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Interference Mitigation Schemes for Wireless Body Area Networks

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Interference Mitigation Schemes for Wireless Body Area Networks

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ABSTRACT

Interference Mitigation Schemes for Wireless Body Area Networks

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Currently, wireless body area networks (WBANs) have attracted many researchers on the design of applications and communication. WBANs are a short-range personal wireless network which comprises of a coordinator and multiple biomedical sensors attached to human body to collect vital signals. In WBANs, interference becomes a major issue because the wireless communication of WBANs may collide with the concurrent transmission of other wireless devices working at the same frequency in the same place. Due to unexpected interference, the network performance is degraded in terms of quality of service (QoS), accuracy, and energy consumption, which can lead to many dangerous situations for medical applications or healthcare services.

Taking motivation from the coexistence problem of multi-WBAN networks, this thesis aims to mitigate the inter-WBAN interference and propose the interference mitigation algorithms by scheduling the transmissions of WBANs. More specifically, we propose and evaluate the three protocols of interference-aware traffic-priority-based link scheduling, link scheduling with interference prediction, and hybrid multi-channel medium access control for WBANs.

In the first work, we propose an interference-aware traffic-priority-based link scheduling (ITLS) to allocate the transmission of sensor nodes according to the traffic priority and interference level. We model the inter-WBAN interference as an interference graph while the scheduling problem of multiple WBANs is formulated as an optimization model. The ITLS algorithm is proposed to schedule transmissions of multiple WBANs on the basis of optimization model which aims to maximize the number of concurrent transmissions from sensor nodes to the

coordinator. The highest priority traffic is allowed to access the transmission immediately, while the others have to suspend their transmission.

In the second work, A link scheduling algorithm with interference prediction (LSIP) for multiple mobile WBANs is proposed, which allows multiple mobile WBANs to transmit at the same time without causing inter-WBAN interference. Taking the mobility of WBAN into account, the interference duration of WBANs is evaluated by using the number of neighbors and the signal-to-interference-plus-noise ratio. For interference prediction, we define a parameter called interference duration as the duration during which disparate WBANs interfere with each other. The Bayesian model is used to estimate and classify the interference using a signal to interference plus noise ratio (SINR) and the number of neighboring WBANs. The hybrid superframe includes the contention access phase using carrier sense multiple access with collision avoidance (CSMA/CA) and the scheduled phase using time division multiple access (TDMA) for non-interfering nodes and interfering nodes, respectively.

In the last work, we propose a hybrid multi-channel medium access control (HM-MAC) protocol for wireless body area networks (WBANs) which can mitigate inter-WBAN interference. A superframe consists of random access phase and scheduled access phase which are dedicated for high priority users to transmit data using carrier sensing multiple access with collision avoidance (CSMA/CA) and low priority users to transmit data using time division multiple access, respectively. For intra-WBAN transmission, multiple channels are used to increase network throughput while avoiding the collision amongst sensors. The channel selection algorithm is proposed to avoid the collision between neighboring WBANs. The sensor nodes update idle channels by listening to the beacon signal and, in consequence, the sensor nodes can change the working channel to reduce inter-WBAN interference according to the priority level.

The performance of each proposed algorithm has been evaluated by a computer simulation with the comparison to the existing works. According the performance evaluation results, ITLS achieve high spatial reuse which improves the network throughput considering the traffic priority, packet length, and the number of interfered sensor nodes at each WBAN. In LSIP, the interference prediction step can improve the successful received packets while applying hybrid

MAC superframe. The HM-MAC protocol can improve the network throughput with low latency while mitigating the multi-WBAN interference.

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최근에 무선 인체 영역 네트워크(WBAN)의 응용 및 통신 설계에 많은 연구가 집중되고 있다. WBAN 은 하나의 중앙 중재기와 여러 개의 생체 의료 센서로 구성된 단거리 개인 무선 네트워크이다. WBAN 에서의 무선 통신은 동일 장소에서 동일 주파수를 사용하는 타 무선 기기들과의 동시 전송으로 인해 충돌이 발생할 수 있으므로 간섭이 중요한 이슈가 된다. 예상하지 않은 간섭으로 서비스 품질(QoS), 전송 정확성, 에너지 소모량 등의 네트워크 성능이 저하되고 의료 및 헬스케어 서비스에 위험한 상황을 초래할 수도 있다.

본 연구에서는 여러 개의 WBAN 공존 환경에서 WBAN 상호간 간섭을 완화하기 위하여 WBAN 전송 스케줄링을 통한 간섭 완화 알고리즘들을 제안한다. 구체적으로는 WBAN 을 위한 트래픽 우선순위 기반 링크 스케줄링 알고리즘, 간섭 예측을 통한 링크 스케줄링 알고리즘, 하이브리드 다중 채널 MAC 프로토콜 등을 제안하고 성능을 비교 평가한다.

첫째, 간섭을 고려한 트래픽 우선순위 기반 링크 스케줄링(ITLS) 알고리즘을 제안한다. ITLS 에서는 트래픽 우선순위와 간섭 레벨에 따라 센서 노드의 전송 순서를 할당한다. WBAN 상호간 갑섭을 간섭 그래프로 모델링하고 다중 WBAN 스케줄링 문제를 최적화 모델로 정형화한다. ITLS 알고리즘은 센서 노드로부터 중앙 중재기로의 동시 전송의 수를 최대화 하기 위하여 취적화 모델을 기반으로 다중 WBAN 전송을 스케줄링한다. 이때, 우선순위가 가장 높은 트래픽은 즉시 전송을 허용한다.

