scheme and parameters as being denoted for the PLCP header in the Table 3.2, Table 3.3 and Table 3.4.

C. PLCP header

After the PLCP preamble, the PLCP header shall be added in order to convey information about the PHY parameters, which is needed at the receiver for decoding the PSDU. The length of the PLCP header is 31 bits and the PLCP header shall be built for transmission as shown in Figure 3.4 [3].

D. PHY header

Table 3.2 Modulation parameters for PLCP header and PSDU in 402 MHz to 450 MHz

Packet component	Modulation (M)	Symbol rate $= 1/T_s$ (ksps)	Code rate (k/n)	Spreading factor (S)	Pulse shape	Information data rate (kbps)	Support
402 MHz – 405 MHz							
PLCP header	π/2-DBPSK ($M = 2$)	187.5	19/31 [a]	2	SRRC	57.5	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	187.5	51/63	2	SRRC	75.9	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	187.5	51/63	1	SRRC	151.8	Mandatory
PSDU	π/4-DQPSK ($M = 4$)	187.5	51/63	1	SRRC	303.6	Mandatory
PSDU	π/8-D8PSK ($M = 8$)	187.5	51/63	1	SRRC	455.4	Optional
420MHz – 450 MHz							
PLCP header	GMSK ($M = 2$)	187.5	19/31 [a]	2	0.5	57.5	Mandatory
PSDU	GMSK ($M = 2$)	187.5	51/63	2	0.5	75.9	Mandatory
PSDU	GMSK ($M = 2$)	187.5	51/63	1	0.5	151.8	Mandatory
PSDU	GMSK ($M = 2$)	187.5	1/1	1	0.5	187.5	Optional

[a] BCH (31, 19) code is a shortened code derived from a BCH (63, 51) code.

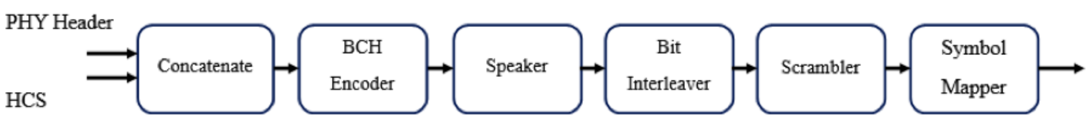

Figure 3.4 PLCP header construction for transmission

In the NB PHY layer, the PHY header consists of information about the data rate of the MAC frame body, the length of the MAC frame body, which does not include the MAC header or the FCS, and information about the next packet whether it is being sent in a burst mode. In addition, the PHY header field shall be consisted of 15 bits, numbered from 0 to 14 as illustrated in Figure 3.5 [3]. The role of these bits will be illustrated as follows.

The first three bits, bit 0 to 2, shall encode the RATE field, which consists of the information about the type of modulation, the information data rate, the pulse shaping, the coding rate and the spreading factor used to transmit the

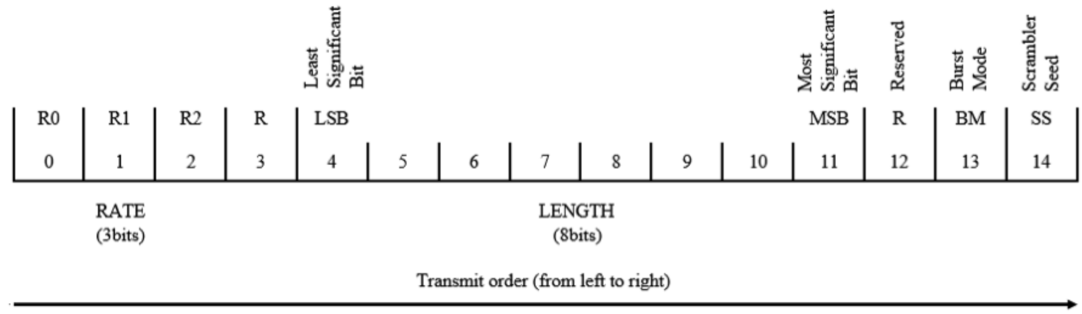

Figure 3.5 PHY header

PSDU. In addition, bits 4 to 11 shall encode the LENGTH field, with the LSB being transmitted first. With the two final bits, bit 13 shall encode whether or not the packet is being transmitted in the burst mode while bit 14shall encode the scrambler seed. In the standard, all other bits that are not yet defined in this clause shall be understood to be reserved for future use and shall be set to zero.

E. D-PSK modulation

The differential phase shift keying (D-PSK) is given as Table 3.6

3.1.4 BCH coding scheme

In the NB PHY layer, the BCH coding scheme is used in some scenarios. In order to improve the robustness of the PLCP header, it shall use a systematic BCH $(31, 19, t = 2)$ code, which is a shortened code derived from a BCH $(63, 51, t = 2)$ code by appending 32 zero (or shortened) bits to the 19 information bits as shown in Figure 3.6 [3]. However, in the case of encoding for the PSDU, a code rate of 51/63 shall be supported by the systematic BCH encoder as shown in Figure 3.7 [3].

The generator polynomial for a systematic BCH (63, 51, t = 2) code, where t is the number of bit errors that can be corrected, is given by Equation (3–1)

$$g(x) = 1 + x^3 + x^4 + x^5 + x^8 + x^{1}0 + x^{12} \tag{3–1}$$

The parity bits are determined by computing the remainder polynomial r(x) as

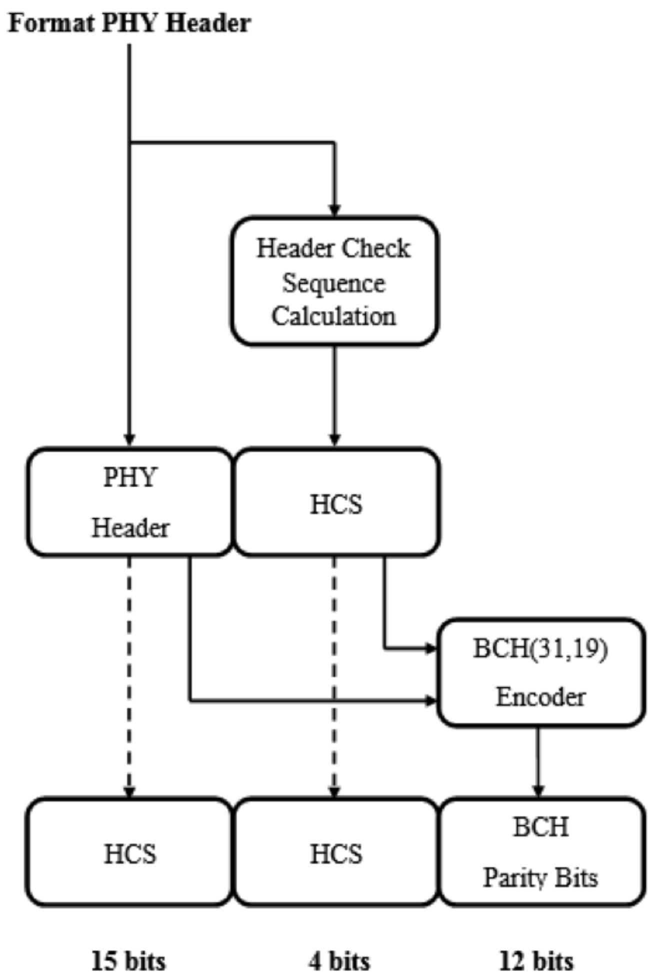

Figure 3.6 BCH coding scheme for PLCP header

shown in Equation (3–2):

$$r(x) = \sum_{i=0}^{11} r_i x_i = x^{12} m(x) g(x) \tag{3–2}$$

where $m(x)$ is the message polynomial shown in Equation (3–3):

$$m(x) = \sum_{i=0}^{50} m_i x^i \tag{3–3}$$

Here r_i, $i = 0, \ldots, 11$ and m_i, $i = 0, \ldots, 50$ are elements of Galois field (2) $(\mathbf{GF}(2))$. The message polynomial $m(x)$ is created as follows: m_{50} is the first bit of the message to be transmitted and m_0 is the last bit of the message, which may be a shortened bit. The order of the parity bits is as follows: r_{11} is the first parity bit

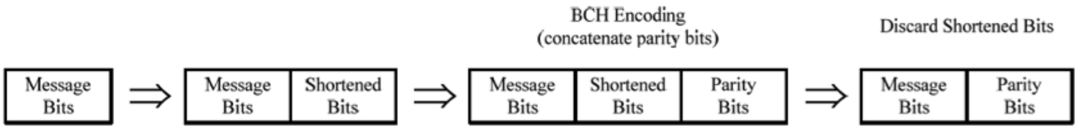

Figure 3.7 BCH encoding process for a single codeword.

transmitted, r_{10} is the second parity bit transmitted, and r_0 is the last parity bit transmitted.

3.2 MAC layer

In the standard IEEE 802.15.6 for the WBANs, the entire channel is divided into superframe structures in which each superframe is bounded by a beacon period of equal length. The hub will select the boundaries of the beacon period and after that select the allocation slots. Moreover, the hub may also shift the offsets of the beacon period. In the standard, the beacons are transmitted in each beacon period except in inactive superframes or unless prohibited by regulations such as in medical implant communication service (MICS) band. The IEEE 802.15.6 network operates in one of the three modes, beacon mode with beacon period superframe boundaries, non-beacon mode with superframe boundaries and non-beacon mode without superframe boundaries. The detail of these modes is illustrated as follows.

3.2.1 Beacon mode with beacon period superframe boundaries

In this mode, the beacons are transmitted by the hub in each beacon period except in inactive superframes or unless prohibited by regulations. The Figure 3.8 [3] shows the superframe structure of the IEEE 802.15.6, which is divided into Exclusive Access Phase 1 (EAP1), Random Access Phase 1 (RAP1), Type I/II phase, Exclusive Access Phase 2 (EAP 2), Random Access Phase 2 (RAP 2), Type I/II phase, and a Contention Access Phase (CAP).

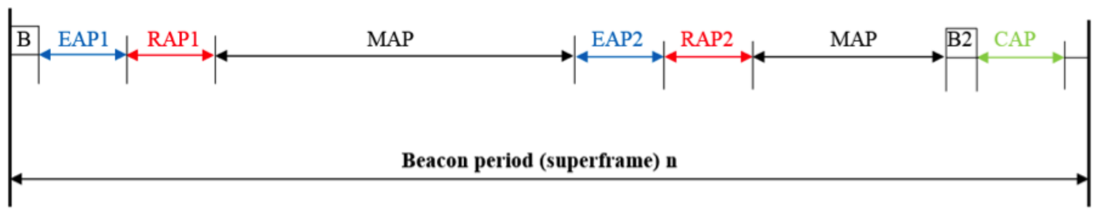

Figure 3.8 Layout of access phases in a beacon period (superframe) for beacon mode

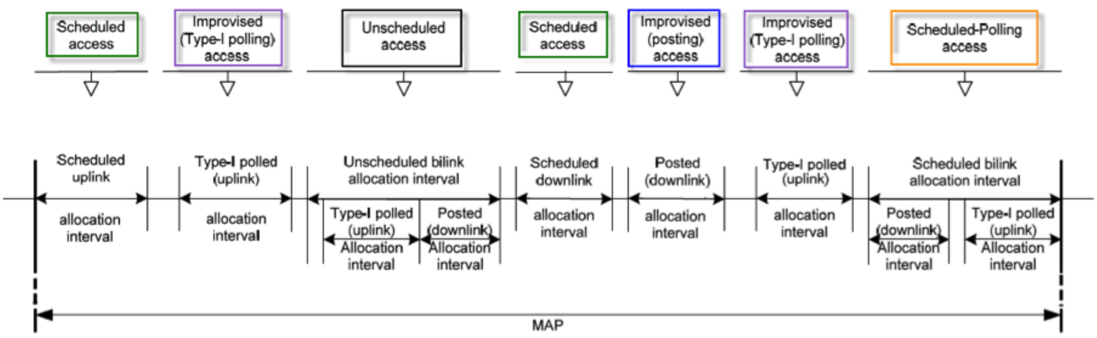

Figure 3.9 Allocation intervals and access methods permitted in a managed access phase

In EAP, RAP and CAP periods, sensor nodes contend for the resource allocation using either the CSMA/CA or the slotted Aloha access procedure. While the EAP1 and EAP2 are used for highest priority traffic such as reporting emergency events, the RAP1, RAP2, and CAP are used for regular traffic only.

In addition, the Type I/II phases are used for uplink allocation intervals, downlink allocation intervals, bilink allocation intervals and delay bilink allocation intervals in which polling is used for resource allocation. Depending on the application requirements, the coordinator can disable any of these periods by setting the duration length to zero. These allocation intervals along with the corresponding access methods whereby they are obtained are illustrated in Figure 3.9 [3].

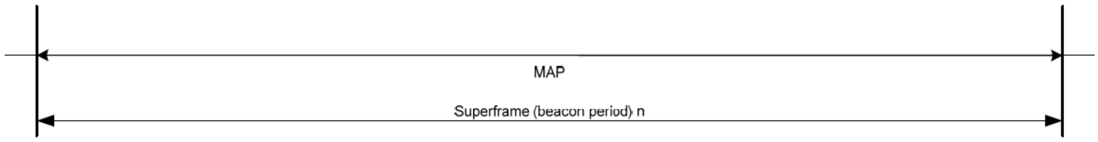

Figure 3.10 Layout of access phases in a superframe (beacon period) for non-beacon mode

3.2.2 Non-beacon mode with superframe boundaries

In this mode, a hub may have only a managed access phase (MAP) as described in Figure 3.9 [3], in any superframe (beacon period) as illustrated in Figure 3.10 [3]. Moreover, in this mode, the entire superframe duration is covered either by a Type I or a Type II access phase but not by both phases.

