A CSMA/CA Based MAC Layer Solution for Inter-WBAN Interference and Starvation

by

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Abstract

With the advancement in wireless communication technologies, E-healthcare system has been proposed to deal with the issues such as inefficiency, high cost, and degradations in service quality in traditional health-care systems. Wireless Body Area Network (WBAN) is widely used in E-healthcare system as it provides continuous monitoring on physiological parameters. However, when two or more WBANs overlap with each other, there exists inter-WBAN interference. The inter-WBAN interference may cause transmission failures, which result in packet losses, throughput degradations, and energy wastes for energy limited sensors. This motivates us to develop a distributed CSMA/CA-based MAC protocol for inter-WBAN interference management. There are three challenges, namely, power optimization, protocol response time, and starvation in designing such a protocol. In this thesis, the power optimization challenge is overcome by an innovative WBAN system. To deal with the challenges in protocol response time and starvation, the proposed MAC protocol extends the CSMA/CA protocol with an adaptive transmission probability that uses frozen time as the adjustment criterion and a back-off counter adjustment mechanism that prioritizes the starving nodes. The proposed protocol achieves throughput improvement, starvation mitigation, and energy efficiency for sensors. Simulation results demonstrate the effectiveness of the proposed MAC protocol for health-care applications in scenarios such as having dinner at a round table or sitting in a hospital waiting room.

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Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

The traditional health-care system is at a crossroads. It is on the verge of revolutionary changes with the rapid development of the wireless communication technologies.

On one hand, acute disease is one of the top causes of deaths, and the traditional health-care system is inefficient in dealing with acute diseases. According to the "List of causes of death by rate", 50 percent of the deaths are caused by heart diseases and strokes [1]. In U.S. alone, 150,000 people are killed by stroke each year [2]. While the traditional health-care system is inefficient in handling these situations, sudden deaths like these can be largely prevented by continuous monitoring the vital physiology signals of an individual so that the predictions can be made and proper medical cares can be applied ahead of time. In worst case, the fastest response is guaranteed on the detection of an emergency, so that the chance of survival is greatly increased.

On the other hand, the rapid growth in aging population is overloading the service capacity of the traditional health-care system and reducing the quality of the service [3–7]. According to the U.S. Census Bureau, the world's population of 65 and older is projected to be tripled, reaching 1.53 billion in 2050 comparing with that in 2009 [8,9]. The situation is worse in many Europe and Asia countries, where the average age will soon reach 50-year-old with the largest age group shifted to 65 year-old and above [10]. The increasing aging population poses great challenges to tradition health-care system in two ways. First, since the elders usually suffer from chronicle illnesses and require long-term monitoring, accurate disease management, and medication screening [9], the traditional health-care system will be overburdened, resulting in a degrade in quality of service. It is reported that 133 million people live with a chronic condition, and the number is expected to reach 171 millions by 2030 [9]. With such a rate of increase, the traditional health-care system will soon be under great pressure. Second, traditional health-care system is not fast enough in handling the emergency situation when a senior fall onto the ground. For elders over 65 years old and above, the leading cause of death is falling [10]. Many of those who survive from a fall will suffer from hip fracture, of which 20 percent will die within in a year [10].

With the recent advancement of wireless communication technologies, e-healthcare system was proposed as a revolutionary solution for the issues mentioned above [7, 11–14]. Utilizing the wireless communication technologies, e-healthcare system provides continuous real-time health monitoring using wearable devices, which reduces service costs, improves service quality and efficiency, improves the ability for the health-care system to deal with emergencies, and extends its capability in making predictions to accurate diseases. The effectiveness of the e-healthcare system is relying on the advancement of Wireless Body Area Network technologies [15], which makes the continuous monitoring of physiological parameters possible by deploying bio-sensors on patients' bodies even during their daily activities [16, 17], thus shifting part of the health-care tasks from the traditional clinical environment to a pervasive user-centered setting [10, 12]. Such a shift greatly reduces the service costs and improves the service qualities by efficient allocations of the clinical resources. In addition, the ability to do continuous real-time health-monitoring makes the early detection and prediction on acute diseases possible.

1.1 Wireless Body Area Network

WBANs collects and monitors the health related data such as body temperature, blood pressure, electrocardiographs (ECG, for heart activity), electroencephalographs (EEG, for brain activity), and motion related activities of a wearer [18]. The collected data can either be processed in real-time by smart phones or forwarded to medical servers [11,15,19,20], so that the historical data can be saved for further analysis [21], and the responsible personnels can be notified in case of an emergency [4,22].

The advancement of the WBAN technology makes continuous real-time health monitoring possible. The WBAN systems are wireless in nature, which allows the patients to move around freely, thus establishing a user-friendly health-care environment that improves the efficiency of the health-care service inside and outside the hospital [23,24]. Before the popularization of the smart phones, a WBAN is usually composed of a central processing node (CPN) and a group of wearable sensors. With the development of mobile technologies, the smart phone replaces the central processing node and becomes the new WBAN standard. As illustrated in Figure 1.1, the sensors are connected to smart phone in star topology, so that each sensor only communicates with the smart phone in the same WBAN. Each WBAN is deployed around the body of a wearer. To achieve better user experience and portability, it is very common to integrate multiple wireless sensors into one these days. Two good examples of such a trend are “Simband” from Samsung and “Apple Watch” from Apple.

Three new characteristics, namely, energy limitation, high mobility, and group-based movement [25] were introduced to Wireless Body Area Nework (WBAN) comparing with the traditional Wireless Sensor Network (WSN). First, the deployed bio-sensors in WBANs are limited in transmission energy and require that the battery replacement be as infrequent as possible. Changing batteries for sensors will cause service pauses and is usually very inconvenient. An extreme case is the implanted sensors, for which there is no chance for battery change [3]. In addition, the wearable sensors are usually very small [7]. Most sensors are less than 1 cubic centimeters [26], which limits the battery size and results in a

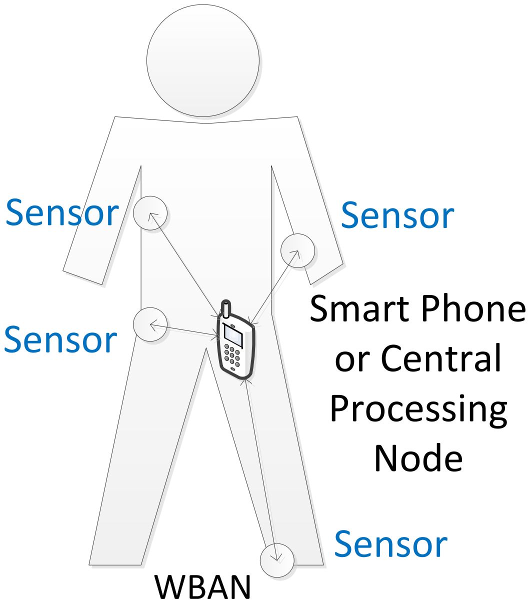


Figure 1.1: Star topology of Wireless Sensor Area Network (WBAN)

limitation in transmission energy. Second, because of the high mobility nature of WBANs, the network topology is dynamic and changing fast. Since WBAN wearers are moving freely in a large area during their daily activities, the WBAN is featured with the high mobility characteristic. Finally, since the sensors are deployed around the body of a wearer, the smart phone and the sensors are moving together with the wearer, which granted WBAN the group-based movement feature. Because of this, the one-hop communication link remains unchanged for each WBAN even if the network topology changes fast.

There are two basic requirements for WBAN applications. Since a WBAN is mainly used in health-care applications and is responsible for the delivery and analysis of vital physiological signals, the first basic requirement is high reliable communication [27]. The second requirement is low power consumption [27], which is a direct reflection of the energy limitation characteristic of WBAN.

In the following sections, it will be discussed in detail how these unique features are resulting in a new issue called inter-WBAN interference, and how they are having an impact on the design of the WBAN system.

1.2 Inter-WBAN Interference

Since there are limited number of frequencies for wearable sensors to communicate with the smart phone within a WBAN, inter-WBAN interference will happen when the number of WBANs whose communication ranges overlap with each other is larger than the number of available frequency bands [18]. Figure 1.2 illustrated a simple inter-WBAN interference scenario between two WBANs when there is only one frequency band available. Since the communication range of WBAN 1 covers the sensors and the smart phone in WBAN 2, when the sensors in WBAN 1 communicate with the smart phone in WBAN 1, the smart phone in WBAN 2 receives the transmitted signal as well. Thus, if the sensors in WBAN 2 start the transmissions at the same time, inter-WBAN interference happens at the smart phone in WBAN 2. The same interference happens for WBAN 1 as well. A direct cause of the inter-WBAN interference issue is the high mobility characteristic of WBAN [28]. Since the wearers are allowed to move around freely, the communication ranges of two or more WBANs can overlap. In literature, this harmful effect is referred to as inter-WBAN interference, inter-network interference, co-channel interference, coexistence, or dynamic coexistence. In this thesis, inter-WBAN interference is used exclusively to describe this harmful effect.

With the popularization of the E-healthcare system, it can be foreseen that the inter-WBAN interference will become a problem. There were approximately 11 million active WBANs in 2009, and the amount of active WBANs was predicted to reach 420 million in 2014 [29]. Thus, in the future, it is inevitable that serval WBANs will coexist in places such as a crowded bus, a hospital waiting room, or a meeting room [30] and suffer from the inter-WBAN interference.

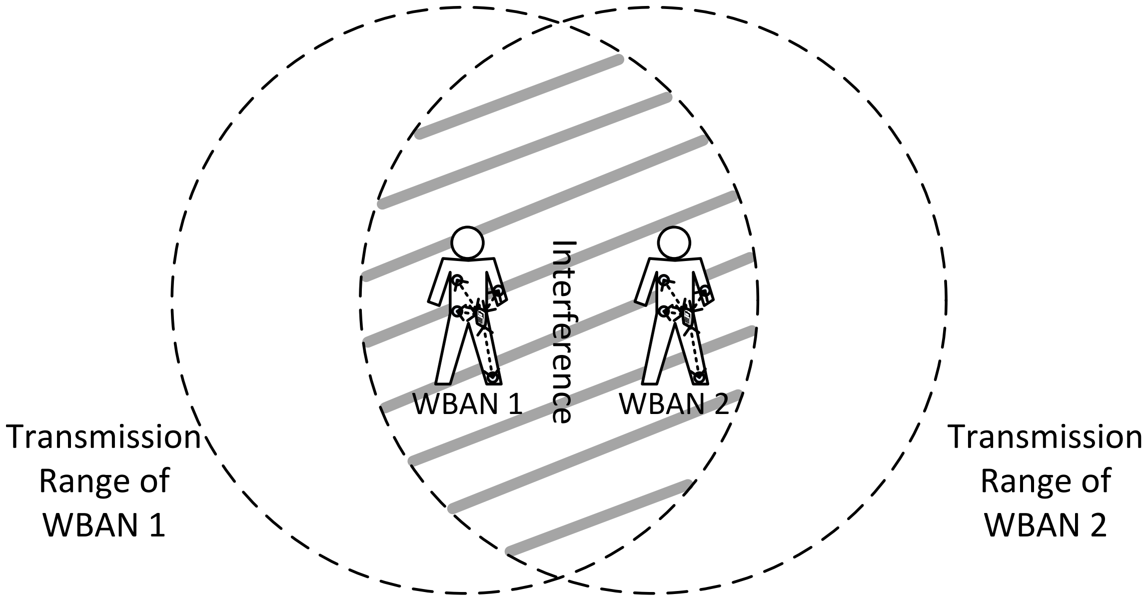


Figure 1.2: Inter-WBAN Interference of Wireless Sensor Area Network (WBAN)

Inter-WBAN interference is particularly harmful for health-care applications and there is a growing demand to address this issue. Inter-WBAN interference causes transmission failures, which results in packet losses, throughput degradation, and energy waste for wearable sensors [23,25,29,31]. This violates the two basic requirements of WBAN applications, namely, high reliable communication and low power consumption. An example of such a growing demand is reflected in IEEE 802.15.6 [32], in which it is a requirement that a system must maintain a reliable performance when ten or more WBANs coexist in a space of six square meters [29].