둘째, 간섭 예측을 통한 링크 스케줄링(LSIP) 알고리즘을 제안한다. LSIP 에서는 여러 개의 이동 WBAN 이 상호 간섭 없이 동시에 전송할 수 있게 해준다. 즉, WBAN 이동성을 고려하면서 이웃 WBAN 의 수와 신호대간섭잡음비(SINR)를 이용하여 WBAN 의 간섭 기간을 파악한다. 이 과정에서 WBAN 들이 상호 간섭하는 기간을 간섭 기간으로 정의하고 이를 간섭 예측에 활용한다. Bayes 모델을 이용하여 간섭을 예측하고 분류한다. 제안한 하이브리드 슈퍼프레임은 비간섭 노드를 위한 CSMA 와 간섭 노드를 위한 TDMA 를 포함한다.

셋째, 하이브리드 다중 채널 MAC (HM-MAC) 프로토콜을 제안한다. HM-MAC 에서 슈퍼프레임은 랜덤 접근 단계와 스케줄 접근 단계로 구성된다. 랜덤 접근 단계에서는 높은 우선순위 사용자가 CSMA-CA 방식으로 전송하게 하고, 스케줄 접근 단계에서는 낮은 우선순위 사용자가 TDMA 방식으로 전송하게 한다. WBAN 내부 전송을 위해서는 센서간 충돌을 피하고 네트워크 성능을 높이기 위해 다중 채널이 사용된다. 또한, 이웃하는 WBAN 간 충돌을 피하기 위한 채널 선택 알고리즘을 제안한다. 센서 노드들은 WBAN 상호간 간섭을 줄이기 위해 우선순위에 따라 채널을 변경할 수 있다.

제안한 각 알고리즘의 성능은 컴퓨터 시뮬레이션을 통하여 평가하고 기존 알고리즘들과 상호 비교한다. 성능의 비교 평가 결과에 따르면, ITLS 알고리즘은 공간 재사용을 높여서 네트워크 성능을 개선함을 보여준다. LSIP 알고리즘은 하이브리드 MAC 슈퍼프레임 사용과 함께 간섭 예측을 통해 성공적으로 수신되는 패킷 수를 증가시킴을 보여준다. 마지막으로 HM-MAC 프로토콜은 다중 WBAN 간섭을 경하하면서 낮은 패킷 전송 시간으로 네트워크 성능을 개선함을 보여준다.

1. Introduction

1.1. Overview of Wireless Body Area Networks

The number of older people is increasing in many parts of the world which results in an improvement in public healthcare and medicine. As reported by the World Health Organization (WHO), the annual deaths due to ageing are estimated to rise to 52 million in 2030 [1]. Simultaneously, the healthcare monitoring system in many countries is facing with the rising in the number of people with chronic disease such as cardiovascular and cancer. In addition, the number of deaths from cardiovascular disease will increase from 17.5 million in 2012 to 22.2 million in 2030, and the cancer deaths from 8.2 million to 12.6 million [1]. The main reason could be the lack of well-functioning healthcare monitoring system for prevention and control chronic disease [1]. Therefore, the early detection is necessary to diagnose disease which may reduce the cost of the healthcare system or prevent the morality [2]. In order to monitor real-time vital signal, the biomedical sensors are used to collect vital signal of human body then transmit to a personal device or a coordinator before forwarding to the doctor or medical gateway. These sensors and the coordinator form a wireless body area network (WBAN), which become an important role in the future of electronic health (e-health). WBAN mainly focuses on monitoring vital signal which is a wireless sensor network consists of low power, short range, and variable-data-rate biomedical sensors. Currently, the standardization of WBANs has been established by IEEE 802.15.4 [3] and IEEE 802.15.6 [4]. Originally, the IEEE 802.15.4 standard defined the physical (PHY) and medium access control (MAC) specifications for low-rate wireless personal area networks at short range (up to 100 m). The IEEE 802.15.6 standard defines the MAC and PHY layers for WBANs in short-range wireless communication within, on, or around the human body. These biomedical sensors can sample, monitor, process, and communicate vital information and provide real-time feedback to users and the medical center. For example, various sensors for monitoring body function can be listed as follows: electrocardiograms (ECG) which monitors heart activity; electromyography (EMG) which monitors muscle function activity; electroencephalogram (EEG) which monitors brain electrical activity; accelerometers which monitors motion capture; blood pressure; and body temperature. These sensors have different characteristics of latency, packet length, and data rate which is described in Table 1 [5, 6]. The collected data can then be transmitted to a hospital or a medical server for medical purposes.

Table 1. Different characteristics of biomedical sensors [5, 6]

Application Type	Data Rate	Latency
ECG [1](12 leads)	288 kbps	250 ms[4]

ECG [2](6 leads)	71 kbps	250 ms
EMG [3]	320 kbps	250 ms
EEG (12 leads)	43.2 kbps	250 ms
Hearing aid	200 kbps	250 ms
Video/med imaging	10 Mbps	100 ms
Voice	50–100 kbps	100 ms
Audio	1 Mbps	100 ms

WBANs have several significant advantages compared to current monitoring systems, such as mobility and location independent monitoring. For example, WBAN is used to monitor patients in residential environments with low hospitalization cost and also allows free daily activities of patients [7]. An example of WBAN helps Parkinson patients at home implements a personalized wearable system for freezing of gait training called GaitAssist [8]. The GaitAssist system consists of inertial measurement units attached on the ankles of the patients that send the accelerometer, gyroscope and magnetometer data via Bluetooth to an Android phone.

In general, the applications of WBANs can be categorized into two main fields: (1) medical applications that comprise of remote patient monitoring, biofeedback, and assisted living and (2) nonmedical applications that comprise of fitness, biometrics, and notification management [9]. Hence, for the medical and healthcare applications of WBANs, the quality and continuity of signals are extremely important. However, radio propagation in WBANs is dynamic because of the mobility of a human body, and human tissues may be affected adversely by different type of biomedical signals. It is clearly shown in [10] that the quality of signals is negatively affected by the propagation around the human body according to the channel models. Also, the effect of different types of human tissues to loss signals is shown in the frequency range between 10 kHz and 1 GHz.