3.2.3 Non-beacon mode without superframe boundaries

In this mode, a hub may provide unscheduled bilink allocation intervals comprising type-II polled allocations and/or posted allocations, as illustrated in Figure 3.11. After determining that the hub for the next frame exchange is operating in non-beacon mode without superframe boundaries, a sensor node may treat anytime interval as a portion of EAP1 or RAP1 and employ CSMA/CA based random access to obtain a contended allocation [3].

3.2.4 Access mechanisms

The access mechanisms used in each period of the superframes are divided into three categories as follows. The first one is random access mechanism, which uses either the CSMA/CA or the slotted Aloha procedure for resource allocation. The second one is improvised and unscheduled access (connectionless contention-free access), which uses unscheduled polling/posting for resource allocation. The third one is scheduled access and variants (connection oriented contention-free access), which schedules the allocation of slots in one or multiple

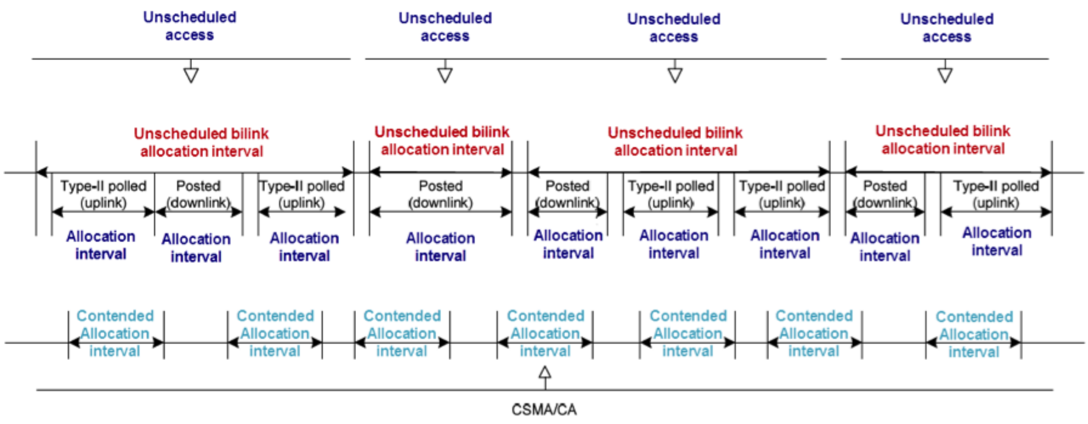

Figure 3.11 Allocation intervals and access methods permitted for non-beacon mode without superframes

upcoming superframes, also called 1-periodic or m-periodic allocations. These access approaches are comprehensively discussed in the standard.

In the thesis we focus on the CSMA/CA protocol so the thesis will explain the basic procedures of the CSMA/CA protocol defined in the standard. In the CSMA/CA, a sensor node sets its backoff counter to a random integer number uniformly distributed over the interval [1, CW] where $\mathrm{CW} \in (\mathrm{CW_{min}}, \mathrm{CW_{max}})$, as in Table 3.7 [3]. The values of CWmin and CWmax vary depending on the user priorities. The sensor node starts reducing its backoff counter by one for each idle CSMA slot of duration equal to pCSMASlotLength. The data is transmitted when the backoff counter reaches zero. The CW is doubled for each failure until it reaches CWmax.

The Figure 3.12 and Figure 3.13 [3] show the CSMA/CA procedure and CSMA slot structure. In RAP1, the sensor node firstly waits for SIFS = pSIFS duration and then unlocks its backoff counter until reaching zero and then the data transmission starts. In CAP, the sensor node locks its backoff counter since the time between the end of the slot and the end of the CAP is not enough for completing data transmission. The backoff counter is unlocked in the next RAP2 period.

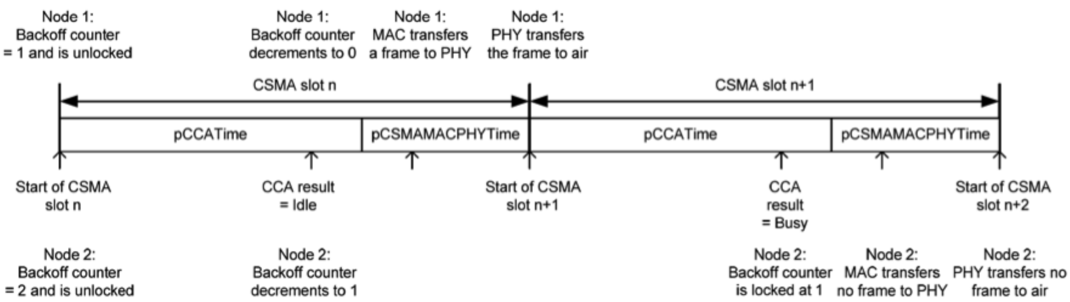

Figure 3.12 CSMA slot structure

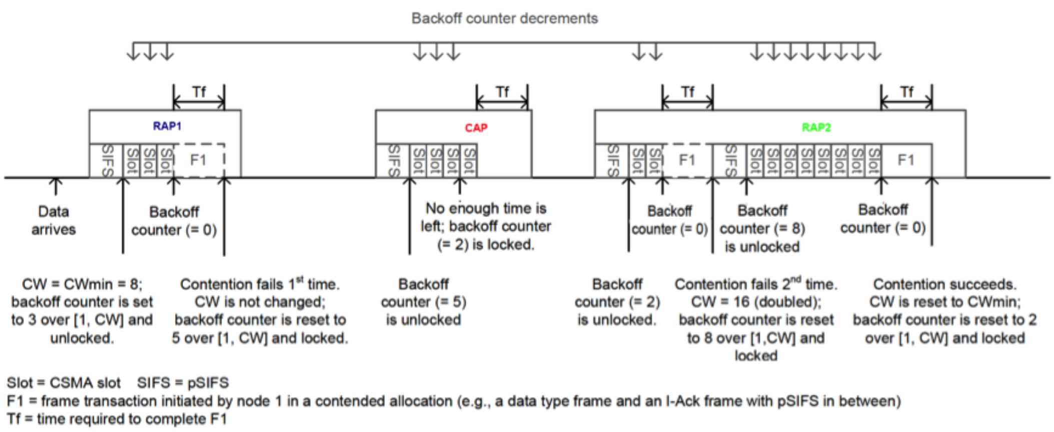

Figure 3.13 CSMA/CA in IEEE 802.15.6

Table 3.3 Modulation parameters for PLCP header and PSDU in 863 MHz to 958 MHz

Packet component	Modulation (M)	Symbol rate $= 1/T_s$ (ksps)	Code rate (k/n)	Spreading factor (S)	Pulse shape	Information data rate (kbps)	Support
863MHz – 870MHz							
PLCP header	π/2-DBPSK ($M=2$)	250	19/31 [a]	2	SRRC	76.6	Mandatory
PSDU	π/2-DBPSK ($M=2$)	250	51/63	2	SRRC	101.2	Mandatory
PSDU	π/2-DBPSK ($M=2$)	250	51/63	1	SRRC	202.4	Mandatory
PSDU	π/4-DQPSK ($M=4$)	250	51/63	1	SRRC	404.8	Mandatory
PSDU	π/8-D8PSK ($M=8$)	250	51/63	1	SRRC	607.1	Optional
902 MHz – 928 MHz							
PLCP header	π/2-DBPSK ($M=2$)	250	19/31 [a]	2	SRRC	76.6	Mandatory
PSDU	π/2-DBPSK ($M=2$)	250	51/63	2	SRRC	101.2	Mandatory
PSDU	π/2-DBPSK ($M=2$)	250	51/63	1	SRRC	202.4	Mandatory
PSDU	π/4-DQPSK ($M=4$)	250	51/63	1	SRRC	404.8	Mandatory
PSDU	π/8-D8PSK ($M=8$)	250	51/63	1	SRRC	607.1	Optional
950 MHz – 958 MHz							
PLCP header	π/2-DBPSK ($M=2$)	250	19/31 [a]	2	SRRC	76.6	Mandatory
PSDU	π/2-DBPSK ($M=2$)	250	51/63	2	SRRC	101.2	Mandatory
PSDU	π/2-DBPSK ($M=2$)	250	51/63	1	SRRC	202.4	Mandatory
PSDU	π/4-DQPSK ($M=4$)	250	51/63	1	SRRC	404.8	Mandatory
PSDU	π/8-D8PSK ($M=8$)	250	51/63	1	SRRC	607.1	Optional

[a] BCH (31, 19) code is a shortened code derived from a BCH (63, 51) code.

Table 3.4 Modulation parameters for PLCP header and PSDU in 2360 MHz to 2483.5 MHz

Packet component	Modulation (M)	Symbol rate $= 1/T_s$ (ksps)	Code rate (k/n)	Spreading factor (S)	Pulse shape	Information data rate (kbps)	Support
2360 MHz – 2400 MHz							
PLCP header	π/2-DBPSK ($M = 2$)	600	19/31 [a]	4	SRRC	91.9	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	600	51/63	4	SRRC	121.4	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	600	51/63	2	SRRC	242.9	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	600	51/63	1	SRRC	485.7	Mandatory
PSDU	π/4-DQPSK ($M = 4$)	600	51/63	1	SRRC	971.4	Mandatory
2400 MHz – 2483.5 MHz							
PLCP header	π/2-DBPSK ($M = 2$)	600	19/31 [a]	4	SRRC	91.9	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	600	51/63	4	SRRC	121.4	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	600	51/63	2	SRRC	242.9	Mandatory
PSDU	π/2-DBPSK ($M = 2$)	600	51/63	1	SRRC	485.7	Mandatory
PSDU	π/4-DQPSK ($M = 4$)	600	51/63	1	SRRC	971.4	Mandatory

Table 3.5 Preamble sequence #1 and #2

Bit	Bit value		Bit	Bit value		Bit	Bit value		Bit	Bit value	
	# 1	# 2		# 1	# 2		# 1	# 2		# 1	# 2
b_0	1	0	b_{23}	0	1	b_{46}	1	1	b_{69}	0	0
b_1	0	1	b_{24}	0	0	b_{47}	0	1	b_{70}	1	1
b_2	1	1	b_{25}	1	0	b_{48}	0	0	b_{71}	0	0
b_3	1	0	b_{26}	1	1	b_{49}	0	0	b_{72}	1	1
b_4	0	1	b_{27}	1	0	b_{50}	0	0	b_{73}	0	0
b_5	1	0	b_{28}	0	0	b_{51}	1	1	b_{74}	1	1
b_6	1	0	b_{29}	0	1	b_{52}	0	1	b_{75}	1	1
b_7	0	0	b_{30}	0	1	b_{53}	0	1	b_{76}	0	0
b_8	0	1	b_{31}	1	1	b_{54}	0	0	b_{77}	1	1
b_9	1	0	b_{32}	0	1	b_{55}	0	1	b_{78}	1	1
b_{10}	1	0	b_{33}	1	0	b_{56}	0	0	b_{79}	0	0
b_{11}	0	0	b_{34}	1	0	b_{57}	1	1	b_{80}	1	1
b_{12}	1	0	b_{35}	1	0	b_{58}	1	1	b_{81}	1	1
b_{13}	1	1	b_{36}	1	0	b_{59}	1	1	b_{82}	0	0
b_{14}	1	0	b_{37}	0	0	b_{60}	1	1	b_{83}	1	1
b_{15}	0	1	b_{38}	0	1	b_{61}	1	1	b_{84}	1	1
b_{16}	1	1	b_{39}	1	1	b_{62}	1	1	b_{85}	0	0
b_{17}	1	0	b_{40}	0	0	b_{63}	0	0	b_{86}	1	1
b_{18}	0	0	b_{41}	1	1	b_{64}	1	1	b_{87}	1	1
b_{19}	1	1	b_{42}	0	1	b_{65}	0	0	b_{88}	0	0
b_{20}	0	0	b_{43}	0	1	b_{66}	1	1	b_{89}	1	1
b_{21}	0	1	b_{44}	0	0	b_{67}	0	0	-	-	-
b_{22}	1	0	b_{45}	1	0	b_{68}	1	1	-	-	-

Table 3.6 D-PSK constellation

Constellation	Ideal constellation positions
$\pi/2$-DBPSK	(0, 1), (0, −1)
$\pi/4$-DQPSK	(cos($\pi/4$), sin($\pi/4$)), (cos($3\pi/4$), sin($3\pi/4$)), (cos($5\pi/4$), sin($5\pi/4$)), (cos($7\pi/4$), sin($7\pi/4$))
$\pi/8$-D8PSK	(cos($\pi/8$), sin($\pi/8$)), (cos($3\pi/8$), sin($3\pi/8$)), (cos($5\pi/8$), sin($5\pi/8$)), (cos($7\pi/8$), sin($7\pi/8$)), (cos($9\pi/8$), sin($9\pi/8$)), (cos($11\pi/8$), sin($11\pi/8$)), (cos($13\pi/8$), sin($13\pi/8$)), (cos($15\pi/8$), sin($15\pi/8$))

Table 3.7 Contention window for CSMA/CA and Slotted Aloha

User Priority	CSMA/CA		Slotted Aloha access	
	CWmin	CWmax	CPmax	CPmin
0	16	64	1/8	1/16
1	16	32	1/8	3/32
2	8	32	1/4	3/32
3	8	16	1/4	1/8
4	4	16	3/8	1/8
5	4	8	3/8	3/16
6	2	8	1/2	3/16
7	1	4	1	1/4

Chapter 4

Markov chain Monte Carlo method for performance analysis of WBANs

4.1 Chapter overview

In order to improve the performance of the WBANs, the PHY layer, MAC layer and network layer have been discussed in a number of literatures. Although there are also many previous works on performance analysis for the WBANs, a noise free was frequently assumed when contention error is taken into account in MAC layer. It means that in these works BERs were not taken into consideration adequately. In this thesis, we propose the MCMC method to analyze performance in the PHY and MAC layers for the WBANs, in which BERs are taken into consideration. In fact, the proposal MCMC method can be considered as development and adjustment of the conventional DTMC method with the key issue is to calculate approximately.