1.3 Starvation in CSMA/CA Protocol

Since a CSMA/CA-based MAC layer solution is proposed to handle inter-WBAN interference issue in this thesis, starvation becomes another important issue and must be introduced first. In this section, nodes, instead of WBANs, are used to demonstrate how starvation happens. The differences between a node-based CSMA/CA network and a WBAN system will be introduced in section 2.2.

Starvation is defined as the harmful effect that some nodes in the network have significantly larger (usually more than ten times [33]) throughputs than those of the others. Although the CSMA/CA-based MAC protocols are effective for networks with fast changing topologies and are widely adopted as distributed MAC protocols with good hardware supports, it is well know that they suffer greatly from unfairness and starvation problems. The starvation problem is caused not only by spatial bias referred to as Flow-in-the-Middle, but also by a generic coordination problem referred to as Information Asymmetry [33]. These two issues are explained in detail in [33] and will be introduced in the following sub-sections.

1.3.1 Flow in the Middle

The first scenario that causes starvation is called Flow-in-the-Middle (FIM). It is a common network topology in which some flows have an advantage over the others. Figure 1.3 is an illustration of a basic scenario when there are only three flows in the network. A flow is a communication link between two nodes. It can either be active or inactive. The direction of the flow is indicated by an arrow. In Figure 1.3, each node is represented by a number, and the interfering relationships are represented by solid lines while the flows are represented by solid arrows. In a network topology like this, Flow A and Flow C will have significantly larger (usually ten times larger [33]) throughputs than that of Flow B. In this situation, Flow B is said to undergo a starvation.

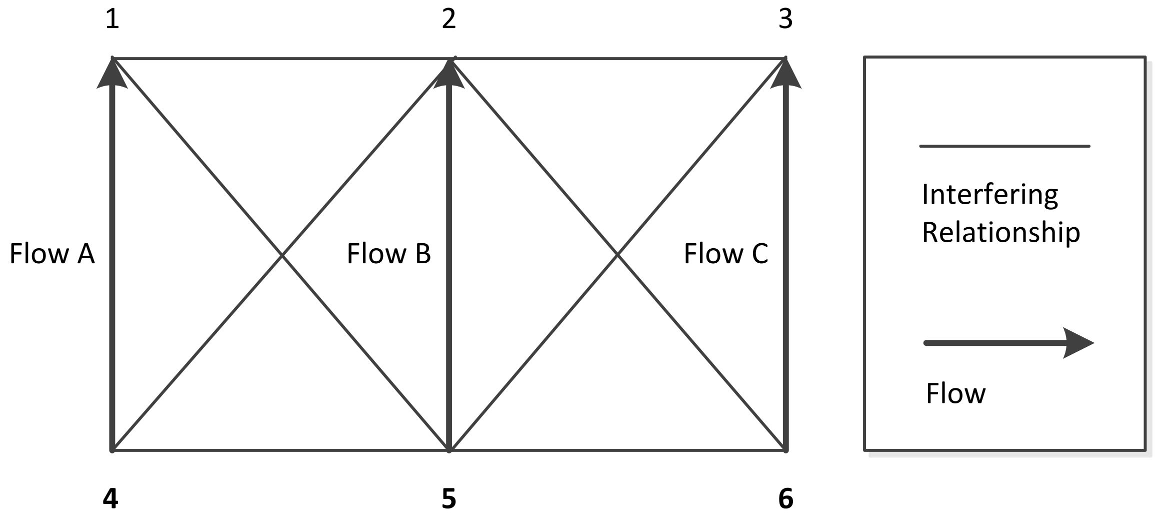


Figure 1.3: Starvation Scenario 1 - Flow in the Middle

The starvation at Flow B is caused by spatial bias and can be explained as follows. When node 4, the sender of flow A captures the channel, node 5, the sender of Flow B is forced to enter the frozen stage in which neither transmission nor back-off counter deduction is allowed according to CSMA/CA protocol. This gives node 6, the sender of Flow C an advantage in capturing the channel since its interfering neighbors, node 5 and node 2 are not transmitting. In this case, when node 6 finishes its back-off during the active period of Flow A, Flow C will be active. Since Flow C and Flow A are unsynchronized, they have a very high probability of being active in turn as soon as one of them becomes active. Thus, the probability that node 5, the sender of Flow B, captures the channel is very small since the only chance for it to deduct its back-off counter is when both Flow A and Flow C are at their back-off stages.

1.3.2 Information Asymmetry

The second scenario that causes starvation is called information asymmetry, which is a direct result of the way the CSMA/CA protocol operates. Using the same legend in Figure 1.3, a common scenario that causes information asymmetry is illustrated in Figure 1.4. In this scenario, the throughput of Flow A is much lower than that of Flow B. The reason is that while node 3, the sender of Flow B can sense whether Flow A is active, node 1, the sender of Flow A can not sense whether Flow B is active. The inequality in network information puts Flow A in an disadvantage, which results in a high packet loss rate for Flow A. Even with RTS/CTS handshaking, the inequality in network information still exist, since the sending attempts of Flow B must be fitted to the back-off periods of Flow A [33].

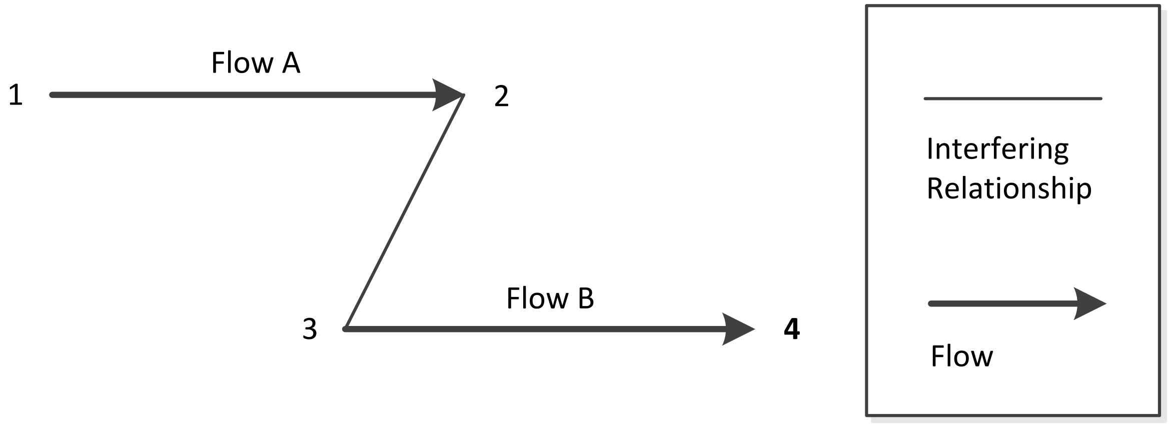


Figure 1.4: Starvation Scenario 1 - Information Asymmetry

1.4 Related Work

In this section, researches on inter-WBAN interference and starvation are discussed.

1.4.1 Inter-WBAN Interference Management

The researches on inter-WBAN interference issue can be categorized to physical layer approaches and MAC layer approaches.

Several pioneer works on inter-WBAN interference issue mainly focus on physical layer analysis and solutions. Zhang *et al* [34] studied the SINR and BER performance of TDMA, FDMA, and CDMA schemes and concluded that TDMA scheme is the best solution as its peak radiation power meets the specific BER requirement. In [35], the analysis for inter-WBAN interference is focused on the probability density function of the total interference. The minimum networked distance to ensure boundary SINR and average SINR is then calculated. To minimize the transmission energy, G. Fang *et al* [23] proposed a distributed inter-network interference aware power control algorithm motivated by game theory. Assuming that the intra-WBAN interference is solved by a TDMA-based MAC scheme, the power control game is formulated by taking the inter-network interferences between WBANs, wireless fading channel, and energy constraint of WBANs into considerations.

Others seek to solve the inter-WBAN interference problem in MAC layer. Two cooperative communication schemes were presented in [29] and [36]. Assuming that the intra and inter-WBAN transmission are scheduled by TDMA scheme, J. Dong and D. Smith [29] proposed and analyzed the performance of a decode-and-forward cooperative communication scheme for WBANs, where the WBAN-of-interest communicates cooperatively via two relays when multiple WBANs coexist in the area. Using packet reception rate as design criteria, L. Wang *et al* [36] proposed a distributed cooperative scheduling scheme that considers single-BAN scheduling as an assignment problem and multi-BAN concurrent scheduling as a game. S. H. Cheng and C. Y. Huang [25] proposed a novel inter-WBAN scheduling algorithm based on random incomplete coloring. Modeling WBANs as nodes and their interference relationships as edges, they achieved higher spatial reuse by sub-graph coloring and fast algorithm convergence by random vertex weight assignment and oriented coloring. Due to different application scenarios, throughput was not considered as a main evaluation criterion in these works. With limited queue size of wireless sensors, low throughput results packet stack-up at the queue, and eventually leads to packet losses, which is a serious problem for health-care applications. M. N. Deylami and E. Jovanov [31, 37, 38] provided a series of researches on IEEE 802.15.4-based WBANs, putting throughput as one of their design and evaluation considerations. In [38], they studied the effect of the dynamic coexistence scenario where multiple 802.15.4-based WBANs are interfering with each other, and mathematically derived the probability of successful communication in such a situation. In [31] and [37], they proposed and implemented a distributed mechanism as minimal amendments to 802.15.4 standard. Using throughput as an indication of the existence of inter-WBAN interference, they assigned the WBAN that detects the harmful coexistence first as the coexistence manager, so that the optimum transmission arrangement can be made. Since the coexistence manager only takes charge when a throughput degradation is detected, their works are effective in handling inter-WBAN interference issue when the response time is not a strict concern, or for networks with static topologies.

1.4.2 Starvation Mitigation for CSMA/CA Protocol

Existing works on starvation mitigation mainly focus on adaptive adjustments on contention window size or back-off interval [39–41]. These researches mitigate the starvation effectively when the response time is not a concern. For WBANs, since the network topologies changes rapidly, the response time of the protocol must be taken into consideration.