In [11], the requirements of WBANs based on the IEEE 802.15.6 standard are reviewed as follows: packet error rate should be less than 10% for a 256 octet payload for 95% of links, the bit rate of a link is in the range of 10 kbps to 10 Mbps, and the time to join or leave a network is less than 3 s. In Figure 1, the communication architecture of WBANs is divided into three tiers: intra-WBAN communication (tier 1), inter-WBAN communication (tier 2), and beyond-WBAN communication (tier 3). The PHY and MAC layer of WBAN is covered by two standards as follows, IEEE 802.15.4 and IEEE 802.15.6. In addition, the IEEE 802.15.4 standard is implemented into a specific application of IEEE 24451 standard [12]. The recent application is a neurorecording system that collects data of patients by using the electrodes and a wireless module. The electrodes aggregate EEG signals of human head; and the wireless module uses three different communication standards of IEEE 802.11, IEEE 802.15.1 and IEEE 802.15.4. Both standards also define the MAC layer for short-range communication which can apply to WBAN. In the comparison of two standards in [13], the MAC protocols of the standards IEEE 802.15.6

achieves better performance than IEEE 802.15.4 in terms of packet loss ratio, average delay, and network throughput. The result of the comparison in [13] is also shown that IEEE 802.15.4 carrier sense multiple access with collision avoidance (CSMA/CA) consumes less energy than IEEE 802.15.6 CSMA/CA. In [13], the design challenges of WBANs are analyzed, focusing on the MAC protocol, radio channel, and power consumption.

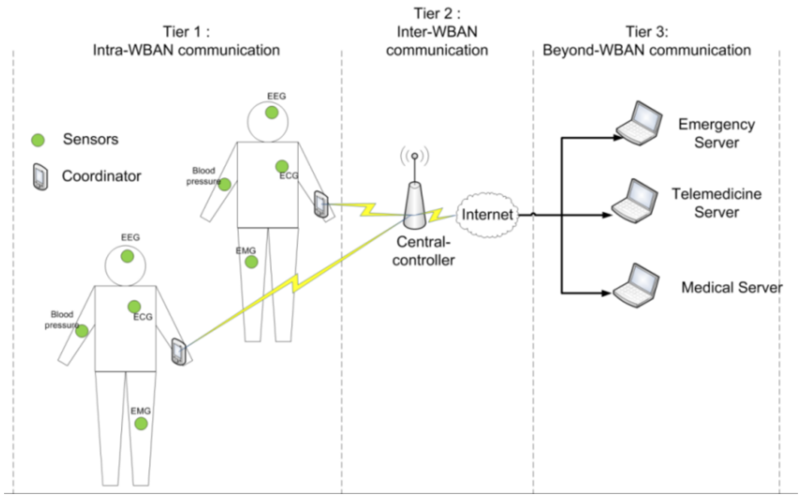


Figure 1. Three-tier WBAN architecture.

The IEEE 802.15.6 standard defines MAC layers and the three different PHY layers and that provide low complexity, low cost, high reliability, low power and short range communication for human body. The PHY layer specification for WBAN communication can be summarized as in Table 2.

Table 2. Frequency bands for different PHY layers of IEEE 802.15.6

Physical layers specification	Frequency	Bandwidth
Human body communication	10 – 50 MHz	4 MHz
Narrowband	402 – 405 MHz	300 kHz
	420 – 450 MHz	300 kHz
	863 – 870 MHz	400 kHz
	902 – 928 MHz	500 kHz
	950 – 958 MHz	400 kHz
	2360 – 2400 MHz	1 MHz
	2400 – 2483.5 MHz	1 MHz
Ultrawideband	3.1 – 4.8 GHz	499 MHz
	6 – 10.6GHz	499 MHz

A WBAN is set up for an individual human body, and therefore, in many practical environments, multiple WBANs are unavoidable. Moreover, because the human body is movable, the sensor devices attached with legs, arms, et al., on a human body are also mobile within a particular scenario. In such operation conditions, intra-WBAN and inter-WBAN interference may severely impair transmission. Therefore, in real applications including mobility or overlapped WBANs, unstable signal integrity may spatially and temporally reduce network performance. For example, in a hospital environment, where many WBANs are used for medical purposes, interference can be caused by the nearby WBANs or other equipment operating at the same frequency band, and the lost signals may lead to a dangerous situation in the medical systems. In addition, due to the mobility level of human, the coexistence WBANs can be categorized into four states: static, semi-dynamic, dynamic, and none (no interference) as in the Table 3 [4].

Table 3. Defined coexistence environment

Environment	Description
Static (S)	A single WBAN in a residential environment or a hospital with a single patient node and a fixed bedside hub.
Semi-dynamic (SD)	Slowly moving ambulatory patients in an elder care facility requiring infrequent and/or event-based low-rate data transfers.
Dynamic (D)	Fast moving ambulatory patients in a hospital with several WBANs collecting continuous data traffic from many sensor nodes.

Hence, it is necessary to consider interference mitigation in the design. WBAN interference can be categorized into three types: (1) Intra-WBAN interference occurs among sensor nodes within the same WBAN; (2) inter-WBAN interference occurs among WBANs working at the same frequency band; and (3) inter-domain interference or cross-interference occurs between a WBAN and other wireless networks (e.g., Bluetooth, Zigbee, or WiFi) [13]. These forms of interference should be avoided or mitigated to ensure signal quality in WBANs.

1.2. Coexistence and Interference in WBANs

In this section, two types of interference in WBANs will be reviewed. The first type is inter-WBAN interference links (1), (2), and (3) which occur in wireless links amongst the WBANs in Figure 2. The second type is inter-domain interference links (4) and (5) which occur in the wireless links between WBANs and other technology in Figure 2.