4.2 The conventional DTMC method

In this section, the thesis shortly describes the conventional DTMC method used in a number of previous works [27,28,. . . ,35] on MAC layer for the WBANs. By employing Markov chain model, the previous works can calculate the access probability of a sensor node and then can calculate the system throughput in saturation or non-saturation conditions separately. The access probability of a sensor node means that the medium is accessed by this sensor or the medium is not set to busy due to either a transmission on the medium or the CSMA/CA slot is outside the access phases in which this sensor is allowed to transmit a packet. The term saturation in this method means that if a sensor node always has a packet to send or in other words there is always a packet in its queue of UP waiting to be served all the time, this sensor is saturated. In fact, saturation condition is the mathematical condition and may be relative with high traffic condition in real.

4.2.1 Analyzing system under saturation condition

With saturation condition described above, many previous works [28, 29, 31, 34] developed the DTMC model in order to calculate the access probability and then the system throughput. The thesis will shortly represent the proposed DTMC model in previous works.

In the previous works, authors considered a single hop WBAN with n_k sensors with user priority k and each sensor in system is assumed to have one *UP*. The backoff count for a node of *UP*$_k$ is an integer distributed in the interval $[1, CW_k]$, in which $CW_k = W_{k,i}$ with $i = 0, \ldots, R$. R is the retry limit taken from IEEE.802.15.6. The minimum and maximum of value of CW_k are set to $CW_{k,mim} = W_{k,0}$ and $CW_{k,max} = W_{k,m_k}$, respectively. When $rezo^{th}$ backoff phase starts, CW_k is set to $CW_{k,mim}$. As a result, contention window in the i^{th} backoff phase of a sensor is calculated as

$$\left(\begin{array}{ll} W_{k,0} = W_{k,min} = CW_{k,min} & \\ W_{k,i} = \min\{2Wk, i-1, CW_{k,max}\} & \text{for } 2 \leq i \leq R \text{ if } i \text{ is even} \\ W_{k,i} = Wk, i-1 & \text{for } 2 \leq i \leq R \text{ if } i \text{ is odd} \end{array} \right. \tag{4–1}$$

The slots in which the sensors pause their backoff count down due to a transmission on the medium are not taken into account when calculating the access probability. Thus, probability that the medium is idle during a slot in RAP1 will be obtained as

$$f = \prod_{i=0}^{7} (1 - \tau_i)^{n_i} \tag{4–2}$$

Here τ_k is the access probability of UP_k sensor. With the UP_k sensors, for $k = 0, \ldots, 6$, probability that the channel is idle during its backoff count down in a slot within RAP1 is calculated as

$$f_k = \frac{\prod_{i=0}^{7}(1-\tau_i)^{n_i}}{1-\tau_k} \tag{4–3}$$

While the idle probability of the UP_k sensors, for $k = 0, \ldots, 6$, can be calculated by equation (4–3), the idle probability of the highest, UP_7 , will be the probability that the channel is idle during its backoff count down in a slot within EAP1 or RAP1 and can be calculated approximately as

$$f_7 = \frac{\text{rap1}\prod_{i=0}^{7}(1-\tau_i)^{n_i}}{(\text{eap1}+\text{rap1})} + \frac{\text{eap1}(1-\tau_7)^{n_7-1}}{eap1+rap1} \tag{4–4}$$

Here eap1 and rap1 denote the lengths of EAP1 and RAP1 in slots, respectively. If the remained time during the current access phase is not long enough for completing a frame transaction the backoff counter shall be locked by the sensor, for example, in case of an emergency event report. Moreover, during EAP, the sensors that do not have the highest priority have to lock their backoff counters. The backoff counter should be locked until beginning of the next access period EPA1 if the sensor hs the highest UP or RAP1 if the sensor dose not have the highest UP. The probability that in a given CSMA/CA slot there is not enough time during the current access period is defined as

$$p_k = \frac{1}{\text{rap1} - L_s}, \qquad k = 0, \ldots, 6 \tag{4–5}$$

$$p_7 = \frac{1}{\text{rap1} + \text{eap1} - L_s} \tag{4–6}$$

Here $L_s = (rts + cts + l_d + ack + 3sifs)_s$ and $L_c = (rts + cts + 3sifs)_s$ are the successful transmission time in slots and the unsuccessful transmission time in slots in case of failure access to the channel, respectively. The length of request to send (RTS), clear to send (CTS), the size of data frames and ACK frame is defined as rts, cts, l_d and ack, respectively, and is calculated in bits or in second. The probability that neither RTS nor CTS is corrupted is denoted as δ and the probability that the packet and the corresponding ACK are transmitted without getting corruption is denoted as σ [28].

The probability that the backoff counter of a sensor is decreased when the counter is equal to j is denoted as $g_{k,j}$, for $k = 0, \ldots, 7$ and $j = 1, \ldots, W_{k,m_k}$. It is clear that this probability is illustrated in a way to consider the slots in which the backoff counter is locked, however, the slots have to be considered when the access probability being calculated. The probability $g_{k,j}$ can be calculated as

$$\begin{aligned} g_{k,j} &= f_k \left(1 - p_k \left((1 - f_k)\left(1 + 2f_k + \cdots + j_k^{j-1}\right) + j f_k^j\right)\right) \\ &= f_k \left(1 - p_k \frac{1 - f_k^j}{1 - f_k}\right) \end{aligned} \tag{4–7}$$

The length of slots in which the backoff counter for a UP_k sensor have to be locked is denoted as L_k, for $k = 0, \ldots, 7$. While the sensors owning the highest *UP* are allowed to transmit a packet or decrease their backoff counters during EAP1 period, all the sensors in the system must lock their backoff counter when there is not enough time for finishing packet transmission. On the other hand, the sensor owning the highest *UP* is not required to lock its backoff counter during EAP1 in stead of busy channel. As a result, L_k can be calculated as

$$\begin{aligned} &L_k = eqp1 + (rts + cts + l_d + ack + 3sifs)_s, \qquad k = 0, \ldots, 6 \\ &L_7 = (rts + cts + l_d + ack + 3sifs)_s \end{aligned} \tag{4–8}$$

The conventional DTMC model illustrates the random process for changing state of a WBAN, which is described as in Fig. 4.1 [28]. In this model $b_{k,i,j}$ is the stationary distribution, $k = 0, \ldots, 7$ is the *UP* value, $i = 0, \ldots, m_k, \ldots, R$ is the backoff stage and $j = 0, \ldots, W_{k,i}$ is the backoff counter value. The fundamental target of this model is to describe and calculate the access probability of sensors. As to be shown in Fig. 4.1, when the state of sensor becomes as $(k, i, 0)$ state, the sensor is allowed to access the channel to transmit a packet. Consequently, the access probability of sensors can be calculated as

$$\tau_k = \sum_{i=0}^{R} b_{k,i,0} \tag{4–9}$$

The input probability to the $zero^{th}$ backoff stage can be calculated as

$$Y_k = \tau_k f_k \delta + b_{k,R,o} \left(1 - f_k \delta\right) \tag{4–10}$$

After analyzing the DTMC model with $k = 0, \ldots, 7$ and $j = 1, \ldots, W_{k,0}$, the stationary distributions can be obtained as

$$b_{k,0,j} = \frac{\left(W_{k,0} - j + 1\right) Y_k}{W_{k,0} g_{k,j}} \tag{4–11}$$

$$b_{k,0,0} = g_{k,1} b_{k,0,1} = Y_k \tag{4–12}$$

$$b_{k,i,j} = \frac{\left(1 - f_k \delta\right)^i Y_k \left(W_{k,i} - j + 1\right)}{W_{k,i} g_{k,j}} \tag{4–13}$$

Here $k = 0, \ldots, 7$; $i = 1, \ldots, R$ and $j = 1, \ldots, W_{k,j}$

$$b_{k,j,0} = \left(1 - f_k \delta\right)^i Y_k \tag{4–14}$$

After combining (4–10) and (4–14), the value of Y_k can be obtained as

$$Y_k = \frac{f_k \delta \tau_k}{1 - \left(1 - f_k \delta\right)^{R+1}} \tag{4–15}$$

After combining (4–10) – (4–15), the total stationary distribution at the i^{th} backoff phase can be obtained as

$$\sum_{i=0}^{R} \sum_{j=0}^{W_{k,i}} b_{k,i,j} = Y_k \sum_{i=0}^{R} \left(1 - f_k \delta\right)^i \left(1 + \frac{1}{W_{k,i}} \sum_{j=1}^{W_{k,i}} \frac{W_{k,i} - j + 1}{g_{k,j}}\right) \tag{4–16}$$

Following the normalization of the DTMC, the total the total stationary distribution at the i^{th} backoff phase is equal to 1. As a result, following equations are obtained as

$$Y_k \sum_{i=0}^{R} \left(1 - f_k \delta\right)^i \left(1 + \frac{1}{W_{k,i}} \sum_{j=1}^{W_{k,i}} \frac{W_{k,i} - j + 1}{g_{k,j}}\right) = 1 \tag{4–17}$$

In the set of equations (4–17), there are 8 unknown variable value τ_k and 8 equations, $k = 0, \ldots, 7$. Consequently, solving these equations, all access probabilities are produced. As a result, the throughput of sensors can be calculated approximately as

$$S_k = \frac{\tau_k f_k X_R \delta_\sigma \left(l_p\right)_s}{rap1 + eap1} \qquad \text{for } k = 0, \ldots, 6 \tag{4–18}$$

$$S_7 = \frac{\tau_7 \left(\psi X_E + \xi X_R\right) \delta \sigma \left(l_p\right)_s}{rap1 + eap1} \tag{4–19}$$

Here

$$X_R = \frac{rap1 - L_{pz} + eap1}{f + \sum_{t=0}^{7} n_t \tau_t f_t \delta L_s + \left(1 - f - \sum_{t=0}^{7} n_t \tau_t f_t \delta\right) L_c}$$
$$X_E = \frac{eap1}{\phi + n_7 \tau_7 \psi \delta L_s + (1 - \phi - n_7 \tau_7 \psi \delta) L_c}$$
$$\phi = (1 - \tau_7)^{n_7}, \quad \psi = (1 - \tau_7)^{n_7 - 1}, \quad \xi = \frac{\prod_{k=0}^{7} (1 - \tau_7)^{n_7}}{1 - \tau_7}$$
$$L_{pz} = (rts + cts + 3sifs + l_d + ack)_s$$

4.2.2 Analyzing system under non-saturation condition

The WBANs under saturation condition are modeled and analyzed in above section. In this section, the thesis will shortly illustrate the conventional DTMC model for performance analysis of the WBANs under non-saturation condition in many previous works [27, 30, 32, 35,37].

In this method, the star topology WBANs consist of one coordinator and many sensor nodes working with CSMA/CA mechanism are analyzed. The DTMC model for performance analysis of the WBANs is described as Fig. 4.2 [30].

In this model, k is the *UP*, m is the frame retry limit, $W_{k,i}$ is the contention window size of UP_k sensor and λ_k is the packet arrive rate of UP_k sensor. The probabilities p_k, q_k and f_k is defined as the collision probability, channel idle probability and the probability that there is sufficient time left for transmitting a packet of the UP_k sensor. In the model in Fig. 4.2, these probabilities can be described as

$$p_k = 1 - (1 - \tau_k)^{n_k - 1} \prod_{i \neq k} (1 - \tau_i)^{n_i} \tag{4–20}$$

$$q_k = \prod_{i=0}^{7} \frac{(1 - \tau_i)^{n_i}}{1 - \tau_k} \tag{4–21}$$

$$f_k = Pr\left\{l_{\textit{remain period}} \geq l_{\textit{frame}}\right\} = 1 \tag{4–22}$$

Here τ_k is the probability that a packet of the UP_k sensor is transmitted. The period $l_{\textit{remained time}}$ and $l_{\textit{frame}}$ are the length of remained time for transmission a packet and the length of frame in second.