Two intuitive MAC protocols that mitigate starvation are proposed in [42] and [43]. Eun Byol Koh and Chong-Kwon Kim [42] proposed an algorithm that solves the Flow-in-the-Middle problem by adjusting the carrier sensing threshold. In their algorithm, the back-off counter of a node is checked periodically, and whether it goes back to zero after a certain time is used to decide whether the node is in FIM state. Mahsa Derakhshani and Tho Le-Ngoc [43] proposed an adaptive CSMA/CA-based access control scheme that assigns a probability to each user with a packet to transmit. The user is only allowed to transmit if he/she gets an "1" from the randomly generated Bernoulli variable. These two MAC protocols provide us some intuitive ideas on fast detection and correction of starvation.

1.5 Challenges

There are three main challenges, power optimization, protocol response time, and starvation, when designing a CSMA/CA-based MAC protocol for health-care applications with wearable sensors.

First, energy efficiency of the sensors must be taken into consideration since the battery of a wearable sensor can be easily exhausted [15,44,45]. Traditional CSMA/CA-based MAC protocol requires constant channel monitoring and complex back-off reduction mechanism. These activities consume a good amount of energy of sensors. How to design an innovative system that is energy efficient for wearable sensors is the first design challenge.

Second, because of the high mobility nature of WBANs, the network topologies are always changing. Due to different application scenarios, this issue was not a top design consideration in previous researches. How to design a MAC protocol that has a short response time in order to adapt to the fast-changing network environment becomes a challenge.

Last but not least, challenges inherited from CSMA/CA multi-hop network still hold for this research. As introduced in Section 1.3, it is well known that the CSMA/CA MAC protocol suffers from severe unfairness and starvation problems. These problems are caused by Flow-in-the-Middle and Information Asymmetry [33]. How to design a MAC protocol that mitigates starvation without trading off too much average throughput has been a research challenge for CSMA/CA-based MAC protocol for a while. With the concept of

WBAN introduced, the response time of the protocol becomes a new design consideration. This poses an even greater challenge comparing with the traditional starvation mitigation problem in CSMA/CA-based multi-hop network.

1.6 Research Motivations

Several factors motivate us to develop a distributed CSMA/CA-based MAC protocol to handle inter-WBAN scheduling.

First, the application scenarios of MAC layer solutions and physical layer solutions will be discussed. As stated in Section 1.4.1, the researches on inter-WBAN interference mitigation can be classified to physical layer approaches and MAC layer approaches. Physical layer approaches utilize methods such as power control algorithm and spatial distance management to either avoid inter-WBAN interference or reduce the impact of inter-WBAN interference [23, 35]. These methods are suitable to places with enough space or for static network and sensors with sufficient power supply. MAC layer approaches, on the other hand, have the potential to avoid inter-WBAN interference without the space constraints. It also reduces the energy wastes for wearable sensors greatly by reducing SINR to SNR.

Second, the motivations that the response time (The time a MAC protocol takes to handle inter-WBAN interference and starvation) and throughput performance are put as the top design priorities will be discussed. As discussed in Section 1.4.1, to the best of our knowledge, either throughput or response time was not a focus in previous works as a result of different application scenarios. For wearable health-care devices, low throughput causes packet loss due to the limited buffer size of the wearable sensors. Packet loss is particularly harmful for health-care applications as every packet contains vital physiological signals. For the same reason, the response time of a MAC protocol in handling inter-WBAN interference and starvation is also very important. If the response time is too large, the packets will start to stacked at the queue and result in packet losses. In addition, since the WBAN wearers are moving constantly, the network topology may change very fast. If the protocol is not responding to the changes fast enough, the algorithms might never reach a convergence.

Finally, the reason that the algorithm is chosen to be CSMA/CA-based will be explained. According to Section 1.1, WBAN is featured with high mobility characteristic, which allows WBAN wearers to move freely in a large radius. As a result, it is practically impossible nor economical to build centralized controllers everywhere. Thus, the protocol for inter-WBAN scheduling must be distributed. Since the CSMA/CA-based protocols perform well in distributed networks with fast changing network topologies, and it is widely adopted with good hardware support, it is chosen as the basis of the proposed protocol.

For the reasons above, I am motivated to design a distributed CSMA/CA-based MAC protocol that adapts to a fast-changing network environment in a timely manner. Throughput is used as the top evaluation criteria in network performance evaluation.

1.7 Contributions

Three contributions were made in this thesis. First, a novel WBAN system is proposed to reduce the power consumption and increase the battery life for wearable sensors. In such a system, the smart phone inside a WBAN is responsible for transmission scheduling. The sensors only enter active state when the paired smart phone wins the transmission opportunity and signals them. In this way, the power consumption of sensors are greatly reduced. Such a design addresses the energy efficiency challenge discussed in Section 1.5.

Second, the inter-WBAN interference problem is solved in two specific real-life scenarios by the proposed MAC protocol. In this thesis, the network topologies of scenarios such as having dinner at a traditional round table or having meeting at a round-table and the scenarios such as sitting in a classroom or a hospital waiting room are extracted. The performance analyses of the proposed protocol are performed for these two types of networks. Based on the analyses, the proposed protocol solves the inter-WBAN interference issue for all scenarios mentioned above, which reaches the main research goal.

Finally, the designed protocol addresses the challenges in response time for both inter-WBAN interference scheduling and starvation mitigation. Comparing with approaches that use throughput as a feedback for interference detection [31, 37, 38], the proposed protocol prevents the inter-WBAN interferences from happening before they take place, thus is proved faster in handling inter-WBAN interference. The starvation is also mitigated in a timely manner because of the innovative starvation prediction criteria and the back-off counter adjustment mechanism incorporated in the protocol. The proposed protocol uses the proportion of the frozen time slots as the criteria for starvation detection and makes predictions before the starvation takes place. Such a prediction is made within 0.1 seconds in the worst case. Furthermore, a back-off counter adjustment mechanism, which makes sure that the transmissions for starving nodes happen earlier, further reduces the response time for starvation mitigation. Thus, in reality, the starvation mitigation takes much shorter than 0.1 seconds.

To sum up, the three contributions of this research address all challenges and the research goal mentioned.

1.8 Thesis Outline

The thesis is organized as follows. In Chapter 2, a WBAN system that is energy efficient for sensors is proposed and the design requirements for MAC protocol is listed. Several real-life scenarios will be discussed and the corresponding network topologies used for performance evaluation will be extracted and demonstrated. Chapter 3 introduces the theoretical backgrounds of this thesis. In Section 3.1, basic knowledge on how CSMA/CA MAC protocol operates is introduced. In Section 3.2, it is shown through mathematical analysis that starvation is identified for the proposed network topologies based on continuous time CSMA Model [46]. In Chapter 4, a fast responding CSMA/CA-based distributed MAC protocol is proposed to address the inter-WBAN interference issue. By dynamically adjusting the transmission probability and the back-off counter adopted from CSMA/CA protocol for each smart phone in WBANs, the proposed MAC protocol mitigates the starvation and handles inter-WBAN interference in a timely manner. Finally, in Chapter 5, it is shown through simulation that for real-life scenarios proposed in Chapter 2, the proposed MAC protocol not only mitigates starvation effectively, but also manages to increase the average throughput when the average contention window size is greater than 64 time slots.

Chapter 2

System Model

The design and modeling of the WBAN system is discussed in this section. One of the biggest design considerations is the energy saving for sensors because of the energy limitation characteristic of WBANs. As introduced in Section 1.1, the sensors in WBAN are usually very small in size, and the dimensions of most sensors are within 1 cubic centimeter [26]. Such a small size limits the battery capacity of the sensors. In addition, the battery changes should be as infrequent as possible after the deployment of the sensors, as the battery changes usually result in service pauses and require the recalibration of the sensors or the reconnection of the sensors and the smart phone. Implanted sensors, for which the battery change is impossible, was also mentioned as an extreme case.

In this chapter, the design requirements of the MAC protocol for wearable health-care devices are discussed first. Then, an energy efficient WBAN system is proposed. Finally, several real-life scenarios and their corresponding network topologies are discussed.

2.1 Design Requirements of the MAC Protocol for Wearable Heath-care Devices

The first and the most important requirement is that the designed protocol must achieve energy efficiency for sensors, with the reasons explained at the beginning of this Chapter.

Second, the designed MAC protocol must be distributed. This requirement is a direct reflection of the high mobility nature of WBANs. As explained in section 1.4.1, it is neither practical nor economical to build centralized controllers everywhere, thus the designed MAC protocol must be distributed.

The third design requirement is that the designed protocol must be fast-responding. Because of the highly mobility nature of WBANs, the network topology is changing fast when WBAN wearers are moving around. There are two aspects in terms of protocol responsiveness, the first one is to achieve fast responsiveness in handling inter-WBAN interference in a dynamic and fast-changing network, and the second one is to achieve fast responsiveness for starvation management in CSMA/CA network.

2.2 An Energy Efficient WBAN System

A basic inter-WBAN interference model is demonstrated in Figure 2.1. As can be seen in Figure 2.1, a single WBAN is composed of a smart phone and a sensor, with each of them considered as a node. The wearable sensor collects physiological information and forwards them to the smart phone in the same WBAN. The reason that there is only one sensor connected to each WBAN in the proposed model is because of the sensor integration trend mentioned in introduction. In order to minimize the energy consumption for sensors, transmission schedule is organized by smart phones. Each smart phone manages its own back-off counter and transmission schedule. Sensors are acting as passive nodes which only start the transmission when the paired smart phones win a transmission opportunity and signal them. It is assumed that the sensing and transmission ranges for sensors and smart

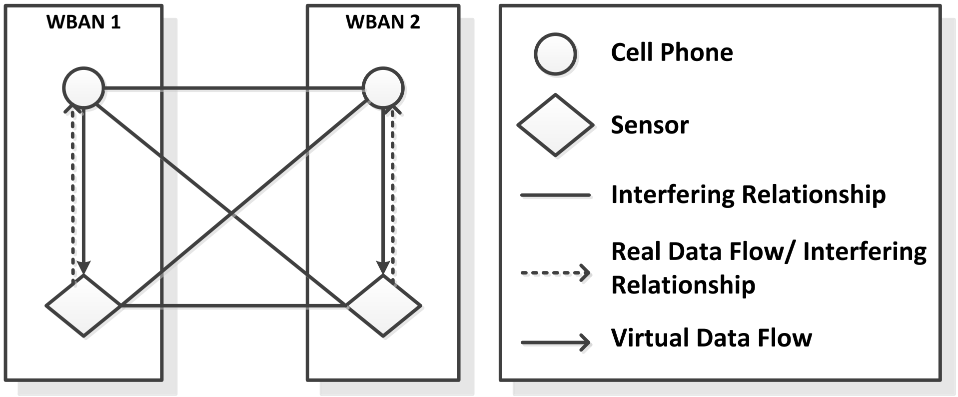


Figure 2.1: Basic model for inter-WBAN interference

phones are the same. The transmission range should not be too large to cause unnecessary interferences. It should be set to a value that is no larger than the necessary range to communicate with the sensors around a WBAN wearer's body. Even so, an inter-WBAN interference is inevitable when two WBAN wearers are close to each other.