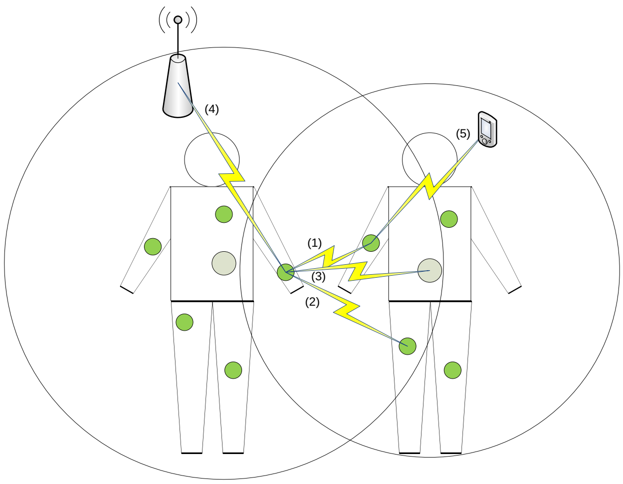


Figure 2. Interference in WBANs.

1.2.1 Inter-WBAN Coexistence and Interference

The coexistence of WBANs is investigated with regards to the inter-user interference effect in some experimentations [14]. It is shown that the network performance is adversely affected in terms of packet delivery ratio and packet rate while increasing the number of WBANs and their transmission data rate. The results of this experiment show that increasing the number of WBANs and the data rate cause high degradation of PDR. Co-channel interference among nonoverlapping WBANs is analyzed in [15]. The network topology was modelled in a two-dimensional geometric model in which each WBAN transmission range was modelled as a unit disk graph. In addition, the performance of the multiple access schemes was investigated in terms of bit error rate, probability of collision, and the statistics of SINR [16]. As a result of the simultaneous measurement of signal and interference, TDMA is the best option in co-channel interference mitigation while CDMA is not suitable. In addition, FDMA is the best scheme for interference mitigation in uncoordinated WBAN networks. Furthermore, dynamic multiple-WBANs environment can cause loss of beacon signal which leads to degradation of vital signal transmission [17]. In order to improve the network performance, it is necessary to detect and predict the coexistence of WBANs [18].

1.2.2. Inter-domain Interference

Inter-domain coexistence and interference occur between many technologies that work simultaneously over the same frequency in a specific place. For example, WiFi and Zigbee devices which work within the 2.4 GHz band can cause interference to WBAN in the nearby place. In a consequence, the network performance of WBANs is degraded which is investigated by experiment in [19]. The effect of other technology on WBANs is explored by estimating BER and symbol error rate. More specifically, WiFi negatively impacts WBANs at the 6th, 7th, 8th, and 9th channels. When there is any Zigbee or WiFi device within WBAN's transmission range, the packet loss rate of WBANs is high.

1.3. Research Objectives

In order to improve the performance, reliability, and energy efficiency in the multi-WBAN networks link scheduling algorithms and medium access control protocols should be carefully designed with regards to the QoS requirement.

First, for improving the transmission reliability in multi-WBAN environment, the link scheduling algorithm is presented and evaluated. The scheduling algorithm allows non-interfering sensor nodes to transmit at the same timeslot without interference which increases the network throughput. The sensors' transmission will be assigned into a specific timeslot, according to the traffic type which can be categorized into different levels, such as medical data, high-priority medical data, or emergency traffic.

Second, the mobility of human causes unpredictable interference to WBANs which can be estimated the interference duration by applying the prediction method. Based on the SINR and the number of neighboring in the history, WBAN can predict the duration of interference then applying the scheduling algorithm to the transmission of sensor nodes. In addition, the superframe of MAC protocol is modified for transmission of different types of sensor nodes such as interfered nodes and non-interfered nodes. The interfered nodes will be allocated into a common schedule, which reduce the interference, while the other non-interfered nodes can access the channel without schedule which decreases the waiting time or latency.

Finally, the benefit of multiple channels is proposed and evaluated which aims to increase the reliability of the data from the sensor nodes as well as the channel usage. The multi-channel MAC protocol is applied to WBANs which can improve the packet delivery ratio with low latency. The hybrid MAC superframe is presented to transmit data of different type of QoS requirements.

1.4. Thesis Layout

The thesis is organized as follows: In the next chapter, some existing interference mitigation schemes for multiple WBANs will be reviewed and qualitatively compared. In Chapter 3, the interference-aware traffic-priority-based link scheduling algorithm (ITLS) is presented and evaluated. In Chapter 4, the link scheduling algorithm with interference prediction (LSIP) for multiple mobile WBANs is presented in details with the performance evaluation. In Chapter 5, the hybrid multi-channel MAC (HM-MAC) protocol for WBANs with inter-WBAN interference mitigation is presented and evaluated. Finally, the thesis is concluded in Chapter 6.

2. Related Works and Background

In this chapter, we review some existing literatures of interference mitigation schemes for WBANs. The interference mitigation schemes are categorized into power control approach, MAC approach, cognitive radio approach, ultra wideband approach, and signal processing approach. We also summarized the pros and cons of the existing works. In addition, we also discuss some issues and challenges of the coexistence aspect in WBANs.

Inter-WBAN interference has been addressed in terms of its effect on the degradation of system performance. In this section, we studied existing methods to mitigate inter-WBAN interference. The existing interference mitigation schemes can be categorized as shown in Figure 3.

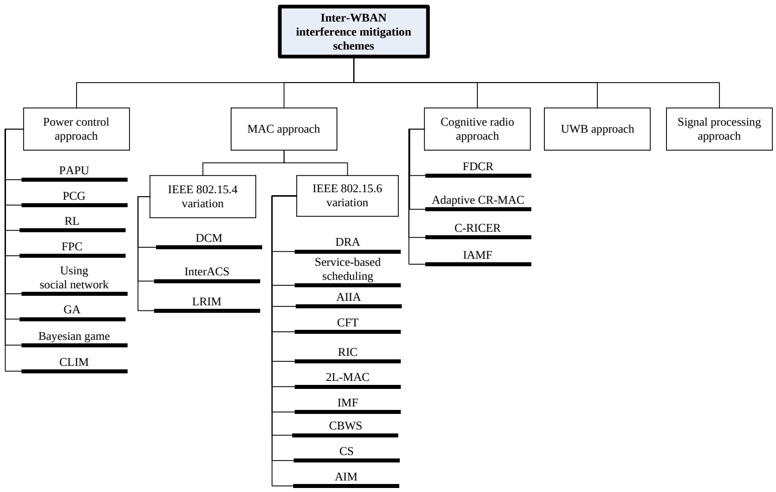


Figure 3. Categories of inter-WBAN interference mitigation schemes.