By analyzing the DTMC model in Fig. 4.2, the state transition probabilities can be illustrated as

$$\begin{aligned}
\Pr\{k,i,j\,|\,\mathrm{k,i,j+1}\} &= q_k f_k, \\
&\quad \text{for } i\in(0,\dots,m),\quad j\in(0,\dots,\mathrm{W}_{k,i-2}) \\
\Pr\{k,i,j\,|\,\mathrm{k,i-1,0}\} &= q_k/W_{k,i}, \\
&\quad \text{for } i\in(1,\dots,m),\quad j\in(0,\dots,\mathrm{W}_{k,i-1}) \\
\Pr\{k,0,j\,|\,\mathrm{k,i,0}\} &= (1-p_k)\lambda_k/W_{k,0}, \\
&\quad \text{for } i\in(0,\dots,m-1),\quad j\in(0,\dots,\mathrm{W}_{k,i-1}) \\
\Pr\{k,0,j\,|\,\mathrm{k,m,0}\} &= \lambda_k/W_{k,0}, \\
&\quad \text{for } j\in(0,\dots,W_{k,0}-1) \qquad (4\text{–}23)\\
\Pr\{k,0,j\,|\,\mathrm{e}\} &= \lambda_k/W_{k,0}, \quad \text{for } j\in(0,\dots,W_{k,0}-1) \\
\Pr\{e\,|\,\mathrm{k,i,0}\} &= (1-\lambda_k)(1-\mathrm{p}_k), \quad \text{for } j\in(0,\dots,m-1) \\
\Pr\{e\,|\,\mathrm{k,i,0}\} &= (1-\lambda_k), \\
\Pr\{e\,|\,\mathrm{e}\} &= (1-\lambda_k).
\end{aligned}$$

As a result, the stationary distributions $b_{k,i,j}$ can be found by analyzing the following equations

$$\begin{aligned}
1 &= \sum_{i=0}^{m}\sum_{j=0}^{W_{k,i}-1} b_{k,i,j} + b_e \\
&= \sum_{i=0}^{m}\sum_{j=0}^{W_{k,i}-1} b_{k,i,j} + \sum_{j=1}^{m} b_{k,i,0} + \sum_{j=0}^{W_{k,0}-1} b_{k,0,j} + b_e \qquad (4\text{–}24)
\end{aligned}$$

$$\sum_{i=1}^{m} b_{k,i,0} = \frac{p_k(1-(p_k)^m)}{(1-p_k)} b_{k,0,0} \qquad (4\text{–}25)$$

$$\sum_{j=0}^{W_{k,0}-1} b_{k,0,j} = \frac{W_{k,0}+1}{2f_k q_k} b_{k,0,0} \qquad (4\text{–}26)$$

Here

$$b_e = \frac{(1-\lambda_k)(1-p_k)}{\lambda_k}\sum_{i=0}^{m-1} b_{k,i,0} + \frac{(1-\lambda_k)}{\lambda_k} b_{k,m,0} = \frac{(1-\lambda_k)}{\lambda_k} b_{k,0,0} \qquad (4\text{–}27)$$

and transmission probabilities τ_k can be calculated as

$$b_{k,0,0} = \frac{2\lambda_k q_k f_k(1-\mathrm{p}_k)}{\left\{\begin{array}{c} 2\lambda_k\theta_k(1-\mathrm{p}_k) + 2\lambda_k q_k f_k \mathrm{p}_k(1-(\mathrm{p}_k)^m)+ \\ \lambda_k(1-\mathrm{p}_k)(\mathrm{W}_{k,0}+1) + 2q_k f_k(1-\lambda_k)(1-\mathrm{p}_k) \end{array}\right\}} \tag{4–28}$$

$$\tau_k = \sum_{i=0}^{m} b_{k,i,0} = \frac{(1-(\mathrm{p}_k)^{m+1})}{1-p_k} b_{k,0,0} \tag{4–29}$$

Here

$$\theta_k = \sum_{i=1}^{m} P_k^i \frac{W_{k,i}-1}{2} \tag{4–30}$$

The probability that there is at least transmission P_tr and the probability that a UP_k sensor successfully transmits a packet can be calculated as

$$P_{tr} = 1 - \sum_{k=0}^{7} (1-\tau_k)^{n_k} \tag{4–31}$$

$$P_{s,k} = \left[\tau_k q_k f_k (1-\tau_k)^{n_k-1}\right] \prod_{i\neq k} (1-\tau_i)^{n_i/P_{tr}} \tag{4–32}$$

Finally, the throughput of the UP_k sensor can be calculated as

$$S_k = \frac{P_{s,k} P_{tr} E[l_p]}{(1-P_{tr})\sigma + P_s P_{tr} l_s + (1-\mathrm{P}_s) P_{tr} l_c} \tag{4–33}$$

Here, $P_s = \sum_{k=0}^{7} n_k P_{s,k}$, $l_s = l_{RTS} + l_{CTS} + l_p + l_{ACK} + 3l_{SIFS}$, $l_c = l_{RTS} + l_{CTS} + l_{SIFS}$ and σ is idle slot time.

4.3 The proposal MCMC method

4.3.1 System model

In the thesis, a star topology WBAN that consists of a single coordinator and n sensor nodes is analyzed. Because the received SNR from every sensor node is assumed to be different, the transmission failed probability as well as the average backoff counter of every sensor node is also different. Although each sensor node can be considered as to belong to different UPs, in this thesis, the UP of all sensor nodes is assumed to be the same as zero-th UP. The extension for multiple UPs is straightforward. The backoff counter of $zero^{th}$ UP is represented

Table 4.1 Contention window for $zero^{th}$ UP

Number of retransmissions	0	1	2	3	4 and over
W	16	16	32	32	64

in Table 4.1 [35]. The DTMC method for analyzing the performance of non-saturation WBANs is described in Fig 4.3 [35] and notations used in this section are listed in Table 4.2 [35]. The thesis assumes that packet generation rates meaning a number of generated packets in one second of all sensor nodes are the same. Therefore, packet arrive rate during a slot time can be calculated as, $\rho = 1 - e^{\lambda T_s}$, in which e and T_s denote the Napier's constant and CSMA slot time, respectively.

4.3.2 Algorithm

The difference of access successful probability $\hat{P}_{i,suc}$ and transmission successful probability $P_{i,suc}$ of sensor node i is explained as follows. The access successful probability denotes the probability when the sensor node i successfully accesses the medium, conditioned on the fact that at least one sensor node is transmitting. The transmission successful probability is the probability that the sensor node i successfully receive ACK from the coordinator. Therefore, we have

$$\begin{aligned} \hat{P}_{i,suc} &= \frac{\tau_i \prod_{j=1}^{n}(1-\tau_j)}{(1-\tau_i)P_{tran}} \\ P_{i,suc} &= \hat{P}_{i,suc}(1-PER_i) \end{aligned} \tag{4–34}$$

Here, P_{tran} denotes the transmission probability and is defined as a probability in which there is at least one sensor node sending a packet. The probability P_{tran} can be calculated as

$$P_{tran} = 1 - \prod_{j=1}^{n}(1-\tau_j) \tag{4–35}$$

Table 4.2 Explanation of the notations

Notation	Explanation
λ	Packet generation rate
ρ	Packet arrive rate during a slot time
m	Frame retry limit
n	Total number of sensor nodes
x	Payload size
τ_i	Access probability during a slot time
$b_{\mathrm{i,k,j}}$	Stationary distribution
$P_{\mathrm{i,idle}}$	Channel idle probability
$P_{\mathrm{i,fail}}$	Transmission failed probability
$P_{\mathrm{i,col}}$	Collision probability
$\hat{P}_{\mathrm{i,suc}}$	Access successful probability
$P_{\mathrm{i,suc}}$	Transmission successful probability
PER_{i}	Packet error rate
BER_{i}	Bit error rate
W_{k}	Contention window of k backoff stage

The transmission of sensor node i is failed due to two reasons. The first reason is collision and the second one is that sensor node i successfully accesses the medium to transmit data but received data is unable to decode at the coordinator. Consequently, the transmission failed probability of sensor i is depicted by

$$P_{i,fail} = P_{i,col} + \hat{P}_{i,suc} PER_i, \tag{4–36}$$

Here

$$P_{i,col} = \tau_i \left(1 - \prod_{\substack{k \neq i \\ k=1}}^{n} (1 - \tau_k) \right), \tag{4–37}$$

The probability $P_{i,col}$ denotes the collision probability and $PER = 1-(1-BER_i)^x$ represents the PER of sensor node i. The sensor node i senses that the medium is idle when no sensor node is transmitting. Thus, the idle probability is expressed as

$$P_{i,idle} = \prod_{j=1}^{n}(1-\tau_j) = 1 - P_{tran}, \tag{4–38}$$

After analyzing the proposal DTMC model as in Fig 4.3, the state transmission probabilities of DTMC method are represented as follows [35].

$$\begin{aligned} \Pr\{i,k,j \mid i,k,j+1\} &= P_{i,idle}, \text{for } k \in [0,m], j \in [0,W_k] \\ \Pr\{i,k,j \mid i,k-1,0\} &= \frac{P_{i,fail}}{W_k}, \text{for } k \in [1,m], j \in [1,W_k] \\ \Pr\{i,k,j \mid i,k,j\} &= 1 - P_{i,idle}, \text{for } k \in [0,m], j \in [0,W_k] \\ \Pr\{i,0,j \mid i,m,0\} &= \frac{\rho}{W_0}, \text{for } j \in [0,W_0] \\ \Pr\{i,0,j \mid empty\} &= \frac{\rho}{W_0}, \text{for } j \in [0,W_0] \\ \Pr\{empty \mid i,k,0\} &= (1-\rho)(1-P_{i,fail}), \text{for } k \in [0,m-1] \\ \Pr\{empty \mid i,m,0\} &= (1-\rho) \\ \Pr\{empty \mid empty\} &= (1-\rho). \text{for } k \in [0,m-1], \end{aligned} \tag{4–39}$$

The relation between stationary distributions $b_{i,k,j}$ and $b_{i,0,0}$ can be obtained by using the state transition probability.

$$\sum_{k=0}^{m}\sum_{j=0}^{W_k} b_{j,k,j} + b_{empty} = 1 \tag{4–40}$$

Moreover, from the state transition probability, we have

$$\begin{aligned} \sum_{i=0}^{m} b_{i,k,0} &= \frac{P_{i,fail}(1-P_{i,fail}^{m})}{1-P_{i,fail}} b_{i,0,0}, \\ \sum_{j=0}^{W_0} b_{j,0,j} &= \frac{W_0+1}{2P_{i,idle}} b_{i,0,0} \\ b_{empty} &= \frac{1-\rho}{\rho} b_{i,0,0}. \end{aligned} \tag{4–41}$$

From above equations, the stationary $b_{i,0,0}$ can be described as a function of $P_{i,idle}$, $P_{i,fail}$, ρ, W_k, and τ_i. Furthermore, The access probability of all sensor nodes can be obtained by solving n following equations.

$$\tau_i = \sum_{k=0}^{m} b_{i,k,0} = \frac{1 - P_{i,fail}^{m+1}}{1 - P_{i,fail}} b_{i,0,0} \tag{4–42}$$

However, the access probability of all sensor nodes relates to each other. In this work, the BER/PER are taken into account. It is clear that the PER of each sensor node affects the access probability of all sensor nodes, including itself. Consequently, solving **n** equations of access probability by mathematical method is considerably complicated. We proposed the MCMC method to easily obtain **n** access probabilities, considering variant PER in each sensor node for each superframe. Let

$$f(\tau_i) = \tau_i - \frac{1 - P_{i,fail}^{m+1}}{1 - P_{i,fail}} b_{i,0,0} \tag{4–43}$$

and then the access probability τ_i is obtained by solving equation $f(\tau_i) = 0$. The thesis constructs the MCMC method to find all access probabilities approximately with which all functions $f(\tau_i)$, for $i = 1, \ldots, n$, are close to zero. The MCMC method is explained as follows.

Step 1: Creating τ_i randomly within (0,1) for initializing.

Step 2: In order to obtain access probabilities with which all functions $f(\tau_i)$, for $i = 1, \ldots, n$ are close to zero, the thesis calculate a sum of absolute functions $f(\tau_i)$,

$$sum = \sum_{i=1}^{n} |f(\tau_i)|, \tag{4–44}$$

and compare with the given threshold, σ. In this step, instead of sum of absolute $f(\tau_i)$, each absolute $f(\tau_i)$ can be compared with the σ. If $sum \leq \sigma$, the algorithm is finished, otherwise go to ***Step 3***. The accuracy of algorithm depends on the σ and the σ should be small enough to let all functions $f(\tau_i)$ be close to zero. However, the smaller the σ is, the more long time the algorithm takes.

Step 3: Adjusting all access probabilities with the given weight, γ, it means that the value $-\gamma f(\tau_i)$ is added to τ_i (for all $i = 1, \ldots, n$) and return to ***Step 2***. In this step, the τ_i is slightly increased or decreased if $f(\tau_i)$ is respectively negative or positive. The given weight γ relates to convergence of the algorithm. In case the γ is large, the algorithm can't converge or takes a long time to converge. In case the γ is greatly small, the algorithm can converge, however, it takes a long time. In this work, authors set the γ be 10^{-6}. The reason is explained that because the packet generation rate is assumed to be over one meaning sensor nodes intend to transmit at least one packet in one second. Moreover, the slot length, T_s, equals to $T_{ACK} + 20\mu s = 125\mu s$ and hence the minimum of access probability is $1 - e^{-T_s} \approx 1.2 \times 10^{-4}$. Therefore, it can be said that $\gamma = 10^{-6}$ and $\sigma = 10^{-8}$ is small enough to obtain the accurate access probabilities.