The biggest difference between the proposed WBAN system and the traditional node-based CSMA/CA network is that the sensors are passive in the proposed WBAN system, which do not perform any CSMA/CA operations such as carrier sensing or back-off. However, they can still cause interference during the packet transmission. Thus, the effect of the passive nature of the sensors must be eliminated to perform the per-flow throughput analysis using the continuous time CSMA model. To achieve that, the direction of virtual data flow is defined as from smart phone to sensor, as opposed to the direction of real data flow, which is defined as from sensor to smart phone. With such a setup, the sensor completely becomes a receiver, and whether it performs a CSMA/CA operation does not matter in mathematical analysis. As demonstrated in Figure 2.1, dashed arrow represents the direction of real data flow and solid arrow represents the direction of virtual data flow. It will be explained in the following sections that the throughput of the virtual data flow should equal to that of the real data flow because of the symmetry nature of the network topologies used in analysis. Only with the introduction of the virtual data flow and the proof of the equality between the virtual and the real data flow in terms of throughput can the continuous CSMA model be used in mathematical analyses in Chapter 3.

2.3 Real-life Scenarios and the Corresponding Network Topologies

To evaluate the performance of the MAC protocol, two common real-life scenarios are proposed and their corresponding network topologies are expressed using the proposed WBAN system.

The first one is the real-life scenario where WBAN wearers are seated around a traditional round dining table or a round meeting table. In this scenario, the only interference a WBAN has is from its two direct neighbors, and the WBANs form up a network with a “ring” topology. In this thesis, such a network is referred to as a ring network. Figure 2.2 is an illustration of the ring network consisting of 6 WBANs, thus 6 flows. As can be observed from Figure 2.2, the ring network is a one-hop network since the sensor only communicates with the paired smart phone in the same WBAN. The one-hop network topology is a reflection of the group-based movement characteristic of the WBAN.

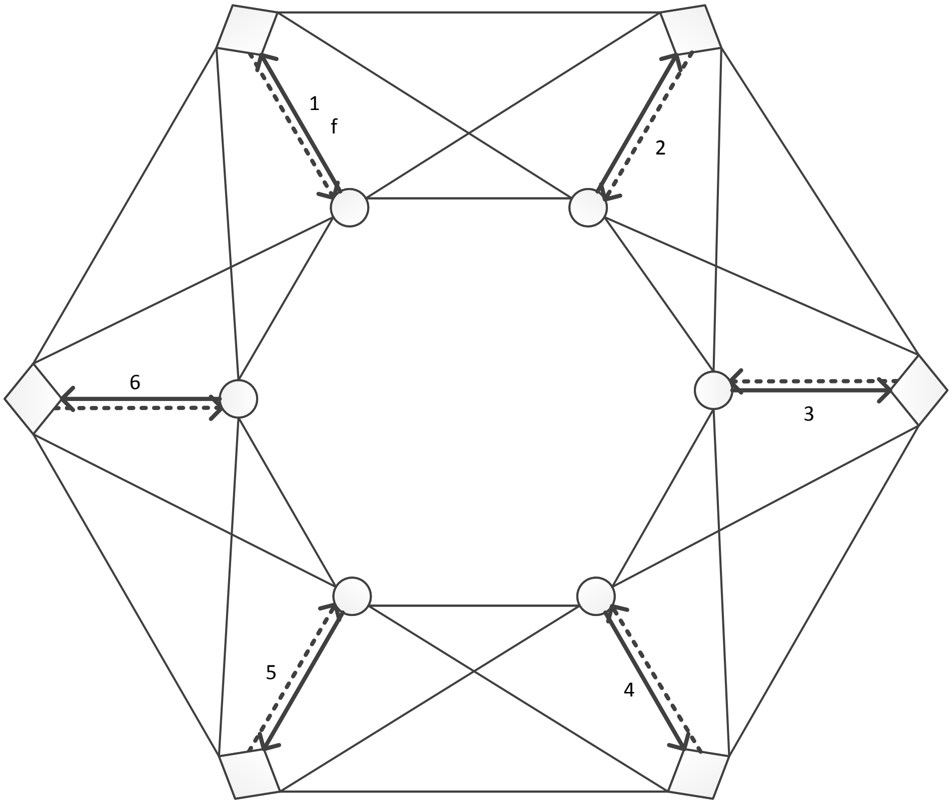


Figure 2.2: Topology of a 6 flow ring network

The second one is the real-life scenario where the WBAN wearers are sitting in a hospital waiting room or a classroom. In this scenario, the WBANs form up a grid. Figure 2.3 is an illustration of grid network for WBANs, where each circle represents a WBAN and each solid line represents an interfering relationship. As can be seen from the Figure, corner WBANs have 2 interfering neighbors, edge WBANs have 3 interfering neighbors, and center WBANs have 4 interfering neighbors. In this thesis, such a network topology is referred to as a grid topology. The interfering relationship is complex when each WBAN node in Figure 2.3 is expanded to a smart phone and a sensor. Figure 2.4 demonstrates the interfering relationship of the center WBAN in a 9-flow grid network. Similarly, the grid network is a one-hop network.

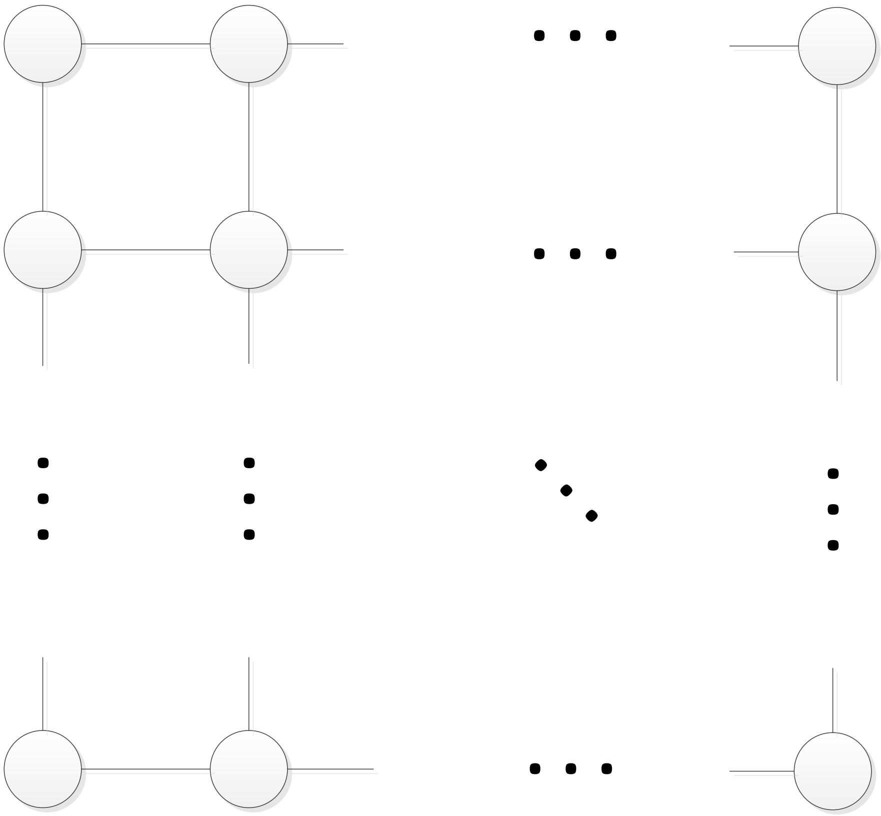


Figure 2.3: An illustration of grid network

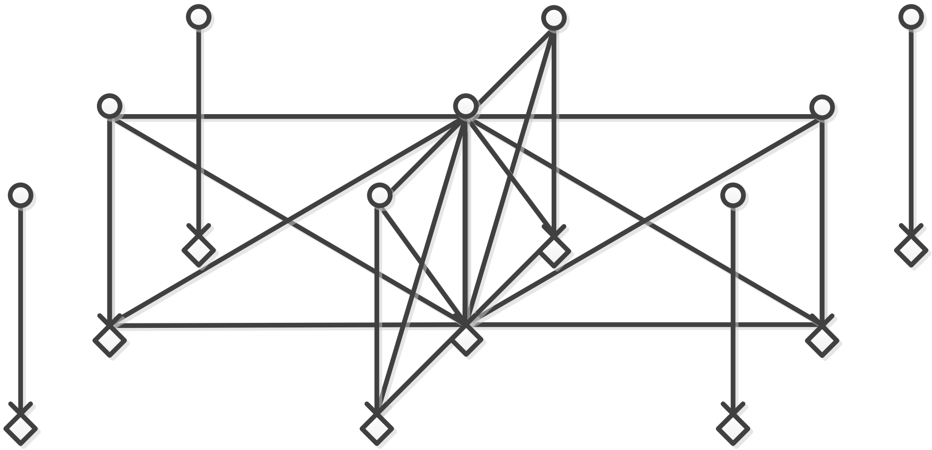


Figure 2.4: Interfering relationship of the center WBAN in a 9-flow grid network

As can be observed in Figure 2.2 and 2.4, both network topologies are symmetric, which means that if the position of the smart phone node is interchanged with that of the sensor node, the network topologies and the interfering relationships remain the same. Because of the symmetry characteristic of these networks, the throughput of the virtual data flow should equal to that of the real data flow. Thus, in following chapters, the virtual flow and the real flow will not be differentiated.

Chapter 3

Theoretical Backgrounds

In this chapter, the basic access scheme of CSMA/CA MAC protocol is first explained in detail. Then, the throughput analysis is performed and the starvation phenomenon is identified.

3.1 Basic Access Scheme of CSMA/CA MAC Protocol

Since the proposed protocol is CSMA/CA based, basic knowledge on how CSMA/CA MAC protocol operates is introduced in this section.

The CSMA/CA protocol is a distributed MAC protocol in which each node handles its own transmission schedule. For an idealized CSMA/CA protocol with basic access mechanism, two-way handshaking technique is used. The basic access scheme is characterized by the immediate transmission of a positive acknowledgment (ACK) by the receiver node after the successful reception of a packet from the sender node [47].

At the beginning, nodes having packets for transmission first verify that the channel is in an idle state via carrier sensing. If the received power is above a given threshold, the medium is considered busy, otherwise, it is considered idle [48]. Consider a random node that has a packet to transmit. When the channel is sensed idle, the node samples a random back-off interval based on the provided distribution. The back-off interval is usually in the unit of mini time slot, whose duration equals to the time required for a node to detect the transmission of a packet from any other nodes. The duration is decided by the propagation delay, the switching time between the receiving state and the transmitting state, and the time needed to signal the MAC layer the state of the channel [47]. The back-off counter of a node is initialized with the value of the generated back-off interval. The back-off counter is reduced by one at the end of each time slot if the channel is sensed idle. If the channel is busy, the back-off counter is not decremented, which is referred to as "frozen". The back-off counter continues the count down once the channel is sensed idle again. Transmission of a node is initiated when the back-off counter of that node is finally reduced to zero. When the packet transmitted from a node is successfully received by the receiver, the receiver transmits an ACK immediately. After the reception of the ACK signal, the sender generates a new back-off interval and repeats the process. However, if the sender did not receive an ACK, it tries to resend the packet instead.