2.1. Existing Interference Mitigation Schemes

2.1.1. Power Control Approach

Because biosensors are placed proximity to the human body, the power consumption at the sensor nodes and coordinator becomes an important factor that affects the network lifetime. As a result, interference mitigation schemes aim to increase the quality and throughput while focusing on power consumption in an interference environment. We study some power control methods as in Figure 3.

The proactive power update (PAPU) algorithm [20] focuses on minimizing power consumption and maximizing throughput at each WBAN which aims to mitigate interference among WBANs. In PAPU, a distributed power control algorithm is used for each WBAN so that WBAN can maximize its own performance. The WBANs within the ranges of interference decide its transmissions based on the exchanging knowledge about its current transmit power, interference power, and channel gain. Each transmission of WBANs is defined by the payoff function, which considers a power price and the current power transmission. The network utilization and power efficiency in the WBAN are low if the power price is high. The simulation result in [20] shows that the convergence time in PAPU is fair in the multiple-WBANs environment. PAPU shows that WBAN uses low power price in interference environment with the fast convergence time and the low power. Because the power price affects the convergence and tradeoff, it is necessary to consider further in the real scenario. In the real mobile scenario, PAPU is not suitable due to the fixed channel gain and interference gain. Moreover, the QoS requirement of transmitted signal was not taken into account in power price.

In [21], another nonlinear power control game (PCG) applies game theory to WBANs to increase the total system throughput, minimize power consumption and penalize high power consumption. PCG adjusts the transmission power to satisfy the given power constraint set as in PAPU algorithm. However, PCG achieves better performance than PAPU because PCG uses adaptive power price while considering the dynamic environment problem. In addition, the tradeoff in PCG is addressed by the power budget of a WBAN. The player in PCG is penalized when the power budget is low or the current channel status is bad. As a consequence, this scheme can cope with a dynamic environment to mitigate interference in WBANs and increase the performance of WBANs in the varying channel scenario. However, the negotiation tasks amongst WBANs can cause long convergence time. Moreover, PCG does not take the QoS requirement of sensors into account.

Another power control scheme with a reinforcement learning (RL) strategy [22] allows a WBAN to act as a single-action learner agent that learns from its experience to reduce interference from other networks. At each WBAN, RL algorithm based on game theory is used to improve its performance. Each WBAN transmit at the maximum data rate, and RL’s payoff function is represented as a reward function to choose the best-responding player. The reward function is updated at each state based on the previous state and the current SINR value. The benefits of this scheme show that WBANs do not negotiate with others, and the users perform well under a dynamic environment (e.g., power levels, channel) by setting a learning rate for WBANs. Furthermore, RL results in a better network performance than PAPU or basic PCG although its long convergence time even though the QoS constraint is not considered.

In [23], another power control that combines genetic algorithm (GA) and fuzzy power controller (FPC) is novel genetic-fuzzy power controller. The input of system model consists of SINR, current interference power, and a feedback channel. The output of system is the current transmission power which works as a feedback channel. The level of transmission power is defined by the fuzzy controller. In addition, the fuzzy rules of FPC are described by GA learning mechanism. The benefit of FPC is similar to that of RL-based algorithms in that WBANs do not need to negotiate with others. The deployments of GA in FGC speeds up the convergence time by applying the current transmit power as a feedback value. Moreover, FPC applies this feedback value to improve the fitness function. The simulation results show that FPC is adaptive to a mobility scenario in which interference is unpredictable because FPC is an independent method with fast convergence time. FPC is more effective than PCG and PAPU even though the QoS constraint of sensors is not mentioned in three schemes.

In [24], the interference amongst WBANs is avoided by using the power control game which takes the mobility of WBAN into account. The power control game in a cyber-physical WBAN system was designed by detecting network topology before adjusting transmission power. In this method, the interaction information between WBANs is conducted in terms of the cumulative distribution function of the distance between WBANs. In order to broadcast message to the nearby WBANs within the transmission range, WBANs discover the distance between others within their transmission range by using Bluetooth and acoustic wave technology. The first benefit of this comes from the interaction steps; WBAN optimizes its power according to the received information from the other WBANs to avoid interference. In addition, WBAN can change its transmit power according to the changing network topology. WBANs also consider the time of social information detection and convergence. WBAN needs to process data fast and accurately because WBANs must broadcast information about its own channel, network utilization, SINR, and channel gain before updating information from others.

In [25], in order to address the QoS requirement, a new power control-based algorithm using GA considers throughput and BER as the major factors for improving WBAN service and reducing power consumption. QoS requirements are covered in two services as follows. The throughput-sensitive service guarantees the minimum throughput requirement of the sensor; and the BER-sensitive service must know the maximum BER threshold of each sensor. Even though GA outperforms PAPU in terms of throughput and BER, GA is not considered in the real-world mobility environments which may cause a slow update in the WBAN and a long convergence time.

In [26], another algorithm which also considers the tradeoff between power consumption and throughput using the Bayesian game to mitigate inter-WBAN interference. Unlike PAPU and FPC, the Bayesian game assigns each sensor node's transmission in its channel based on the type of sensors. Therefore, WBAN can change its power at the node level according to the knowledge about the dynamic environment or the type of nodes. The benefit of the Bayesian game is that it does not exchange the information between WBANs. However, the scheduling does not consider the severity of the interference at each sensor node or the convergence time.