4.3.3 Throughput of system

If the transmission is successful, the sensor node receives a ACK packet, otherwise the sensor node receives nothing from the coordinator after a certain duration time. This means that the duration time of successful transmission is the same as that of failed transmission. Therefore, the throughput of sensor node i, which is calculated by the ratio of successfully transmitted information data and the average transmission time, is represented as

$$C_i = \frac{P_{tran} P_{i,suc} x r}{(1 - P_{tran})T_s + P_{tran} P_{suc} T + P_{tran}(1 - P_{suc} T)}, \qquad (4\text{–}45)$$

Here, $P_{suc} = \sigma_{1=1}^{n} P_{i,suc}$ denotes the total successful probability of all sensor nodes.

The successful transmission time is defined as total duration time to transmit a packet, included the duration time to transmit a data packet T_{DATA}, interframe spacing T_{pSIFS}, ACK packet T_{ACK} and delay time α.

$$T = T_{DATA} + T_{ACK} + 2T_{pSIFS} + 2\alpha, \qquad (4\text{–}46)$$

Let's T_p, T_{PHY}, T_{MAC}, T_{BODY} and T_{FCS} denote the duration time to transmit a preamble, PHY header, MAC header, MAC frame body and frame check sequence, respectively. Hence, the duration time to transmit a data packet is represented as follows.

$$\begin{aligned} T_{DATA} &= T_p + T_{PHY} + T_{MAC} + T_{BODY} + T_{FCS} \\ &= \frac{Preamble}{R_s} + \frac{PHYheader}{R_{PLCP}} + \frac{8(MACheader + x + MACfooter)}{R_{PSDU}} \end{aligned} \tag{4–47}$$

An immediate ACK carries no payload, thus its transmission time is given by

$$\begin{aligned} T_{ACK} &= T_p + T_{PHY} + T_{MAC} + T_{FCS} \\ &= \frac{Preamble}{R_s} + \frac{PHYheader}{R_{PLCP}} + \frac{8(MACheader + MACfooter)}{R_{PSDU}} \end{aligned} \tag{4–48}$$

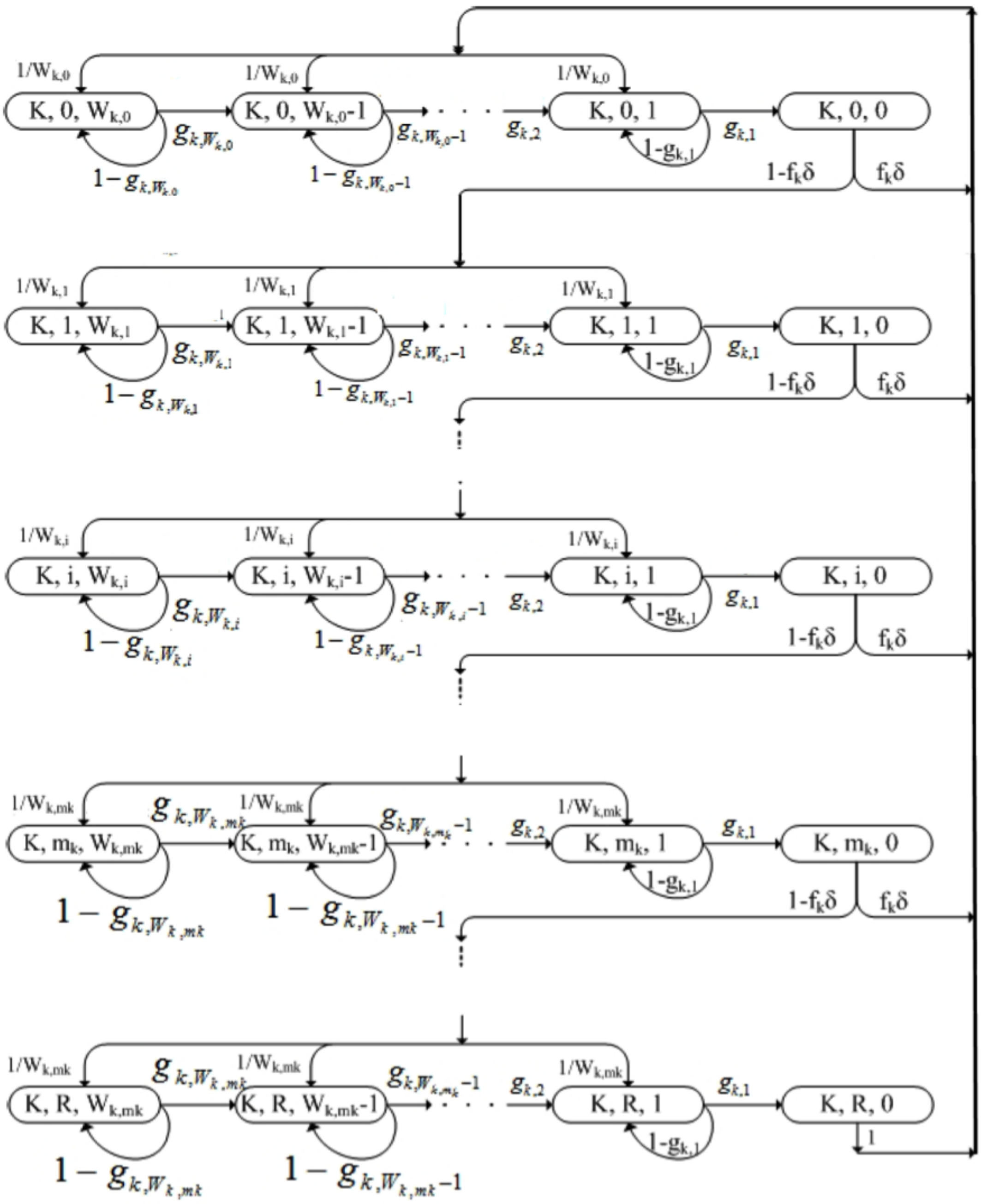

Figure 4.1 The conventional DTMC model for saturation WBANs

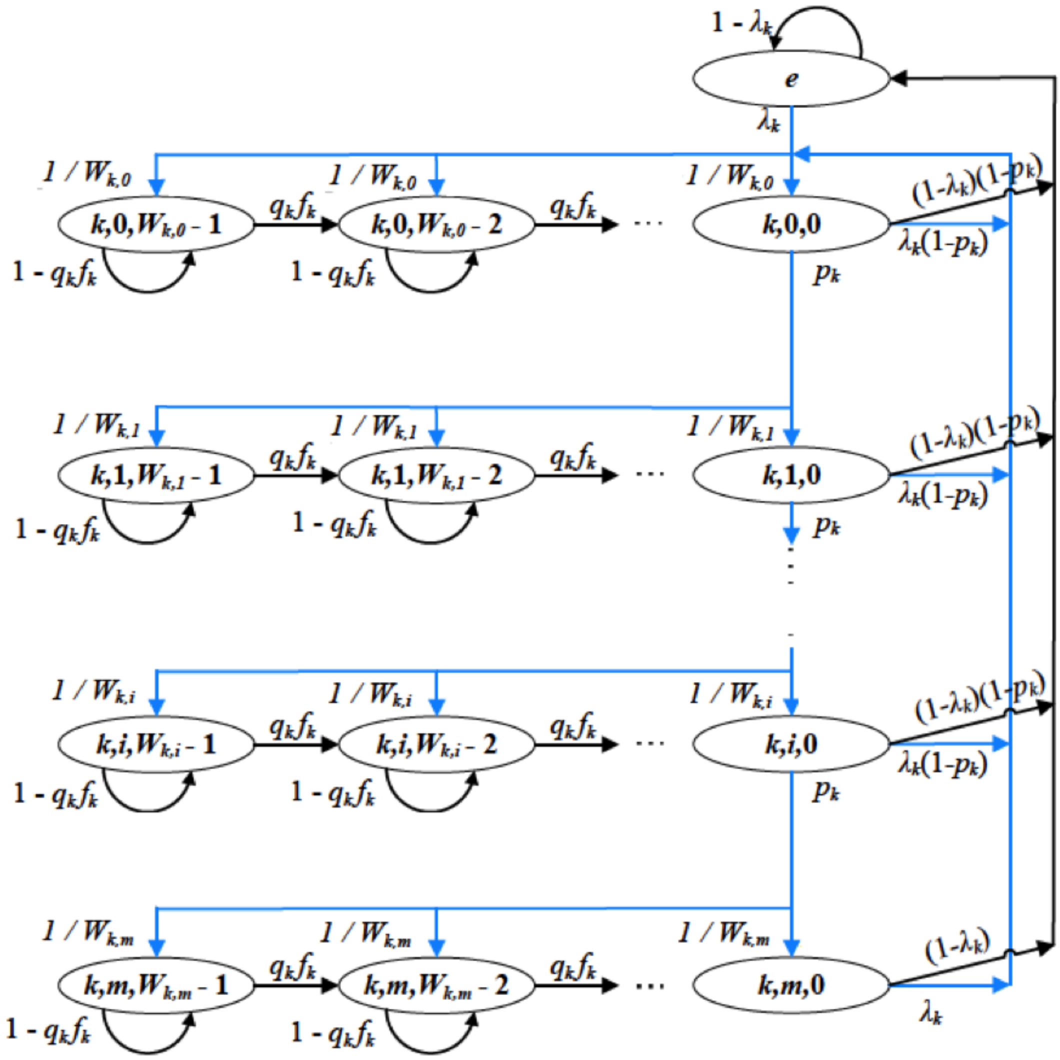

Figure 4.2 The conventional DTMC model for non-saturation WBANs

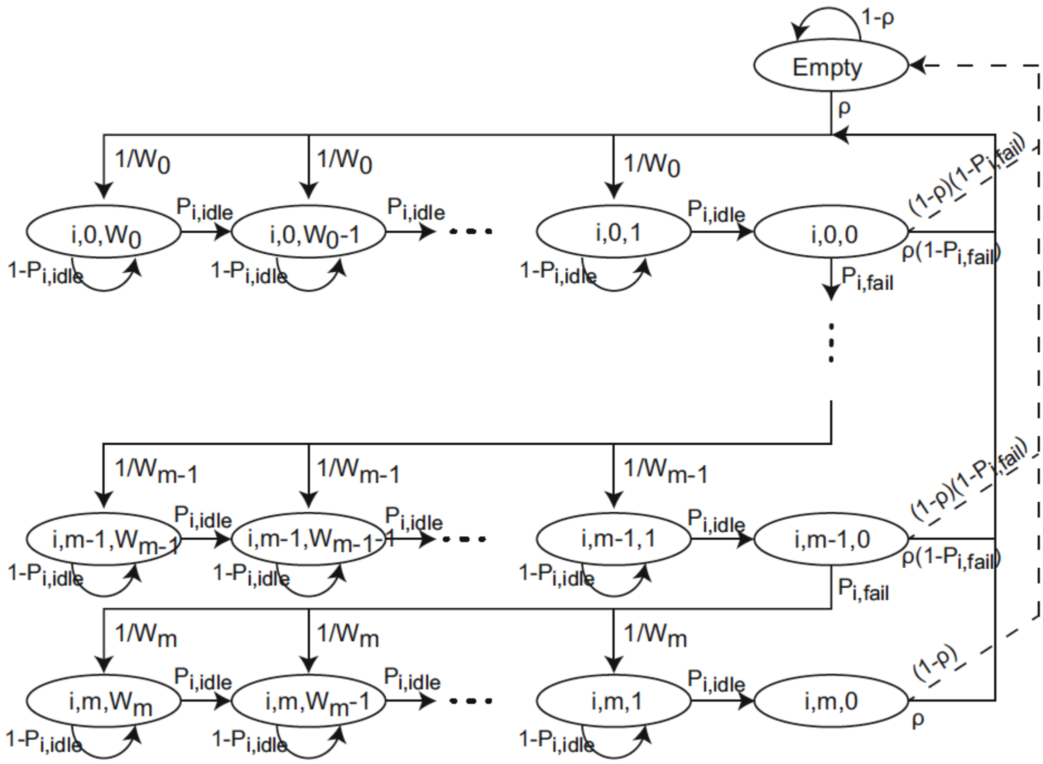

Figure 4.3 The DTMC model for analysis of non-saturation WBANs

Chapter 5

Dynamic statistical method for performance analysis of WBANs

5.1 Chapter overview

By using Markov chain model, saturation and non-saturation conditions, many previous works [27, 28,$\cdots$, 35] can calculate access probability and throughput of system. Nevertheless, with both saturation and non-saturation conditions, the access probability and packet arrival rate was assumed to be fixed and effect of remained packets, which was transmitted unsuccessfully due to collision or busy channel, was not considered adequately. The target of the thesis in this chapter is to evaluate the system performance more accurately and flexibly, taking into account the remained packets and using statistical mathematics instead of saturation and non-saturation conditions. The results of the thesis is expected that proposal method can achieve the same results in saturation and non-saturation conditions, however, in time-saturation that can be considered as a connecting condition or takes place between saturation condition and non-saturation condition, the proposal method gives more correct result because in this condition the effect of remained packet is considerable. In addition, that the system performance changes following operation time, different user priority levels and some other parameters is analyzed as well. At the current state, the thesis only finished at algorithm and the simulation program and comparison between the simulation results and reproduced results from other relative researches will be let for future work.