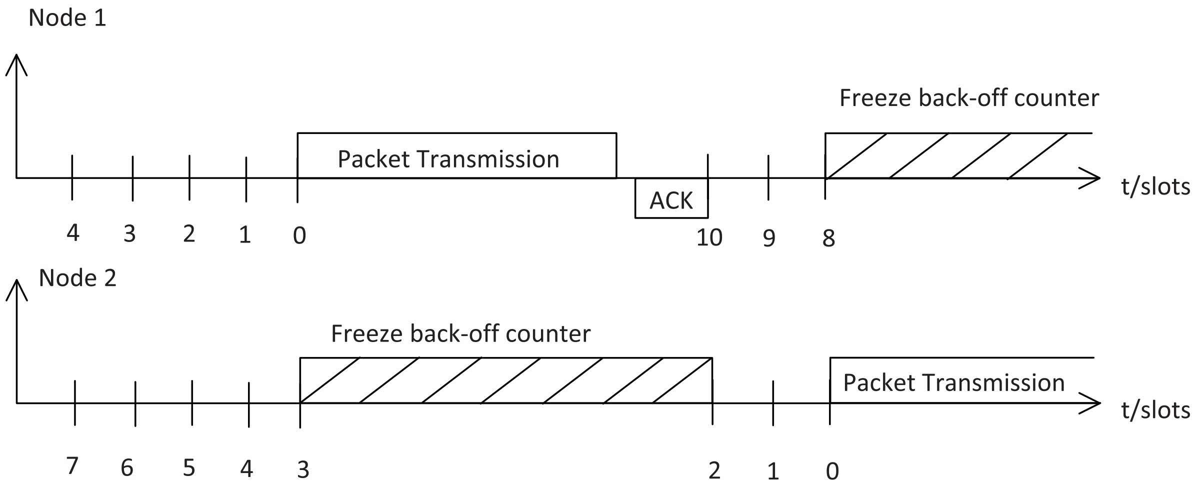


Figure 3.1: Operation of Ideal CSMA/CA Protocol - Basic Scheme

Figure 3.1 demonstrates the operation of the ideal basic access scheme for CSMA/CA protocol. Here, an ideal CSMA/CA protocol refers to a protocol that has no propagation delay. In Figure 3.1, Node 1 and Node 2 are neighboring nodes whose transmission ranges overlap. At the beginning, the channel is idle and both nodes generate a random back-off interval. The back-off interval is 4 for Node 1 and 7 for Node 2. When Node 1 finishes its back-off, the channel is sensed idle and its packet is transmitted. The ACK is received immediately after the packet transmission. Then, a new back-off interval is generated for Node 1. During the packet transmission of Node 1, the back-off counter of Node 2 is frozen at 3. When the ACK is received by Node 1 and the channel becomes idle again, the back-off counter for Node 2 continues to decrease until it reaches 0 and the packet transmission is initiated.

Although CSMA/CA protocol can avoid the collision most of the times, it can not completely eliminate the collision. A collision happens if a receiver receives more than one packet broadcast by different senders at the same time. Even if some of the packets are not broadcast for that receiver, as long as the transmission ranges of the senders cover the receiver, signals with the same frequencies will superimpose at the receiver, and makes the received signal non-decodable. A collision usually happens as a result of the hidden terminal problem and transmission delay. As discussed in Chapter 2, hidden terminal problem does not happen in the network topologies proposed in this thesis. Thus, in this thesis, transmission delay is the only cause of collision. Consider the situation where there are only two pairs of interfering senders and receivers in the network. If the two interfering senders finish their back-offs at the same time, with the existence of transmission delay, both of them sense an idle channel and decide to transmit their packets. As a result, collision will happen at both receivers and the packet transmissions will fail. In this research, only this type of collision is considered.

3.2 Mathematical Analysis for CSMA/CA Protocol

In this section, throughput analysis for the basic access scheme of the CSMA/CA MAC protocol is performed on the two proposed network topologies using continuous time CSMA model from [46]. To simplify the analysis, the assumptions are listed as follows:

1. Basic access scheme is used in the analysis (2 way handshaking instead of RTS/CTS 4-way handshaking)
2. Packet length is fixed and is the same for all WBANs, since health-care applications usually gather and transmit data periodically
3. Channel capacity is the same for all channels
4. ACKs and NACKs are obtained instantly
5. A packet can be retransmitted as many times as possible until it is received successfully
6. The back-off interval follows an exponential distribution with its mean equals to μ time slots
7. Zero propagation delay in carrier sensing, so that there is no delay in freezing the back-off counter on the detection of packet transmission from neighboring nodes
8. Although there are no delays in carrier sensing, to simulate collision in real-life, it is assumed that the propagation delay does exist when interfering nodes finish their back-off at the same time and decide to transmit at the same slot. This results in a collision. Note that if there is no propagation delay when this happens, continuous back-off will take place
9. The network is always saturated, that is, there are always packets waiting for transmission when the smart phone of a WBAN wins a transmission opportunity

10. To simplify the analysis, it is assumed that only one channel is available for packet transmission, that is, channel switching behavior is not considered when performing the throughput analysis

The original Markov chain model for CSMA/CA throughput analysis was proposed by R. R. Boorstyn, *et al* [46]. Markov state at each time instant is represented by nodes that are currently transmitting and is denoted by a set. Note that the CSMA/CA protocol does not allow interfering nodes to transmit at the same time so that only the sets containing non-interfering nodes are valid Markov states. In [49], the original Markov chain model, which is used for per-node throughput calculation, is extend to perform per-flow throughput calculation. The rules for creating Markov states remain the same, except that the elements in Markov states are now flows instead of nodes. Representing a wireless network with a graph $G = (\nu, \varepsilon)$ and a flow in the network with ε, a flow $f = (u, v)$ is said to be the interfering flow of flow $g = (i, j)$ if either $(u, j) \in \varepsilon$ or $u = j$ [49]. Using the 6-flow ring network in Figure 2.2 as an example, the valid Markov states are {1}, {2}, ..., {6}, {1, 3}, {1, 4}, {1, 5}, {2, 4}, {2, 5}, {2, 6}, {3, 5}, {3, 6}, {4, 6}, {1, 3, 5}, and {2, 4, 6}.

According to [49], for flow f, assuming that the back-off time and transmission duration are exponentially distributed with mean equals to $1/\lambda_f$ time slots and μ_f time slots respectively, if $m \in M$, with $m_f \in \{0, 1\}$ indicates whether flow f is active for each state, the stationary distribution can be expressed as

$$\pi_m = \frac{\prod_{f:m_f=1} \lambda_f \cdot \mu_f}{\sum_{n \in M} \prod_{f:n_f=1} \lambda_f \cdot \mu_f} \tag{3.1}$$

The throughput of flow f can then be calculated as

$$T(f) = \sum_{m \in M : m_f = 1} \pi_m \tag{3.2}$$

The per-flow throughput for ring and grid network can be calculated based on equation 3.1 and 3.2.

For a 6-point ring network, since the network topology is symmetrical, the per-flow throughput is the same for all flows. Based on the assumptions, packet length, channel capacity, and average back-off time are the same for all flows. Let $\theta = \lambda_f \cdot \mu_f = \lambda \cdot \mu$, the throughput for a ring network is

$$T(f) = \frac{\theta + 3\theta^2 + \theta^3}{1 + 6\theta + 9\theta^2 + 2\theta^3}$$

For a 9-point grid network, the throughput of a flow depends on the number of interfering flows around that flow. The flows in a 9-point grid network can be divided into three categories. The first category is for flows in the corner (f_{corner}), which is interfered by only two flows.The second category is for flows at the edge (f_{edge}). These flows has three interfering neighbors. The last category is for the flow at the center of the network (f_{center}), which has four interfering neighbors. The throughputs of these three different categories of flows are calculated as follows

$$T(f_{corner}) = \frac{\theta + 6\theta^2 + 9\theta^3 + 3\theta^4 + \theta^5}{1 + 9\theta + 24\theta^2 + 22\theta^3 + 5\theta^4 + \theta^5}$$

$$T(f_{edge}) = \frac{\theta + 5\theta^2 + 6\theta^3 + \theta^4}{1 + 9\theta + 24\theta^2 + 22\theta^3 + 5\theta^4 + \theta^5}$$

$$T(f_{center}) = \frac{\theta + 4\theta^2 + 6\theta^3 + 4\theta^4 + \theta^5}{1 + 9\theta + 24\theta^2 + 22\theta^3 + 5\theta^4 + \theta^5}$$

Since $\theta = \lambda_f \cdot \mu_f = \mu_f / \frac{1}{\lambda_f}$, and the average packet transmission time is usually much larger than the average back-off time, $\theta \gg 0$. Subtract the numerator of $T(f_{center})$ with that of $T(f_{edge})$, we get $-2\theta + 12\theta^3 + 5\theta^4$. For $\theta \gg 0$, the throughput of the center flow is apparently much larger than those of the flows at the edge. Similarly, the throughputs of the corner flows are also much larger than those of the edge flows. Thus, the edge flows are suffering from starvation. The calculated results will be verified by simulations in Chapter 5.

Chapter 4

A Fair CSMA/CA-Based MAC Protocol

In this chapter, the operation of the proposed protocol is discussed first. How CSMA/CA basic access scheme is incorporated into the proposed WBAN systems is explained in detail with all parameters defined and symboled. Then, the algorithm is provided using the symbols defined. Finally, the proposed protocol is verified against the design requirements proposed in Section 2.1.

4.1 Operation of the Proposed Protocol

To solve the inter-WBAN interference issue, the proposed protocol is operated by the smart phone in every WBAN as explained in Section 2.2. This provides a proper coordination between the WBANs by setting up a transmission schedule. In this way, the chance of inter-WBAN interference is greatly reduced. The advantage of this approach is that it is able to prevent the inter-WBAN interference by scheduling the packet transmissions ahead of time rather than doing post-adjustments after the throughput degradations are observed.

To mitigate starvation and improve throughput, the proposed MAC protocol extends the basic CSMA/CA protocol with an adaptive transmission probability and a back-off counter adjustment mechanism that prioritizes starving nodes.

To mitigate starvation, an adaptive transmission probability, P_t, is used to extend the CSMA/CA protocol. Integrating the system model presented in Chapter 2 and the CSMA/CA basic access scheme explained in Section 3.1, the proposed protocol is explained as follows. At the beginning, the smart phone of each WBAN generates its own back-off interval based on an exponential distribution with mean equals to μ. Then, it performs carrier sensing to determine the channel status. With collision avoidance, if the smart phone of a WBAN detects the transmission activity from another WBAN within the interference range, it enters frozen state in which neither transmission nor back-off counter decrement is allowed. However, if the channel is sensed idle, the back-off counter is decremented unless it reaches zero, in which case whether a transmission will be allowed is determined by an adaptive transmission probability.

To explain how this probability is calculated, the method to identify starvations is introduced first. As discussed in Section 2.1, the starvation must be mitigated in a fast and effective way. To achieve that, each smart phone monitors its transmission status for a fixed duration, which is referred to as a time window. Let L_w denote the length of the time window in terms of number of slots. There is a trade-off in determining L_w. On one hand, it should be large enough so that enough statistics can be gathered before a decision is made. On the other hand, it should not be too large, or the response time of the protocol will be too long. In this thesis, the length of the time window is chosen so that it allows at least five transmissions to take place given P_f, where P_f is defined as an acceptable proportion of frozen time within the duration of a time window before a starvation is identified. Within each time window, the smart phone counts the actual frozen time, denoted by i_f from the beginning of the time window to current time. If the amount of frozen time over the amount of time span is greater than P_f, the smart phone decides that it is about to enter a starvation state. In this case, the transmission probability of that WBAN is set to 1 by the smart phone. In other cases, the transmission probability is decided by $\max[1/N_i, ((i_f/L_w)/P_f)]$, where N_i denotes the approximated average number of the interfering WBANs for WBAN i.