In order to decrease the power while ensuring the performance of the transmission, cross-layer interference management defines the interference-limited communication range around the receiver [27]. Compared to the other power control mechanisms, this method is effective while applying to WBANs in a hospital environment to reduce transmission range. As a result, it cannot interfere with other WBANs even though the QoS constraint of sensor nodes is not considered. The power control algorithms use TDMA; therefore, new MAC protocols that are suitable for IEEE 802.15.6 requirements must be established.

A comparison of power control schemes is presented in Table 4.

Table 4. Comparison of the interference mitigation schemes in the power control approach

Interference Mitigation Scheme	Throughput	Energy Consumption	Mobility Support	Negotiation	QoS Guarantees	Self-Learning Ability	Channel Parameter	Convergence Time	Tradeoff
PAPU [20]	Low	High	No	Yes	No	No	Channel gain, power, interference gain	Slow	Low
PCG [21]	Low	Medium	Yes	Yes	No	No	Power budget, SINR	Slow	Low
RL-based [22]	High	Medium	Yes	No	No	Yes	SINR	Slow	High
FPC [23]	High	Medium	Yes	No	No	Yes	Power, SINR, power feedback	Fast	High
Using social networks [24]	Medium	High	Yes	Yes	No	No	Interaction information, channel gain, power, interference gain	Medium	Medium
GA [25]	High	Medium	No	Yes	Yes	No	Channel gain, power, interference gain	Slow	Medium
Bayesian game [26]	High	High	Yes	No	Yes	No	Channel gain, power, interference gain	Slow	Low
CLIM [27]	N/A [7]	Low	No	No	No	No	Channel gain, SINR	N/A	N/A

2.1.2. MAC Approach

Interference between WBANs can be mitigated by changing their working channel or manually allocating their superframe. In this approach, a MAC protocol is investigated to increase throughput and decrease transmission power while mitigating interference.

In an interference scenario, dynamic coexistence management (DCM) [28] is a MAC scheduling algorithm designed to control the coexistence of WBAN based on IEEE 802.15.4 standard. Each WBAN manage their own working status independently. At first, the DCM algorithm detects the lost beacons or data so that the WBAN can estimate the degradation of performance before switching the channel. The coordinator detects a lost beacon at the end of a contention-free period in the superframe. Then, the coordinator will scan the current working channel for data retransmission. However, the QoS requirement is not taken into account although the likelihood of successful transmission is high. In addition, the high power consumption of WBANs may cause the increase temperatures of the sensors in WBANs.

In [29], interference-aware channel switching (InterACS) uses an interference framework that decides to change the operating channel of WBAN to another idle channel. In the framework for interference, the coordinator records the node's activity and status, then selects the channel based on the current SIR value to avoid interference. The state of nodes is observed with regards to SINR, if the SINR is below a threshold value, the coordinator requires the sender to change to a different channel. However, InterACS applies only the switching channel into WBANs to mitigate interference without considering packet loss or dynamic interference scenario.

In [30], a lightweight and robust interference mitigation scheme (LRIM) detects interference by estimating beacon delivery ratio. In order to estimate the transmission environment, the traffic efficiency (TE) is defined according to the successfully received packets, the number of backoffs, and the number of retransmissions. The threshold of TE and BDR is used to estimate the interference level. Then, LRIM applies channel hopping to avoid interference. Therefore, LRIM is more effective than InterACS. LRIM employs a node as a watcher, it results in high efficiency of channel sensing without affecting the performance of the whole network. Because the mobility of WBANs and the QoS constraint are not considered, the channel sensing and switching tasks may cause high end-to-end delay.

In order to achieve high spatial reuse, dynamic resource allocation (DRA) scheme [31] is a new MAC protocol which considers the interfering nodes for rescheduling transmissions among WBANs. The coordinator detects the interference based on the SINR, if the SINR of a sensor node is below a threshold, the coordinator lists the sensor nodes to the interfering list. Each WBAN within the interference range creates its own list of interfering nodes in every WBAN. WBANs must exchange information to the neighbors before reassigning their time slots according to the knowledge of network. DRA improves the spatial reuse compared to conventional orthogonal channel scheme. Because DRA investigates the shadowing effect and threshold value of the SINR, the network performance is high despite of the fading effect caused by human mobility. However, WBAN requires a low SINR threshold and update the knowledge of network upon every change in the network according to SINR. The fair decision between SINR and spatial reuse must be achieved because the convergence time is estimated on the broadcast at each round.

In the service-based scheduling scheme [32], the coordinators of interfering WBANs will exchange data before transmitting data. The coordinator will sort the network traffic of sensor based on the priorities in IEEE 802.15.6. The QoS requirement of traffic is the basic factor to schedule data to the superframe in an interference scenario. The superframe is described as in IEEE 802.15.6 [4] with beacon mode. Therefore, WBANs with higher priority can occupy the channel to transmit data while the others suspend their transmissions. Moreover, the power consumption is low because the packets do not collide. Nevertheless, this scheduling scheme does not consider dynamic environment, changing topology, or high-density WBANs.

In [33], a hybrid multiple-access algorithm of CSMA/CA and TDMA is used in asynchronous internetwork avoidance (AIIA) which updates its own schedule based on the information from other WBANs. The AIIA table includes knowledge about the location of the contention-free period in the superframe of neighboring WBANs. In AIIA, the coordinator updates the timing offsets between its timer and a neighboring GW's timer and, then a TDMA transmission schedule is designed for neighboring WBANs. Therefore, in multiple mobile WBANs scenario, AIIA performs well because it can transmit data to its neighbors without synchronizing steps, more particularly, AIIA reallocates time slots to the sensor nodes without negotiating with other WBANs. In the simulation results, AIIA achieves higher-capacity WBANs and lower energy consumption. However, AIIA does not consider the QoS of sensors, also the convergence time of the constructing table. In addition, the length of the TDMA duration may affect the performance of the AIIA.