5.2 Service time calculation

Service time (T_m) is defined as total time to transmit a packet of m^{th} UP sensors included the *backoff* time (T_W), time to transmit a data packet (T_{data}), short interframe spacing (T_{pSIFS}), time of acknowledgement packet (T_{ACK}) and delay time (α) which is defined as the sum of propagation and signal processing delay.

$$T_m = T_W + T_{data} + T_{ACK} + 2T_{pSIFS} + 2\alpha \tag{5–1}$$

Let's T_s denote a CSMA slot length, the value of the average backoff time can be calculated as

$$T_{\overline{W}} = \overline{W_m} T_s \tag{5–2}$$

Here, $\overline{W_m}$ is average backoff counter defined more detail below, in formula (5–6).

5.3 System model

In this method, we consider the WBAN system consists of a coordinator and N sensors nodes. The structure of the WBAN is star topology without multiple hoping, Fig. 5.1 [43]. There are also multiple UPs in the system. In order to build algorithm more obviously and simply, firstly the channel is assumed as ideal channel. After successful building all equations for algorithm, the method is extended for non-ideal channel with additional BER and PER parameters.

5.4 Algorithm

In this thesis, the average backoff time is used, the average service time is considered and the performance in each service time is analyzed. The probability

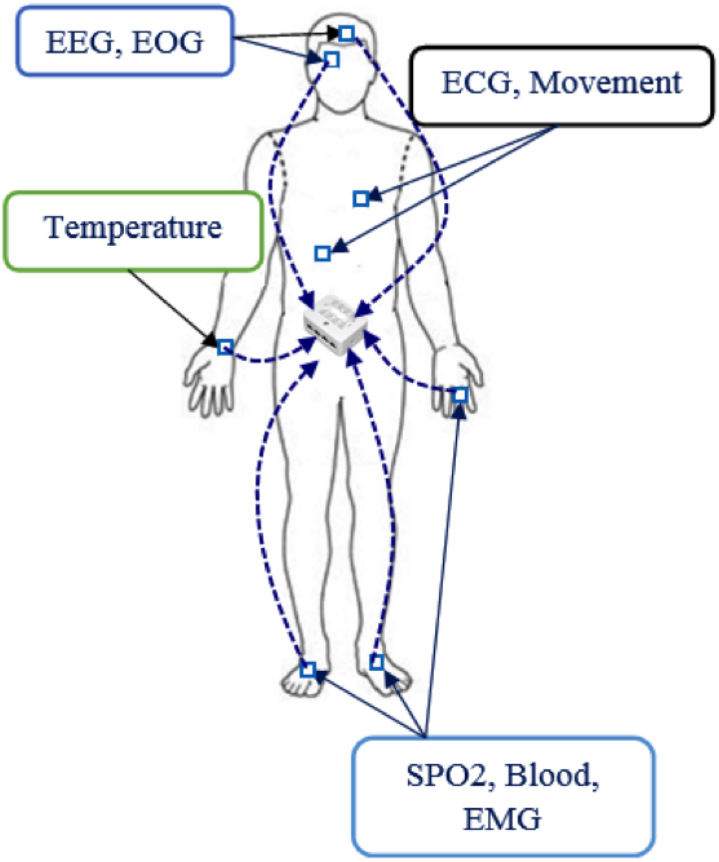

Figure 5.1 A star topology WBAN

that there is a packet to transmit after T_m duration time of a m^{th} UP sensor is described by

$$\rho_m = 1 - e^{-\lambda_m T_m} \tag{5–3}$$

Here λ_m denotes the packet arrival rate of the m^{th} UP sensors.

A packet of the m^{th} UP sensors is successfully transmitted if both two following conditions are satisfied. The first condition is that one or more than one m^{th} UP sensors have packet to send but only one m^{th} UP sensor accesses the channel. The second condition is that all other q^{th} UP sensors $(q \neq m)$ do not have packet to send or if they have packet to send, their backoff counters must be higher than backoff counter of the m^{th} UP sensor accessing the channel. Let p_{sucm}, p_{suc_1m} and p_{suc_2m} denote successful probability that a packet of the m^{th} UP sensors is successfully transmitted, probability of the first condition and probability of the second condition, respectively. As a result, the successful transmission probability of the m^{th} UP sensors, p_{sucm}, can be calculated as

$$p_{sucm} = p_{suc_1 m} p_{suc_2 m} \tag{5–4}$$

In the first condition, we assume that the total number of the m^{th} UP sensors is N_m and the number of the m^{th} UP sensors having a packet to send is i_m, $i_m \in [1, N_m]$. The probability that the m^{th} UP sensors have i_m sensors having a packet to send can be obtained as

$$p_{suc_1 m_1} = \begin{pmatrix} N_m \\ i_m \end{pmatrix} \rho_m^{i_m} (1-\rho_m)^{N_m - i_m} \tag{5–5}$$

Only one sensor of m^{th} UP sensor successfully transmits when its backoff counter is smallest and there is not other sensors have the same backoff counter or other sensors do not have packet to send. The average backoff counter of the m^{th} UP sensors can be calculated as

$$\overline{W_m} = \begin{cases} \frac{W_{\min}}{2} + P_{fail_m}^2 W_{\min} + P_{fail_m}^4 \frac{W_{\max}}{2} & \textit{for even UPs} \\ \frac{W_{\min}}{2} + P_{fail_m}^2 \frac{W_{\max}}{2} & \textit{for odd UPs} \end{cases} \tag{5–6}$$

Here, P_{fail_m} is the transmission fail probability of the m^{th} UP sensors.

The smallest backoff counter of the m^{th} UP sensor having smallest backoff counter is assumed as W_m, $W_m \in [1, \overline{W_m} - 1]$. The backoff counter of other m^{th} UP sensors must be higher than W_m meaning it must be within $[W_m + 1, \overline{W_m}]$. The probability that the backoff counter of a m^{th} UP sensor is set as W_m is represented as $\begin{pmatrix} i_m \\ 1 \end{pmatrix} \frac{1}{\overline{W_m}}$, and the probability that the backoff counter of the other m^{th} UP sensors are within $[W_m + 1, \overline{W_m}]$ is represented as $\left(\frac{\overline{W_m} - W_m}{\overline{W_m}}\right)^{i_m - 1}$. Consequently, the probability that in i_m m^{th} UP sensors having a packet to send there is one sensor takes the smallest backoff counter and others take higher backoff counter can be obtained as

$$P_{suc_1 m_2} = \sum_{W_m = 1}^{\overline{W_m} - 1} \begin{pmatrix} i_m \\ 1 \end{pmatrix} \frac{1}{\overline{W_m}} \left(\frac{\overline{W_m} - W_m}{\overline{W_m}}\right)^{i_m - 1} \tag{5–7}$$

As a result, the probability of the first condition, P_{suc_1m}, is calculated as

$$\begin{aligned} P_{suc_1m} &= \sum_{i_m=1}^{N_m} P_{suc_1m_1} P_{suc_1m_2} \\ &= \sum_{i_m=1}^{N_m} \left(\begin{array}{c} N_m \\ i_m \end{array} \right) \rho_m^{i_m} (1-\rho_m)^{N_m-i_m} \sum_{W_m=1}^{\overline{W_m}-1} \left(\begin{array}{c} i_m \\ 1 \end{array} \right) \frac{1}{\overline{W_m}} \left(\frac{\overline{W_m}-W_m}{\overline{W_m}} \right)^{i_m-1} \end{aligned} \quad (5\text{–}8)$$

Here $\left(\begin{array}{c} N_m \\ i_m \end{array} \right)$ denotes the binomial coefficient indexed by N_m and i_m.

In the second condition, we assume that the total number of the q^{th} UP $(q \neq m)$ sensors is N_q and the number of the q^{th} UP sensors having a packet to send is i_q, $i_q \in [0, N_q]$. Probability that the q^{th} UP sensors have i_q sensors having a packet to send can be obtained as $\left(\begin{array}{c} N_q \\ i_q \end{array} \right) \rho_q^{i_q} (1-\rho_q)^{N_q-i_q}$, the same with formula (5-5). If any q^{th} UP sensor has packet to send, its backoff counter should be higher than W_m. The probability that all i_q q^{th} UP sensors having packet to send but their backoff counter are higher than W_m is $\left(\frac{\overline{W_q}-W_m}{\overline{W_q}} \right)^{i_q}$ in which if $\overline{W_q} \leq W_m$, $\frac{\overline{W_q}-W_m}{\overline{W_q}}$ is assumed to be zero. Therefore, The probability of the second condition, P_{suc_2m}, can be calculated as

$$P_{suc_2m} = \prod_{\substack{q=0 \\ q \neq m}}^{7} \sum_{i_q=0}^{N_q} \left(\begin{array}{c} N_q \\ i_q \end{array} \right) \rho_q^{i_q} (1-\rho_q)^{N_q-i_q} \left(\frac{\overline{W_q}-W_m}{\overline{W_q}} \right)^{i_q} \quad (5\text{–}9)$$

Finally, the successful transmission probability of the m^{th} UP sensors in formula (5–4), P_{sucm}, can be rewritten as

$$\begin{aligned} P_{sucm} &= P_{suc_1m} \times P_{suc_2m} \\ &= \sum_{i_m=1}^{N_m} \left(\begin{array}{c} N_m \\ i_m \end{array} \right) \rho_m^{i_m} (1-\rho_m)^{N_m-i_m} \sum_{W_m=1}^{\overline{W_m}-1} \left(\begin{array}{c} i_m \\ 1 \end{array} \right) \frac{1}{\overline{W_m}} \left(\frac{\overline{W_m}-W_m}{\overline{W_m}} \right)^{i_m-1} \\ &\times \prod_{\substack{q=0 \\ q \neq m}}^{7} \sum_{i_q=0}^{N_q} \left(\begin{array}{c} N_q \\ i_q \end{array} \right) \rho_q^{i_q} (1-\rho_q)^{N_q-i_q} \left(\frac{\overline{W_q}-W_m}{\overline{W_q}} \right)^{i_q} \end{aligned} \quad (5\text{–}10)$$

The throughput in each T_m duration time, S_{T_m}, and the throughput of the m^{th} UP sensors 1s, S_m, can be calculated as

$$\begin{aligned} S_{T_m} &= P_{sucm} E[x]; \\ S_m &= n_{T_m} S_{T_m} \end{aligned} \quad (5\text{–}11)$$

Here, $E[x]$ is the average packet payload size and n_{T_m} denotes the number of T_m duration times in each second, $n_{T_m} = \mathit{floor}\left(\frac{1}{T_m}\right)$.

In order to evaluate the effect of the remained packet, the successful probability after t times of T_m, $P_{sucm}(t)$, will be used. Therefore the successful probability P_{sucm} is replaced by $P_{sucm}(t)$, in which ρ_m is replaced by $\rho_m(t)$ that is the probability that a m^{th} UP sensor has a packet to send after t times of T_m. In IEEE 802.15.6 based on CSMA/CA, the packet is discarded after the retry limit. According to application, the time-out data is deleted even the number of retransmission does not reach the retry limit. The time-out of data is set as k times of T_m, meaning that at the time $t = k + 1$ packets generated at time $t = 1$ are discarded. As a result, $\rho_m(t)$ can be calculated as

$$\rho_m(t) = \begin{cases} = \rho_m & ;\mathit{for}\ t = 1 \\ = \rho_m + \rho_m(t-1) - \frac{P_{sucm}(t-1)}{N_m} & ;\mathit{for}\ 1 < t \leq k \\ = \rho_m + \rho_m(t-1) - \frac{P_{sucm}(t-1)}{N_m} - \rho_m(t-k)\prod_{l=t-k}^{t-1}\frac{P_{failm}(l)}{N_m} & ;\mathit{for}\ t \geq k \end{cases} \tag{5–12}$$

Here, $P_{failm}(t)$ is the fail transmission probability at time t of the m^{th} UP sensors due to the q^{th} UP $(q \neq m)$ sensors accessing the channel or the m^{th} UP sensors transmitting packet unsuccessfully because of collision or error. The probability $P_{failm}(t)$ can be calculated as

$$P_{failm} = 1 - P_{sucm}(t) - P_{idle} \tag{5–13}$$

Here, P_{idle} is the probability that all the sensors of system do not have a packet to send, $P_{idle} = \prod_{m=0}^{7}(1-\rho_m)^{N_m}$.