Finally, how to use the adaptive transmission probability to mitigate starvation when the back-off counter of a smart phone is reduced to zero is presented as follows. At this point, the smart phone of each WBAN will generate a random number based on uniform distribution on interval [0, 1]. The generated number is then compared with the transmission probability of that WBAN, a transmission is permitted only if the generated number is smaller than the transmission probability. Otherwise, the smart phone will be force to generate a random back-off interval and enters back-off stage.

To further improve the throughputs of starving WBANs, the back-off counters of the starving nodes are adjusted to the smaller value of $i_b/3$ and $\mu/4$ as soon as the transmission probability reaches "1", where i_b represents the current value of the back-off counter. In this way, for starving nodes that are guaranteed to have a transmission, the transmission happens earlier. Such a design improves the throughput when the average back-off time is large. All variables used in the design are defined in Table 4.1 and the MAC protocol is presented in Algorithm 1.

Table 4.1: Definition for Variables in Algorithm 1

Variables	**Definition of the Variables**
P_t	transmission probability
N_i	approximated average number of the interfering flows
L_w	length of the time window
P_f	acceptable proportion of the frozen time
μ	average back-off time
t	time passed since the beginning of the time window
i_f	amount of the frozen time since the beginning of the time window
i_b	back-off counts left

The rationale that the proposed protocol solves the starvation issue is explained as follows. By using the adaptive transmission probability to control the transmission, WBANs that are constantly transmitting will have much smaller transmission probabilities than those for starving nodes, since they have a much smaller amount of frozen time slots. As a result, these WBANs have smaller chances to transmit their packets when they finish their back-offs, so that the starving WBANs have better chances of reducing their back-off counters. On the other hand, for WBANs that suffer from starvation, the acceptable proportion of frozen time slots is set in a way that their transmission probabilities will eventually reach "1". Thus, their packets are guaranteed to be transmitted once they finish their back-offs so that they have a better chance of getting out of the starvation state.

Algorithm 1 A FAIR CSMA/CA-BASED MAC PROTOCOL

```
procedure TRANSMISSION STAGE
    $t \leftarrow t + 1$;
    if $t = L_w$ then
        $i_f \leftarrow 0$;
        $t \leftarrow 0$;
    $P_t \leftarrow max(1/N_i, ((i_f/L_w)/P_f))$;
    if $P_t > 1$ then
        $P_t = 1$;
    $k \leftarrow$ a random number from $[0, 1]$;
    if $k \leq P_t$ OR this is the first transmission then
        transmission permitted;
    goto top.
procedure BACKOFF STAGE
    if $P_t = 1$ then
        if $i_b \neq 0$ AND $i_b$ have not been adjusted yet then
            $i_b \leftarrow min(i_b/3, \mu/4)$;
```

4.2 Verification of the Design Requirements

The design requirements of the proposed protocol are met in the following ways. First, the energy efficiency requirement is met by the innovative communication method of the proposed WBAN system in Section 2.2. Second, since the protocol is CSMA/CA-based, the distributed requirement is also satisfied. Third, both aspects of the fast-responding requirement are satisfied. The inter-WBAN interference scheduling is fast responding in the sense that the proposed CSMA/CA-based protocol prevents the inter-WBAN interferences from happening before they take place. This is different from other approaches, such as the coexistence manager assignment approach in [31,37,38], which uses throughput as a feedback to make post-adjustments after the detection of the interference phenomenons. The starvation management is fast responding because of the innovative starvation prediction method and the back-off counter adjustment mechanisms used. Unlike other protocols that use throughput as the starvation detection criteria, the proposed protocol predicts the starvation by monitoring the proportion of the frozen time slots. Such a design is capable of preventing the starvation before the throughput degradation takes place. Note that the starvation analysis and proper adjustments are made within a time window. Based on the definition of the time window and the length of the time slot, the longest adjustment is made within 0.1 seconds. In fact, the average response time is much shorter than 0.1 seconds not only because of the application of the back-off counter adjustment mechanism, which reduces the value of the back-off counter and allows the starving nodes to transmit packets much earlier, but also because that, statistically, the average starvation detection time is half the length of the time window without the back-off counter adjustment mechanism. To sum up, the designed protocol satisfies all design criteria listed in Section 2.1.

Chapter 5

Performance Evaluation

In this chapter, the throughput evaluation of the proposed protocol and the basic access scheme of the CSMA/CA protocol are performed based on the simulations on the two network topologies proposed in Section 2.3. The simulation setups are explained in Section 5.1 and the simulation results are presented and analyzed in Section 5.2. In Section 5.2, the correctness of the mathematical analyses is first verified using the simulated results. Then, the fairness of the CSMA/CA basic access scheme is compared with the proposed protocol by calculating the standard deviations of per-node throughputs. The percentage drop in standard deviation, which means an improvement in throughput fairness, is then compared with the percentage drop/increase in average throughput.

5.1 Simulation Setup

First, the simulation environment and the parameter setups are presented. The simulation is programmed in Matlab. A 6-flow ring network and grid networks of size 9, 16, 25, and 36 are simualted. Both CSMA/CA basic access scheme and the proposed scheme are applied to these networks. To reach convergence for per-node throughput, simulations are running for 10^7 time slots. For ring and grid networks, the approximated average number of interfering flows are set to 3 and 5 respectively. The reason that the approximated average number of interfering flows is set to 5 for grid network is that, as the network size of a grid network increases, the majority of the flows in the network will have 4 interfering neighbors, thus, to guarantee fairness, it is ideal that each of them has a minimum transmission probability of $\frac{1}{5}$. Other simulation parameters are chosen according to [47, 50] and are listed in Table 5.1. In this study, the length of the time window is set to 2000 time slots based on the value of average packet length, channel capacity, and the length of the time slot.

Table 5.1: Parameters Used to Obtain Numerical Results

Packet Payload	8184 bits
MAC Header	272 bits
PHY Header	128 bits
Packet Length	8584 bits
Channel Capacity	1 Mbits/s
Slot Time	50 μs
Minimum Average Back-off time	16 slots
Maximum Average Back-off time	1024 slots

Second, the programming logic in Matlab code is explained. In the Matlab simulation program, each node keeps its own CSMA/CA back-off counter and transmission statistics. During the simulation, the interfering relationships of a specific type of network is first generated based on the network size provided. In each cycle, either the transmission counter is deducted or the back-off counter is frozen/deducted for each node based on the MAC protocol used, the interfering relationships, and the transmission schedule. When the simulation finishes, the statistics for each node are gathered to calculate per-flow and average throughputs.

Finally, the protocol performance are evaluated with the saturated throughputs and their standard deviation. The throughput is calculated as the percentage of time used for a successful transmission. The standard deviation of the WBANs' throughputs is an indicator of fairness. A decrease in standard deviation suggests an improvement in fairness. To show the effectiveness of the proposed MAC protocol in mitigating the starvation, its performance is compared with that of the CSMA/CA basic access scheme.

5.2 Simulation Results

In this section, the mathematical analyses are verified using the simulation results. Then, the throughput performance is evaluated. Finally, the effectiveness of starvation mitigation is demonstrated and the trade-offs between the starvation mitigation and average throughput are discussed.

5.2.1 Verification of the Mathematical Analysis

First, the mathematical analyses in Section 3.2 are verified with the simulations. The theoretical result versus the numerical results for throughput in ring network is presented in Figure 5.1. The theoretical result is plotted in solid blue line, and the numerical results obtained from simulations are plotted with red cross symbols. The vertical axis represents the throughput, while the horizontal axis represents average back-off time in the unit of time slots. As can be observed from the plot, the numerical results fit perfectly along the theoretical curve.

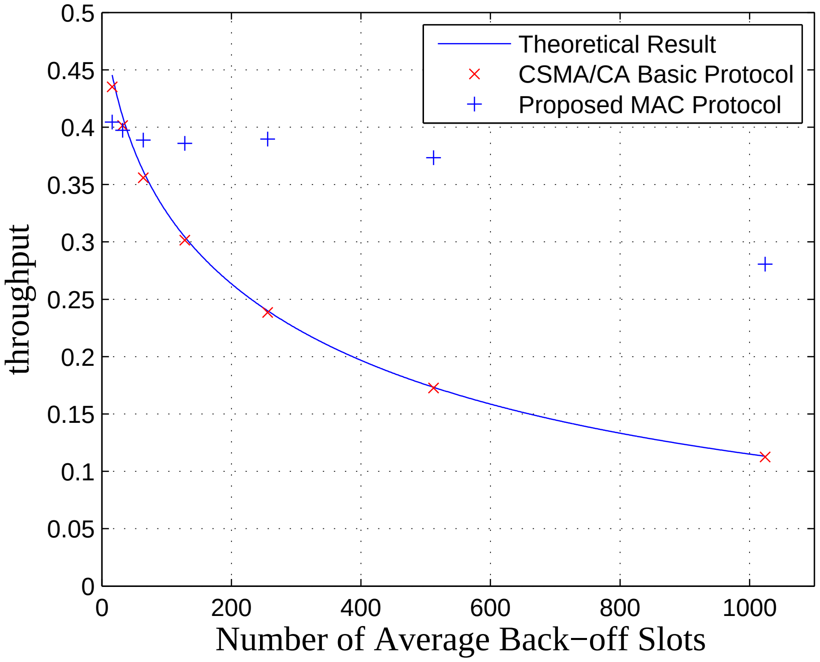


Figure 5.1: Throughput Performance of CSMA/CA Basic Access Scheme (Theoretical and Numerical) versus Proposed Scheme for Ring Network

Similar to ring network, the mathematical analyses for grid network are also verified with the numerical results from Figure 5.2 to Figure 5.4. According to the analysis in Section 3.2, the 9-point grid network suffers greatly from starvation. Such a starvation is clearly observed in plots. A huge difference in throughput can be observed by comparing Figure 5.2 or 5.4 with Figure 5.3, especially at a small average back-off interval. In fact, this harmful effect also exists in larger grid networks. This is observed on Figure 5.5, which will be analyzed in detail later in this section.