In order to reduce the energy consumption in an interference environment, the continuous frame (CFT) transmission implements TDMA to allocate the transmission of sensors [34]. CFT is a non-negotiation method because CFT uses CCA for carrier sensing, and then assigns the time slot if the channel is idle. Because CFT performs the carrier sensing, it results in better performance than TDMA. CFT reduces unnecessary transmissions resulting in energy efficient. Nonetheless, CFT does not consider end-to-end delay and QoS. If interference occurs among vital medical signals, retransmission may cause a long end-to-end delay.

The random incomplete coloring (RIC) method in [35] considers the inter-WBAN scheduling as a problem of graph coloring which achieves high spatial reuse in WBANs. In RIC, TDMA is used for both intra- and inter-WBAN schedules. Two neighboring WBANs which share the same edge of interference graph will be assigned different colors or channels. The coordinators broadcast the coloring message to other WBANs which contains the color and the random value information. If the coordinator wins the slot or is assigned by a color, the coordinator will send a beacon to its sensor nodes. As a consequence, the sensor nodes will transmit data via the scheduled TDMA slot. Because the sensor can transmit after receiving the beacon from its coordinators, RIC results in fast convergence time and low power consumption. The wasted energy is low if a transmission is suspended. Despite these advantages, the mobility of WBANs or the QoS requirement of the vital signal are not considered in the superframe. Because RIC colors the transmissions of nodes randomly, the priority of each sensor in WBANs is not considered that may cause a dangerous situation in healthcare service scenarios. For example, the node that transmits the emergency signal may not be colored and therefore may not transmit.

The 2L-MAC scheme [36] is the two-layer interference mitigation for WBAN which consists of two phases: polling with backoff mechanism and channel switching. The hub or the coordinator always performs carrier-sensing CCA to check the channel status before polling its sensor nodes. The hub broadcasts a polling frame to the sensor nodes if it senses an idle channel. When the nodes receive the polling frame, they transmit data to the hub. Otherwise, the hub performs the backoff procedure and waits until the channel is idle. The QoS requirement is the primary value that 2L-MAC uses to determine when to transmit a signal. The advantage of the cross-layer design is to avoid collisions at the physical layer and the accessibility of the idle channel. In order to prevent the polling from many hubs, a coordinator polls the idle channel with a back-off mechanism. Sensors switch to available channels, therefore, the mechanism satisfies both the throughput and the QoS requirement of the WBAN. Despite that, the wake-up event at the sensor node is long which results in high power consumption in the WBAN. Also, the back-off mechanism causes high end-to-end delay.

In [37], WBAN uses a quantitative measure of adaptive mechanism which is the interference mitigation factor (IMF) for mitigating inter-WBANs interference. The SINR value in a WBAN is used to maintain link quality, then WBAN adapts different schemes such as modulation, data rate, and duty cycle. At first, the IMF defines the reduced transmit power level in the adaptive transmission status. Then, each WBAN selects its data rate, modulation scheme, and duty cycle value according to the IMF. The threshold for the switching technique is set based on the SINR value. The IMF is simply based on the standard MAC superframe but effective because it can be widely applied to existing WBANs. Nevertheless, collisions at the physical layer may occur because the IMF mechanism does not perform the channel scanning. In addition, the priority of the signal in WBANs is not considered.

In [38], WBANs explore the interference at node-level with respect to the type of sensor nodes. Because sensors can be categorized into various types that send data periodically or nonperiodically, all sensors in a WBAN may not be active at the same time. Because of the mobility of WBANs, sensors in different WBANs can be active simultaneously, causing interference. Clique-based WBAN scheduling (CBWS) places the sensors in different groups to avoid interference, then use the coloring method to schedule the sensors. In the system model, one or more WBANs will group into a clique by using a distributed method. The sensor nodes in the clique are formed into virtual groups according to their group IDs. The sensors in a group will be assigned into time slots by the random coloring algorithm. The multiple WBAN network is represented as a graph in which the vertices represent the set of groups and the edges represent the links between groups. The color set represents the resources in time domain or frequency domain, for example, time slots or frequency bands, respectively. The color mapping algorithm assigns different colors to the vertices so that the sensors can transmit in different time slots. Based on the assigned colors, each group can perform during the assigned time slot. Different to other coloring algorithms, CBWS considers interference at the node level with respect to the function of sensor nodes. In addition, CBWS groups the sensors into clique based on the position of coordinators and sensors in WBANs before reallocating them into time slots. Therefore, groups of the same type of sensors residing in the interference area can be rescheduled, it results in a continuous communication link and low power consumption.

CBWS applies the random coloring algorithm as RIC [35], but on the basis of the graph setup. RIC assigns the color to the WBANs so that does not consider the function of sensor nodes. In contrast, CBWS assigned colors to the active sensors, which results in long network lifespan and low power consumption while mitigating interference.

In [39], cooperative scheduling (CS) with graph coloring is the hybrid interference mitigation of graph coloring and the scheduling scheme. The scheduling scheme is similar to DRA [31], in which the sensors within a interfered region will transmit orthogonally. In CS, two nearby interfering WBANs form one cluster in which the sensor nodes in the cluster will transmit orthogonally. The coloring method assigns colors to every cluster so that clusters with different colors can transmit simultaneously. Similarly to CBWS and RIC, CS models the network as a graph in which the vertices represent the wireless nodes and the edges represent the interferers. The color set consists of the time slots that will be scheduled to the vertices.

Similar to DRA [31] and CS [39], the adaptive internetwork interference mitigation (AIM) algorithm [40] aims to increase spatial reuse. AIM reschedules the sensors of the interfering WBANs into synchronous and parallel transmission. The nodes are assigned into time slots according to the priority of sensor nodes. More particularly, the node with higher priority will be scheduled more time slots. On the other hand, the other nodes in the transmission area suspend their transmissions. AIM can be explained in three phases: In the first phase, the coordinator of a WBAN calculates the interference level using the sensor node’s information such as packet length, received power, and priority level. After exchanging messages from the coordinators between WBANs, the coordinator assigns the sensor nodes’ transmissions into the orthogonal channels. In the second phase, the each WBAN forms its interference list, similar to DRA [31]. Every coordinator broadcasts its interference list in the information exchange phase. Finally, WBANs schedule their transmissions based on the traffic priority. In the simulation results, AIM achieves high efficiency in case of considering priority, otherwise, AIM achieves low efficiency.