In some scenarios, a sensor may have more than one packet to send and then $\rho_m(t)$ may be more than one. In these scenarios, the data in the newest packet is updated and the data in other packets is outdated. Consequently, only the newest packet is kept to send and others are deleted as the time-out packets. Therefore, $\rho_m(t)$ is defined as $\rho_m(t) = \min(\rho_m(t), 1)$ for all t. The throughput of the m^{th} UP sensors after t times of T_m is calculated as

$$S_{T_m}(t) = P_{sucm}(t)E[x] \tag{5–14}$$

The throughput of the m^{th} UP sensors after t_n seconds can be obtained as

$$S_m(t) = \sum_{t=(t_n-1)}^{t_n n_{t_m}} S_{T_m}(t) \tag{5–15}$$

The average system throughput after t_n seconds can be obtained as

$$S(t_n) = \frac{1}{N} \sum_{m=0}^{7} S_m(t_n) \tag{5–16}$$

Here, N is the total number of sensors

5.5 Performance analysis under non-ideal channel

At the above step, the thesis have developed algorithm for performance analysis of WBANs under ideal channel. It means that if one sensor successfully accesses the channel, it will successfully transmit a packet because of no noise or interference. In other words, the successful transmission probability, $P_{sucm}(t)$, in Equation (5-10) has almost the same meaning with the successful access probability, $\hat{P}_{(i,suc)}$, in Equation (4-34). As a result, when the proposal dynamic statistical method is extended for non-ideal channel or real channel with additional BER and PER parameters, the successful transmission probability in Equation (5-10) should be changed as the successful transmission probability, $P_{(i,suc)}$, as in Equation (4-34). Finally, the successful transmission probability under non-ideal channel condition, $P_{realsucm}(t)$, is calculated as

$$P_{realsucm}(t) = P_{sucm}(t)(1 - PER_m) \tag{5–17}$$

Moreover, the throughput of the m^{th} UP sensors after t times of T_m in the non-ideal channel or real condition is calculated as

$$S_{realT_m}(t) = P_{realsucm}(t)E[x] \tag{5–18}$$

Finally, when we analyze the system on MAC layer, however, consider system working in non-ideal channel, the coding scheme is employed, leading to the proposal methods for performance analysis of WBANs can be considered as cross layer analysis.

Chapter 6

Proposal adaptive BCH code rates for WBANs

6.1 Chapter overview

In this thesis, we propose the MCMC and dynamic statistical methods to analyze performance in the PHY and MAC layers for WBANs, in which BERs are taken into consideration. With the MCMC method, the BERs are theoretically analyzed depending on different BCH code rates, and then the BCH code rate for every sensor node is optimized in sense of the highest throughput while assuming the signal to noise ratio (SNR) of every sensor node is different.

Furthermore, the dependence of throughput on the BER is clearly explained by calculating the access probability for every sensor node in large SNR region. The BCH code was adopted as an example and then adaptive BCH code rates for WBANs were proposed. The application of proposal method to other error correcting codes is straightforward.

6.2 Packet error rate

As explanation in the previous section, the BER/PER is taken into account and the access probability is changed depending on PER. In this section, we describe a method to calculate the PER of system.

Because of using the DBPSK modulation, the BER after demodulation is represented by $p_i = \frac{1}{2}e^{-SNR_i}$ [41], here SNR_i is the received SNR at the coordinator while the sensor node i is transmitting. Furthermore, due to application of the BCH code, the BER after decoding is described as follows [42].

$$BER_i = \sum_{j=t+1}^{m} \left(\begin{array}{c} N_q \\ i_q \end{array} \right) p_i^j (1-p_i)^{m-j}, \tag{6–1}$$

Where m and t denote the block length and the error correction capability of BCH code, respectively. Finally, the PER can be calculated as

$$PER_i = 1 - (1 - BER_i)^x. \tag{6–2}$$

According to the standard, the payload of frame can be changed within [0, 255] bytes and let the longest block length of BCH code be 127 bits. The detail of BCH code is represented in Table 6.1. Here h denotes the number of information bits in every block code. Thus, the code rate, r, becomes $r = \frac{h}{m}$. In this thesis, the BCH code is adopted as an example, however, the other error correcting codes can be easily applied by changing (6-1).

6.3 Constant BCH code rate

In this work, we analyze the performance of WBANs with different received SNR of coordinator and discuss the relationship between SNR and BCH code. Thus, we assume that the received SNR of coordinator from every sensor node is different and varies within [1dB, 10dB]. Let the received SNR from sensor node i be set as i dB, for $i = 1, \ldots, 10$. This means that the WBANs consisting of one coordinator and 10 sensor nodes are analyzed. The retry limit and the packet generation rate are fixed to be 5 times and 5 packets/second, respectively. The other parameters are the same as explanation in previous sections.

In this section, the code rate of all sensor nodes is assumed to be the same and the payload is fixed as 200 bytes. An example of throughput of every sensor node corresponded to several code rates is shown in Fig. 6.1 [35], the representation of BCH code is as (m,h,t). According to the SNR, the throughput of all sensor nodes, which equip the same code rate, is different. For small error correction

Table 6.1 Examples of BCH code

m	h	t	m	h	t	m	h	t
7	4	1	63	39	4	127	92	5
15	11	1		36	5		85	6
	7	2		30	6		78	7
	5	3		24	7		71	9
31	26	1		18	10		64	10
	21	2		16	11		56	11
	16	3		10	13		50	13
	11	5		7	15		43	14
	6	7	127	120	1		36	15
63	57	1		113	2		29	21
	51	2		106	3		22	23
	45	3		99	4		15	27
							8	31

capability meaning high code rate, the throughput of the sensor nodes in high SNR region is high because of low PER, on the contrary, the throughput of the sensor nodes in low SNR region is close to zero due to high PER. Moreover, for high error correction capability, the throughput of sensor nodes in both low and high SNR regions is the same. The reason is explained by (6-2) and Fig. 6.2 [35]. It can be said that the payload is large (1600 bits), the PER therefore is close to one for low SNR, and then sharply decreased while increasing the SNR.

On the other hand, the access probability of every sensor node corresponded to several code rates is shown in Fig. 6.3 [35]. For low SNR and low error correction capability, the access probability reaches to the largest value 3.5×10^{-3} due to the high number of retransmissions. On the other hand, the access

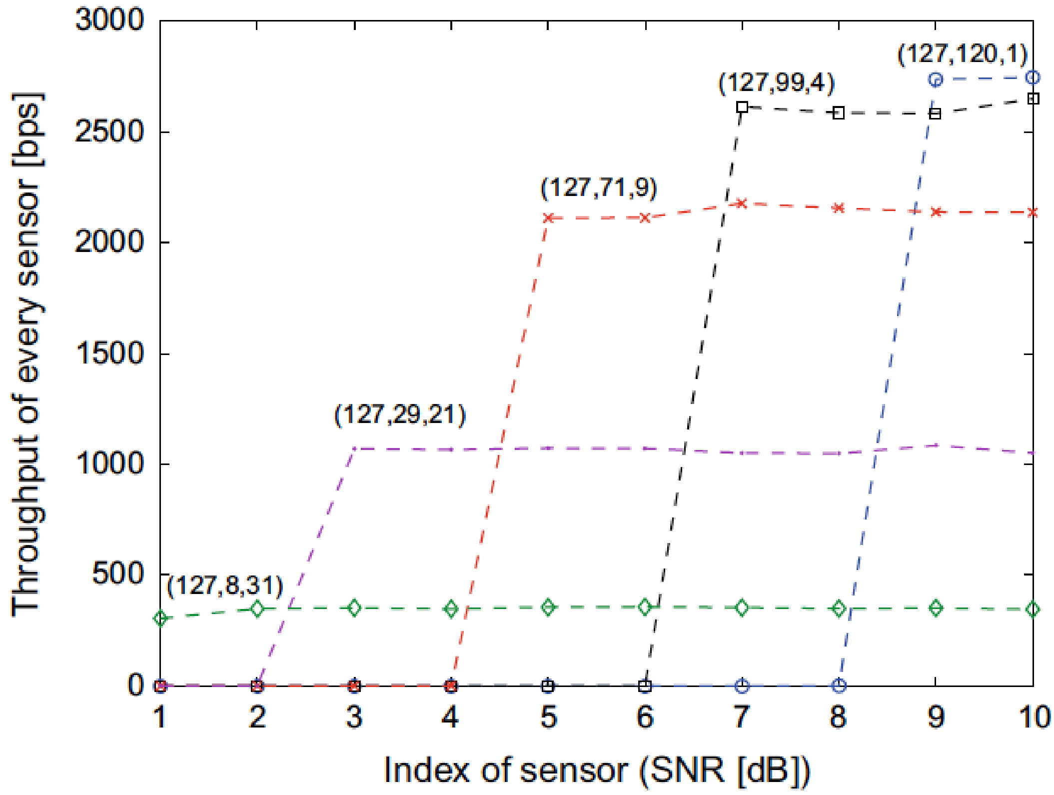

Figure 6.1 The throughput of every sensor

probability achieves the smallest value 6×10^{-4} with for high SNR and/or high error correction capability, which is the same as the access probability of noise free systems. The dependence of the access probability on SNR because of chain of causes and effects is explained as that the SNR affects BER, and then BER affects PER as well as the successful transmission probability. If one sensor node unsuccessfully transmits data, it needs to retransmit the data, consequently, that makes the access probability increase.

Figure 6.4 [35] shows the total throughput of all sensor nodes while the error correction capability is varying. As explained above, when the error correction capability is large, the number of sensor nodes that successfully transmitted is large, however, the throughput of every sensor node is low due to low code rate. Therefore, the total throughput of all sensor nodes is low. On the contrary,

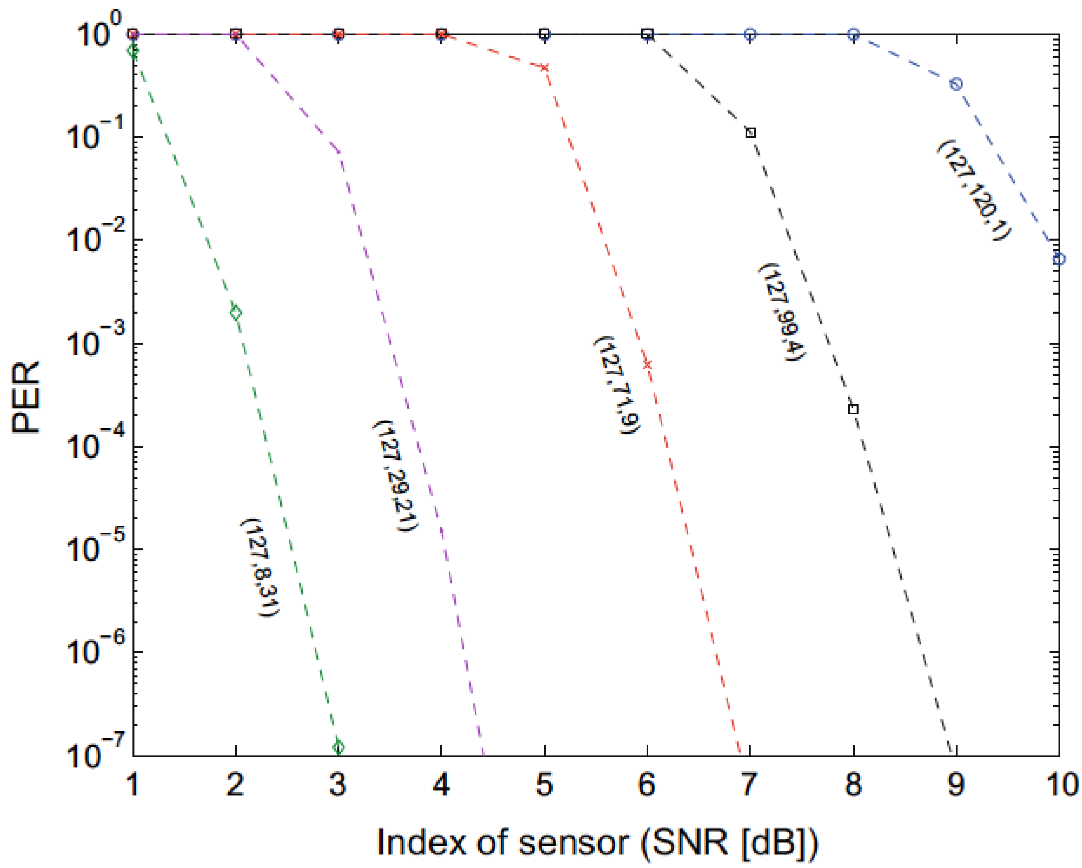

Figure 6.2 The PER of every sensor

when the error correction capability is small, the throughput of some sensor nodes is large, however, the throughput of many sensor nodes is close to zero. As a result, the total throughput of all sensor nodes is also low. In this system model, the total throughput achieves the maximum where the error correction capability is nine.

From view of total throughput, the (127,71,9) of BCH code should be adopted, whereas from view of error correction capability, the (127,8,31) of BCH code should be used. It can be said that there is the trade-off of the error correction capability and the access probability, which restricts the performance of system. In order to improve the performance of system, adaptive code rates for WBANs are proposed in following section.