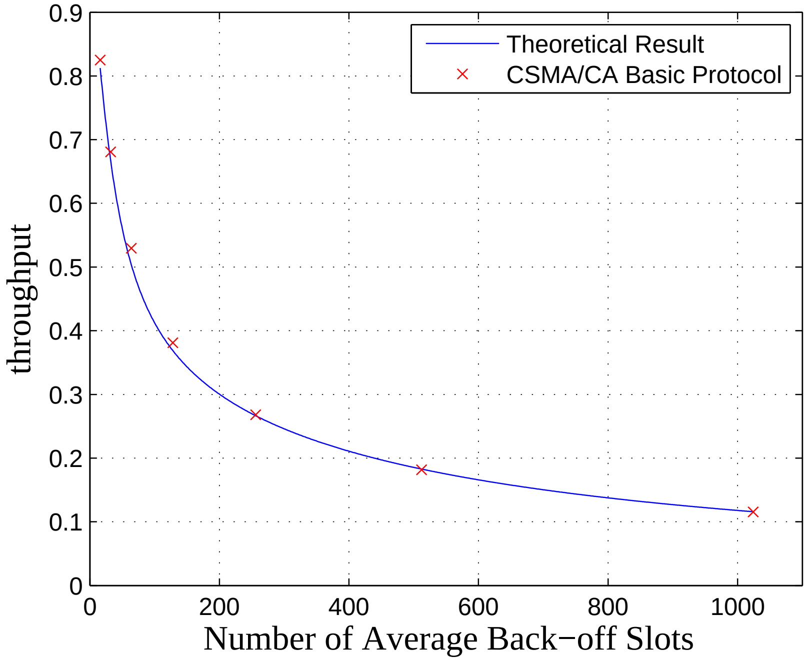


Figure 5.2: Throughput Performance of CSMA/CA Basic Access Scheme for 9 Point Grid Network - Flow at Corner

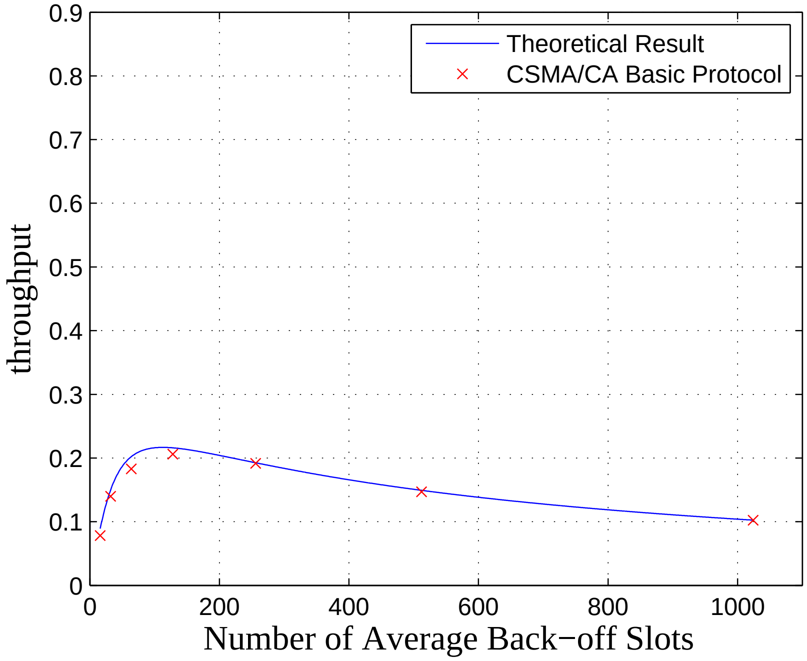


Figure 5.3: Throughput Performance of CSMA/CA Basic Access Scheme for 9 Point Grid Network - Flow at Edge

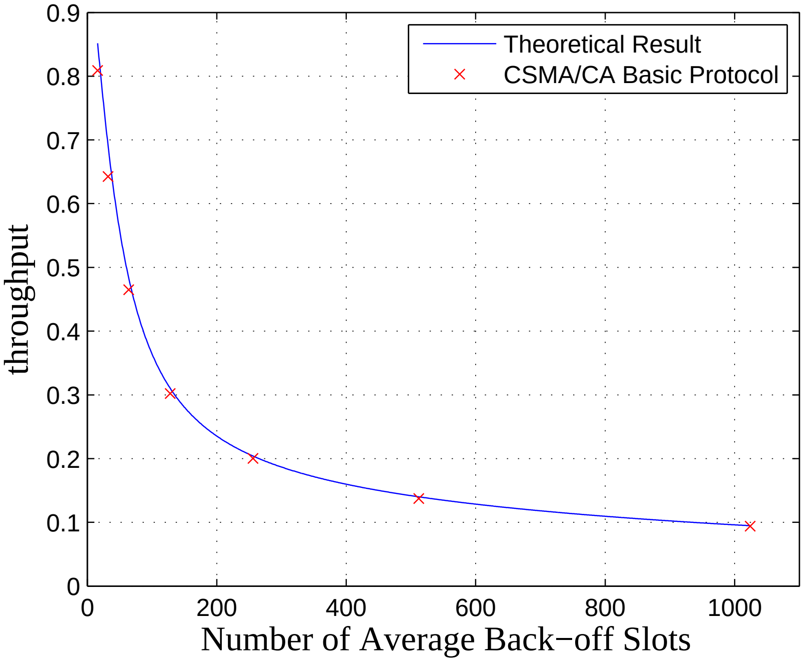


Figure 5.4: Throughput Performance of CSMA/CA Basic Access Scheme for 9 Point Grid Network - Flow in the Center

Now that the mathematical analyses are verified, the throughput performance and the effectiveness of starvation mitigation will be evaluated.

5.2.2 Throughput Performance

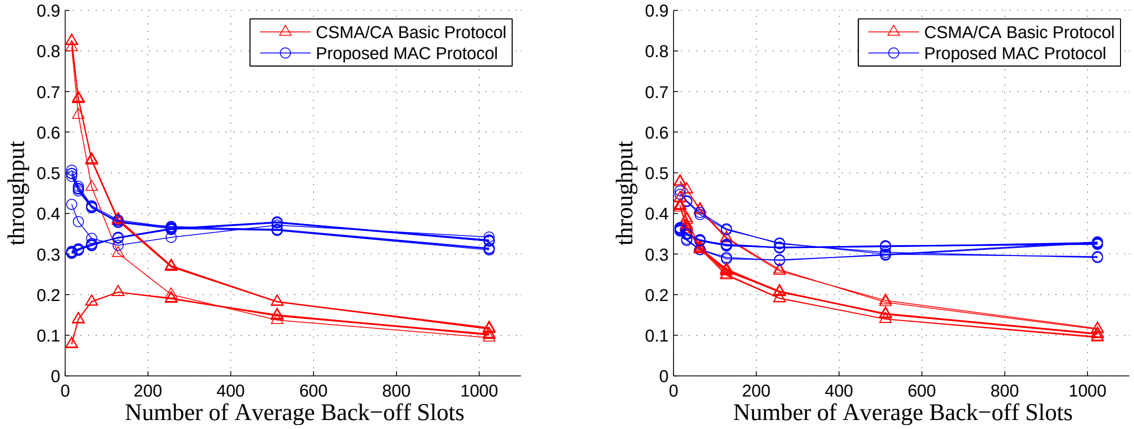
For ring network, the numerical results of the proposed MAC scheme are also plotted in Figure 5.1 with blue plus symbols. As can be seen in the plot, the throughput performance of the proposed MAC scheme is on-par with that of the CSMA/CA basic access scheme when the average back-off interval is equal to 32 time slots, and outperforms the CSMA/CA basic access scheme when the average back-off interval is greater than 32 time slots.

For grid networks, Figure 5.5 shows the per-node throughput performance of the proposed MAC protocol versus the CSMA/CA protocol in grid networks of size 9, 16, 25, and 36. Throughout the plots, the vertical axis represents the throughput, and the horizontal axis represents the average back-off time in the unit of time slots. The simulation results of the basic access scheme of the CSMA/CA protocol are plotted with red solid lines with triangle while the simulation results of the proposed MAC protocol are plotted with blue solid lines with circle.

The first observation is that the throughputs of individual WBANs are improved in the proposed MAC protocol, especially when the number of average back-off interval is large. As can be seen from Figure 5.5(a) to Figure 5.5(d), for CSMA/CA protocol, the throughputs drops to around 0.1 at 1024 average back-off interval for all networks alike, while for the proposed MAC protocol, the throughputs stay stable at around 0.3 for large average back-off interval.

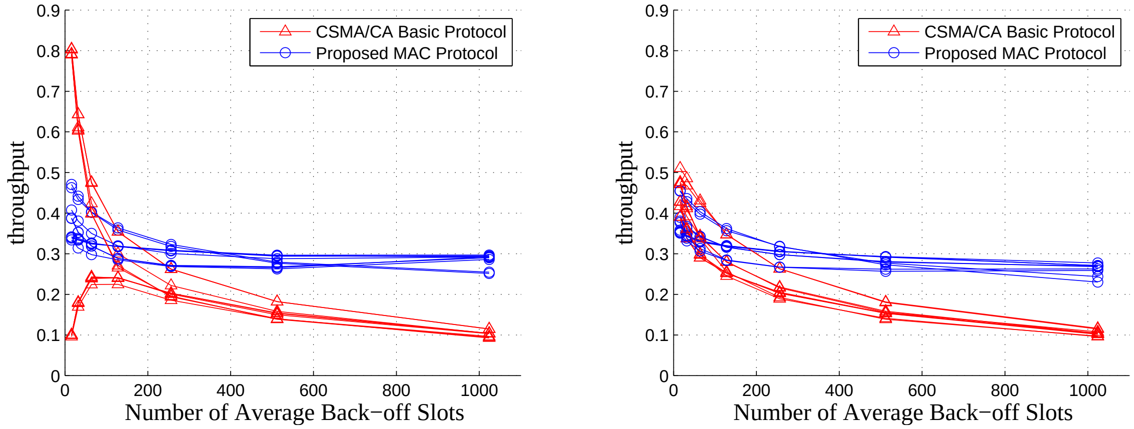
To quantify the changes in throughput performance, average throughput comparison between the basic access scheme in CSMA/CA protocol and the proposed MAC protocol are calculated and presented in Figure 5.6. Throughout the plots, the vertical axis represents the percentage change, and the horizontal axis represents the average back-off time in the unit of time slots. The average throughput of the CSMA/CA Basic Access Scheme is plotted with solid red lines with triangles and the average throughput of the proposed scheme is plotted with solid blue lines with circles. As can be observed in Figure 5.6, for all grid networks under test, the proposed MAC protocol outperforms the basic access scheme of CSMA/CA protocol in terms of average throughput when the average back-off interval is greater than 64 time slots. When the average back-off interval is smaller than 64 time slots, the degradation in throughput is within 0.1.