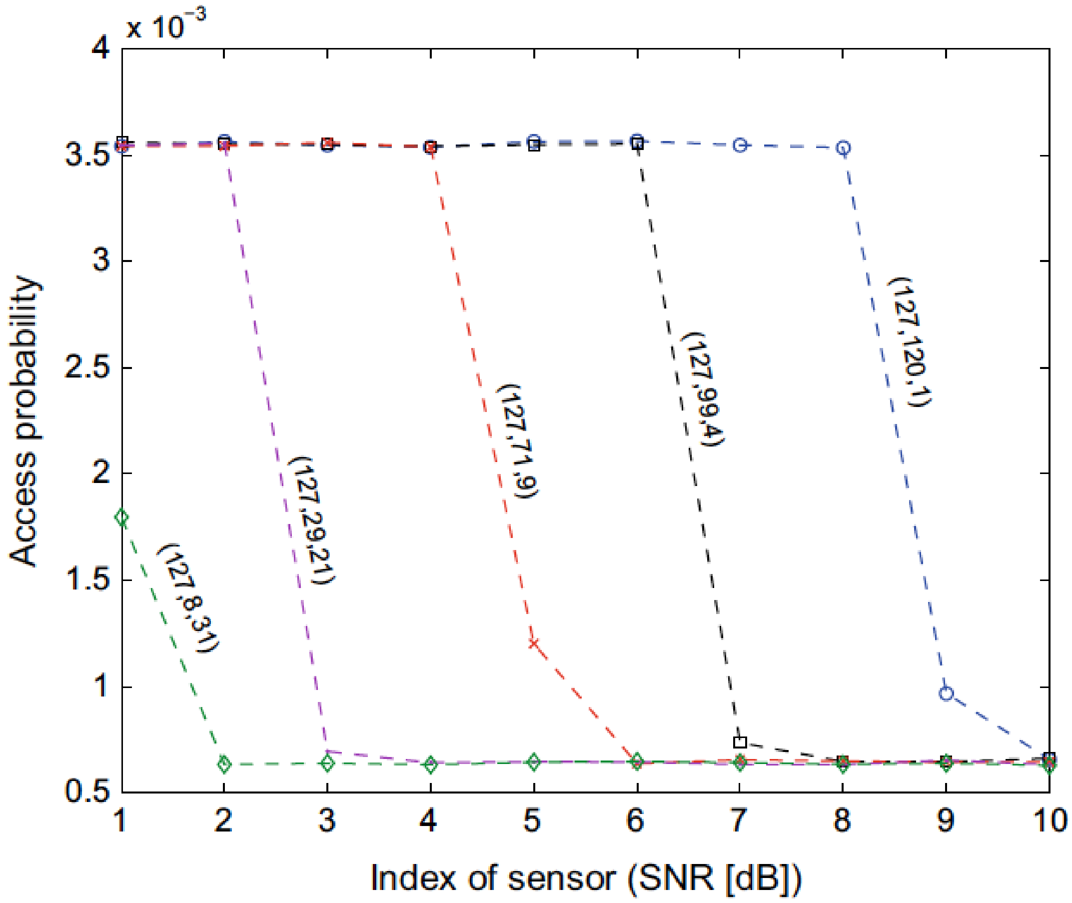

Figure 6.3 The access probability of every sensor

6.4 Adaptive BCH code rate

The optimal code rate for every SNR is defined as the value that achieves the maximal throughput regardless of other sensor nodes. Therefore, the optimal code rate is changed depending on the SNR, it is called as adaptive BCH code rate for WBANs.

$$OptiBCH_i = \underset{\forall BCH\ code}{\arg\max} \left(\lambda x r (1 - PER_i)\right) \tag{6–3}$$

The optimal BCH code rate of this system model is summarized in Table 6.2.

The bound of throughput in case all sensor nodes have the same code rate (Fig. 6.1), named bound for constant code rate, is compared to the throughput of adaptive BCH code rate in Fig. 6.5 [35]. The throughput of adaptive BCH code

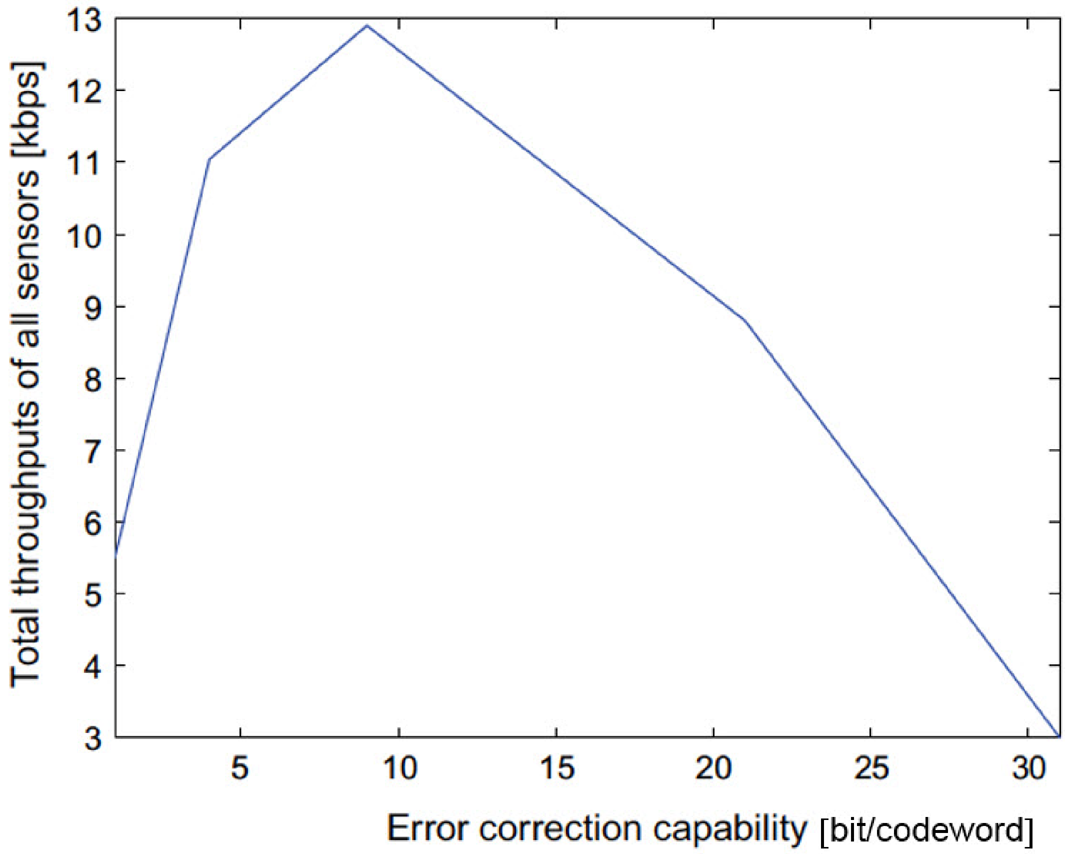

Figure 6.4 The total throughput of all sensors

rate is considerably higher, especially in high SNR region. It can be explained that in high SNR region, the throughput reaches the maximum where the error correction capability is small. However, for constant code rate, the PER of many sensor nodes is close to one, thus the number of retransmissions and the access probability of these sensor nodes greatly increases. Therefore, the collision probability increases and the average access successful probability decreases, meaning that the bandwidth efficiency is low. On the other hand, for adaptive BCH code rate, the number of retransmissions is small due to low PER, therefore, the access probability of every sensor nodes is small. This means that the access successful probability and the bandwidth efficiency are high. As a result, the throughput of adaptive BCH code rate is higher.

Table 6.2 Optimal BCH code rate for every SNR

SNR	1	2	3	4	5	6	7	8	9	10
m	127	127	127	127	127	127	127	127	127	127
h	8	15	29	43	64	78	99	106	113	120
t	31	27	21	14	10	7	4	3	2	1

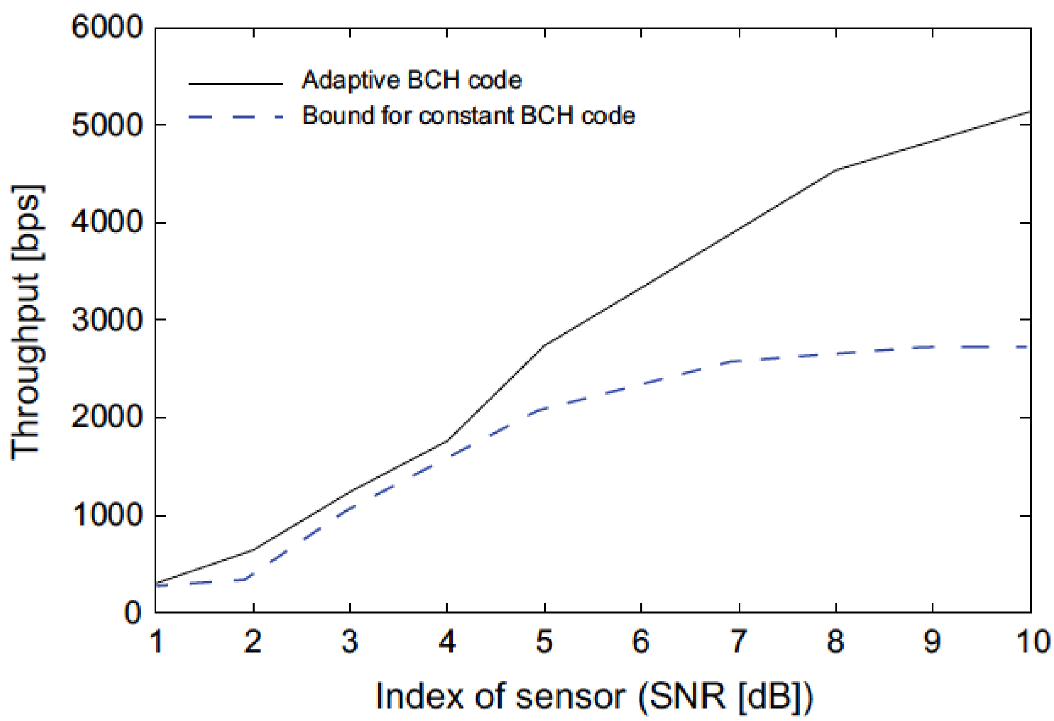

Figure 6.5 Comparing throughput of adaptive BCH code rate and bound for constant code rate

Chapter 7

Conclusion

A dependable and efficient MAC protocol is really important with WBANs when they are applied for medicine or even though for non-medicine. Better MAC protocol can produce low energy consumption or at least can guarantee the timely delivery of emergency traffic. Therefore, beside of improving MAC protocol, correctly analyzing it is necessary. There have been many works on performance analysis of IEEE 802.15.6, especially based on CSMA/CA scheme. The performance analysis on WBANs MAC layer can be clarified into two groups, using Markov chain model to simulate the state of sensor in WBANs and non-Markov chain model approach.

By employing DTMC model, many previous works can illustrate the state of all sensor in WBANs or simulate how sensors working and affecting together in the system. As a result, previous works can calculate the access probability of all sensors and then calculate throughput and energy consumption or delay and consider these as final results. After reviewing carefully previous works, the authors of the thesis found out limitations as frequent assuming that channel is ideal and finishing such at analyzing, not optimizing or proposing any new technology, protocol or system. In order to overcome these limitations, the thesis developed MCMC method to analyze performance of WBANs under non-ideal channel by taking into account BER and PER. The MCMC method can be considered as development or adjustment of the DTMC method with key idea is to find the access probability approximately. Moreover, not finishing at analyzing performance, the thesis propose adaptive BCH code rates for WBANs and the thesis also proved that this adaptive code can produce significantly higher throughput for WBANs.

On the other hand, the DTMC method consists of method limitations as using assumption like saturation condition and non-saturation condition, and not taking into account remained packets. The saturation condition in this thesis can be explained as if a sensor in WBANs always has a packet to send or in its UP queue there is always a packet waiting to be served, the sensor is saturated. In fact, saturation condition is likely to be relative with high traffic. The remained packets are the packets transmitted unsuccessfully due to collision or error. As a result, there are some previous works on MAC layer for WBANs not using the DTMC method. However, these works have limitations as consideration system having only a sensor node and a coordinator, or system with many sensors but only single UP, consequently, the effect each other of sensors in the same UP or different UPs is not taken into account. From these points, the thesis proposed dynamic statistical method for performance analysis of the WBANs on MAC layer, taking into account remained packets and analyzing system performance changing following operation time and due to variable packet arrival rate, the number of sensors, payload size, retry limit and user priority levels. The proposal method has been expected to be more flexible and precise.

The thesis produced three main results, proposing two methods, the MCMC and dynamic statistical method, for performance analysis of WBANs, and then proposing the adaptive BCH code rates for WBANs with higher throughput, which was already proved. The thesis still contains drawbacks or unsolved problems. Firstly, the proposal adaptive BCH code may cause system to become more complex and this is not solved yet in the thesis. Secondly, with the proposal dynamic statistical method in this thesis is only finished at algorithm. For the future work of this thesis, the authors hope to apply the MCMC method to other coding schemes with deep analysis of changing the complexity and energy consumption of system when adaptive coding scheme is employed. With the proposal dynamic statistical method, authors need to develop simulation program to produce the throughput or energy consumption of system and compare these with outstanding previous work results to prove the proposal method and then extend the proposal method with real channel under noise and interference condition, employing cross layer with coding in order to optimize parameters of system.

Published Papers

Reviewed Journal Papers

(1) Do Thanh Quan, Pham Thanh Hiep, Ryuji Kohno. “Performance Analysis Method for IEEE 802.15.6 Based WBANs with Adaptive BCH Code Rates”. Wireless Personal Communications. Volume: 91. DOI: 10.1007/s11277-016-3639-4. Pages: 1-15. August, 2016.

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International Conference Papers

(1) Do Thanh Quan, Pham Thanh Hiep, Takumi Kobayashi, Kento Takabayashi, Ryuji Kohno. “Proposal Methods for Performance Analysis of WBANs Based on CSMA/CA”. International Symposium on Medical Information Communication Technology (ISMICT 2017), Lisbon, Portugal. February, 2017.

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