The second observation is that the starvation behavior in CSMA/CA protocol is greatly mitigated by the proposed MAC protocol according to Figure 5.5(a) and Figure 5.5(c), which represent networks of size 9 and 25 respectively. For CSMA/CA protocol, it can be observed that when the average back-off time is smaller than 128 time slots, the throughputs of some WBANs are significantly smaller than those of other WBANs, and the



(a) 9-Point Grid Network

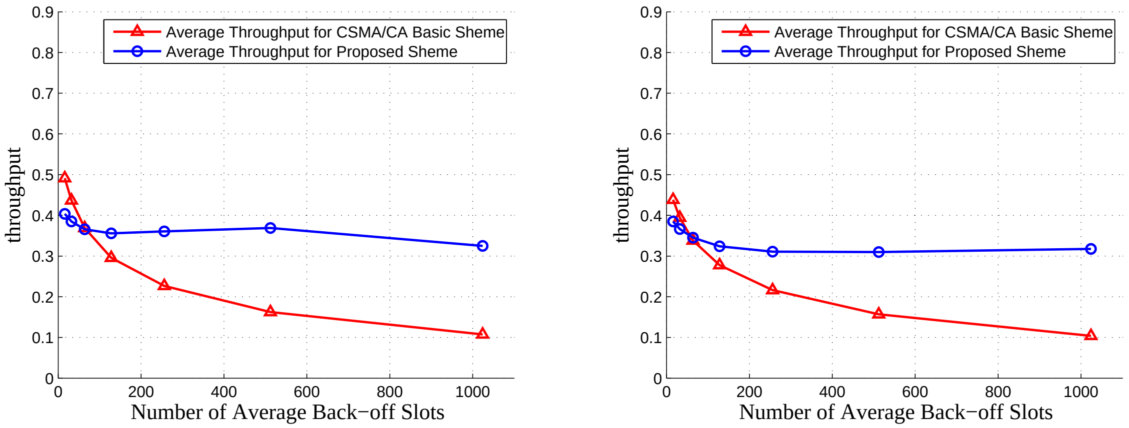
(b) 16-Point Grid Network



(c) 25-Point Grid Network

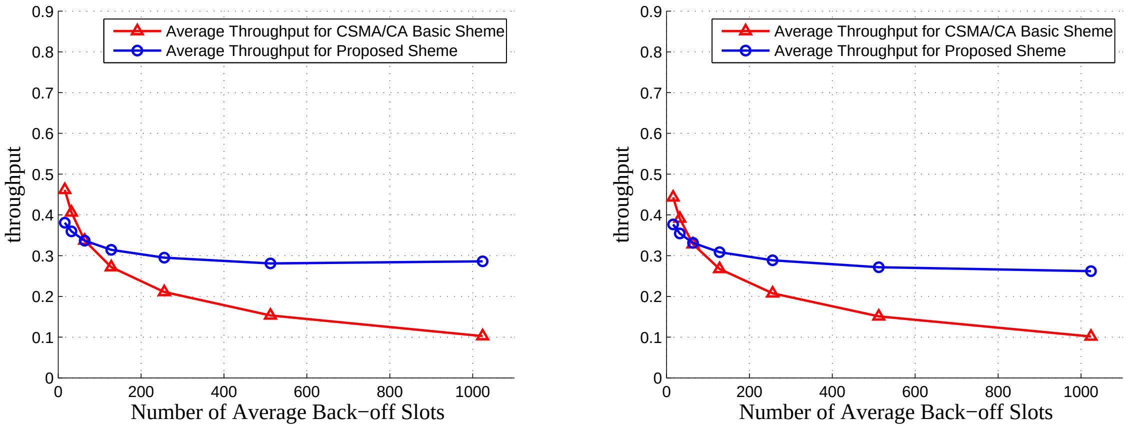
(d) 36-Point Grid Network

Figure 5.5: Per Node Throughput Comparison between CSMA/CA Basic Protocol and Proposed Protocol



(a) 9-Point Grid Network

(b) 16-Point Grid Network



(c) 25-Point Grid Network

(d) 36-Point Grid Network

Figure 5.6: Average Throughput Comparison between CSMA/CA Basic Scheme and Proposed Scheme

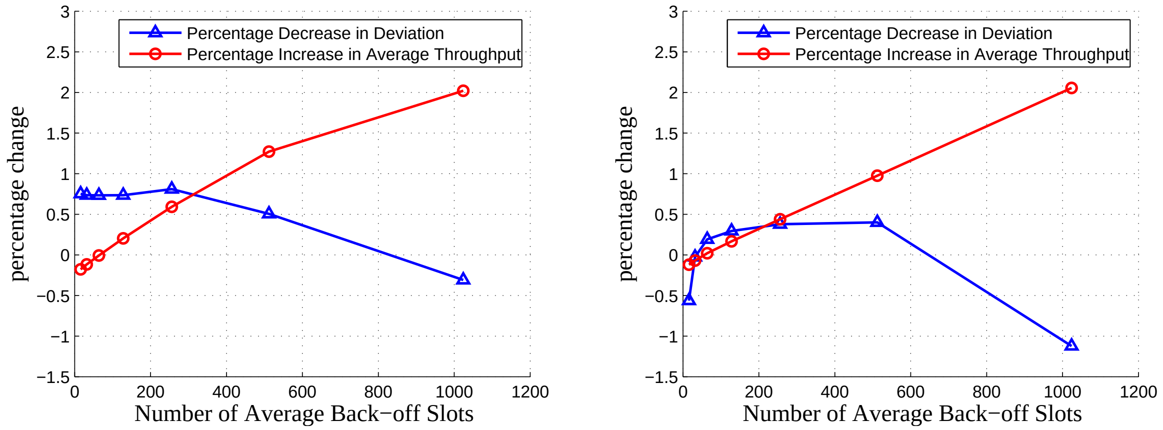
smaller the number of average back-off slots, the larger the throughput differences between WBANs. For example, in a 9-point grid network, when the number of average back-off interval equals to 16 time slots, the largest throughput of a WBAN is 0.8242, while the smallest throughput of a WBAN is 0.0791. In comparison, for the proposed MAC protocol, the largest throughput is 0.5062, while the smallest throughput is 0.3026. Thus, the proposed MAC protocol greatly mitigates the starvation for grid networks.

Note that when the average back-off interval is small, the starvation is mitigated by trading off average throughputs. To quantify the trade-off between the fairness improvement and average throughput degradation, the standard deviation for throughputs are calculated for both CSMA/CA basic scheme and the proposed scheme. Then, the percentage decrease in throughput deviation, which means an improvements in fairness and a mitigation in starvation, is calculated. The percentage increase in average throughput is also calculated, and both results are plotted in Figure 5.7 for a clear idea of the trade-offs. The results are discussed in Section 5.2.3.

5.2.3 Starvation Mitigation

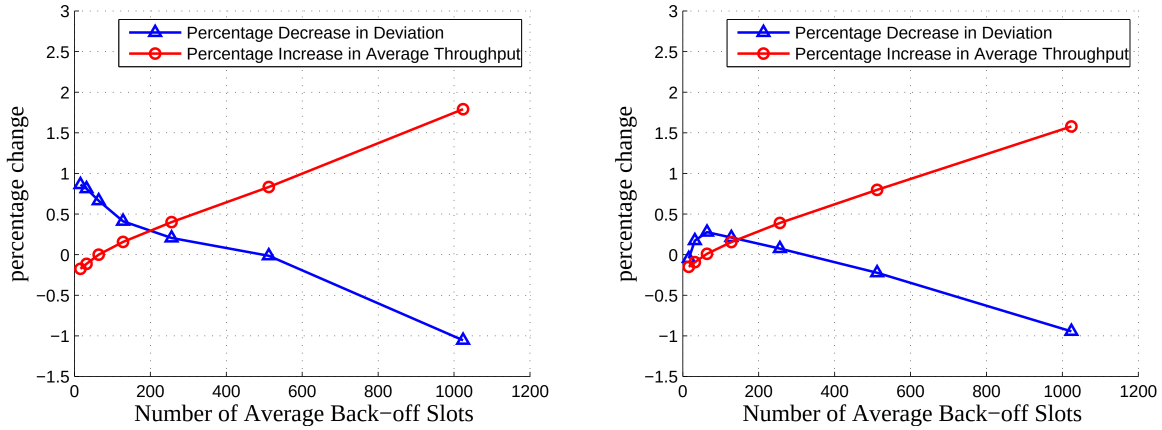
Figure 5.7 is a comparison between the decrease in the standard deviation of throughputs and the increase in average throughput for grid networks of size 9, 16, 25, and 36 respectively. The percentage decrease in deviation is plotted in solid blue lines with triangles and the percentage increase in average throughput is plotted in solid red lines with circles.

As can be seen from Figure 5.7(a), for a 9-point grid network, the proposed MAC protocol achieves 75.09% increase in deviation with only a 17.88% drop in average throughput comparing with the basic access scheme of the CSMA/CA protocol when the average back-off interval is 16 time slots. The throughput starts to increase when the average back-off interval is larger than 64 time slots. In fact, the throughput degradation is only 0.84% when the average back-off interval equals to 64 time slots. Finally, although the percentage decrease in throughput deviation drops below 0 when the average back-off interval reaches 1024, since the actual value of deviation is only 0.0119, and such a large back-off time



(a) 9-Point Grid Network

(b) 16-Point Grid Network



(c) 25-Point Grid Network

(d) 36-Point Grid Network

Figure 5.7: Percentage Decrease in Deviation and Percent Increase in Throughput versus Average Back-off Time

is rarely used, this is still acceptable. Similar conclusion can be drawn for 25-point grid network from Figure 5.7(c).

For grid networks with even number of WBANs, a drop in fairness is observed from Figure 5.7(b) and Figure 5.7(d) when the average back-off interval is small . The reason is that for grid networks with even number of WBANs, the starvation is not an issue. For example, the highest standard deviation for a 16-point grid network is only 0.0430 when the average back-off time is 64 time slots. Nevertheless, the proposed MAC protocol improves the fairness when the average back-off time is from 32 to 512 time slots for the 16-point grid network and from 32 to 256 time slots for the 32-point grid network. In addition, the proposed MAC protocol increases the average throughput. It should be noted that, although the long term fairness is guaranteed for grid networks with even number of WBANs, there is no guarantee that the temporal starvation is also eliminated. How well the CSMA/CA protocol and the proposed protocol perform against the temporal throughput criteria is an interesting future research topic.

Chapter 6

Conclusion and Future Work

In this thesis, an energy efficient WBAN system that uses smart phone for channel access control as well as a CSMA/CA-based MAC protocol that manages the inter-WBAN interference and mitigates the starvation have been proposed. The mathematical analysis has been performed for CSMA/CA basic access scheme on two network topologies, namely, ring network and grid network extracted from two real-life scenarios. Through mathematical analysis, starvation is identified in grid network. To deal with starvations in a timely manner, an adaptive transmission probability and a back-off counter adjustment mechanism were incorporated in the basic access scheme of the CSMA/CA protocol.

In simulation, the accuracy of the mathematical analysis is first verified. Then, the throughput analyses are performed on the two types of proposed networks. In ring network, the proposed MAC scheme improves the average throughput when the average back-off interval is greater than 32 time slots. In grid network, the proposed MAC protocol is proved to be fast and effective in mitigating starvations and increases the average throughput when the average back-off time is greater than 64 time slots.

To sum up, the propose MAC protocol successfully solves the inter-WBAN interference issue by inter-WBAN scheduling. In addition, it solves the starvation problem presented in CSMA/CA-based MAC protocols in a timely manner.

Several topics remain open for future researches. First, temporal throughput, which is defined as the throughput in small and continuous time fragments, should be evaluated. The goal of the MAC protocol is to provide both temporal throughput fairness as well as long term throughput fairness. In the future, temporal throughput performance must be taken into consideration during the design and the evaluations of the MAC protocol. Second, although intuitively, the proposed MAC protocol is fast responding in random network topologies, it is a good practice to fully evaluate the performance of the protocol in random network topologies with licensed throughput evaluation software. Finally, It is also a good practice to compare the temporal and the long-term throughput performance of the proposed protocol with the existing starvation mitigation protocols.

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