Table 5. Comparison of the interference mitigation schemes in the MAC approach

Interference Mitigation Scheme	Throughput	Spatial Reuse	Collaborative Method	QoS Guarantees	Channel Parameters	Channel Access	End-to-End Delay	Number of WBASNs
DCM [28]	High	No	No	No	Beacon, data loss detect	TDMA	Low	High
InterACS [29]	Medium	Low	No	No	SINR	TDMA	High	Very low
LRIM [30]	High	No	No	No	BDR, TE	CSMA/CA	High	Medium
DRA [31]	High	High	Yes	No	SINR	TDMA	Medium	High
Service-based scheduling [32]	Medium	Medium	No	Yes	Transmit only sensing idle channel	TDMA	High	Low
AIIA [33]	High	Medium	Yes	No	Superframe time offset	TDMA, CSMA/CA	High	Low
CFT [34]	Medium	No	No	No	CCA	TDMA	High	Medium
RIC [35]	Medium	Medium	Yes	No	Coloring message	TDMA	High	High
2L-MAC [36]	High	No	No	Yes	SIFS period	TDMA	High	Medium
IMF [37]	High	No	No	No	SINR	TDMA	High	Low
CBWS [38]	High	High	Yes	Yes	Group ID	TDMA	Medium	High
CS [39]	High	High	Yes	No	SINR	TDMA	High	High
AIM [40]	High	Low	Yes	Yes	SINR	TDMA	High	High

2.1.3. Cognitive Radio Approach

In [41], the fast dynamic cognitive radio (FDCR) algorithm is implemented in adaptive cognitive enhanced platform (ACEP) to schedule access for a WBAN's node to the idle spectrum. ACEP is designed according to CR-WBAN models and an interference subsystem, an observer subsystem, and a WBAN subsystem. The interference subsystem is considered as the presence of WiFi interference in a medical environment. Two observation nodes form an observer subsystem which monitors the whole system's working status. In the WBAN subsystem, the coordinator is implemented with FDCR which senses the spectrum and estimates interference behavior patterns. In an ACEP system, the coordinator senses the spectrum and estimates interference behavior patterns based on the IEEE 802.15.6 standard MAC algorithm. FDCR then changes the channel access and sensing times with regard to the spectrum occupancy condition, results in increasing the stability of the WBAN's access to channels. The FDCR algorithm can be divided into two phases: channel sensing and channel access. The coordinator senses the channel to check if the spectrum status is busy or idle in the channel sensing phase. In the channel access phase, the nodes access the channel based on the parameters received from the coordinator.

In [42], a hybrid cognitive validation platform (HCVP) is implemented in WBAN with an adaptive cognitive radio MAC algorithm to minimize WBAN interference. HCVP is a structure for cognitive radio evaluation and consists of two parts. The lower part based on real hardware comprises the PHY and MAC layers, and the upper part based on computer software that contains the cognitive radio algorithm, the network layer, and other layers. In HCVP, the coordinator is cooperated with the cognitive radio software of the computer and WBAN nodes are connected to a computer.

HCVP is implemented at the coordinator of WBAN and consists of spectrum sensing, channel estimation, and channel accessing. The working status of the spectrum is indicated by RSSI. Cognitive radio software performs channel estimation, which estimates the channel usage and the optimization of access times. The second phase can be divided into two stages which uses RSSI and packet collision rate as follows: RSSI is used to estimate channel usage distribution; then, the packet collision rate is used to show the channel status by comparing to the result of the first stage. However, it is necessary to consider the optimized tradeoff between throughput and sensing time. In the channel access phase, the coordinator senses the spectrum, then collects the result of an optimized access time and compares it to the collision rate threshold. The coordinator broadcasts a beacon if the channel is idle. Nodes in WBANs continuously wait for a beacon which has the boundary information about a superframe setting according to an optimized access time. If nodes receive a beacon, each node checks the spectrum for a short period time before accessing the channel to avoid interference between WBANs.

A hospital may be the scenario with the highest probability of interference for WBANs. Many people wearing WBANs may be staying in a specific room or walking in a hall of a hospital. In [43], a cognitive framework is applied to WBANs for avoiding interference in hospitals. The Cognitive-Receiver Initiated CyclEd Receiver (C-RICER) MAC protocol comprises three main tasks: The first task is channel sensing aims to sense the channel and creates a full interference map including the frequency channels. Secondly, the power adaptation reduces transmission power to reduce interference. Lastly, channel adaptation enables the coordinator to switch to another channel.

As in [43], interference within a hospital is considered in [44]. Medical devices in the hospital are chosen as the primary users while cognitive radio is implemented in devices attached to the human body as a cognitive framework. The interference-aware management framework (IAMF) includes of the database, measurement, evaluation and update function, strategy function, and internal and external dissemination. The first task detects regions of overlap between WBANs and estimates the location of mobile cognitive radio nodes. The cognitive radio platform is implemented with power control and frequency hopping methods to avoid interference.

The cognitive radio WBAN (CR-WBAN) model is based on UWB technology for medical applications in hospital scenarios [45]. The architecture model of the CR-WBAN has an IR-UWB transceiver with on-off keying modulation and an MB-OFDM transceiver. The frequency band is assigned to the UWB band (3.1 to 10.6 GHz). In [46], a three-tier WBAN architecture for medical applications in the hospital is presented in which cognitive radio can be implemented in the WBAN controller node or the access point to transmit data to the server. A central controller-based architecture comprises of three components equipped with cognitive radio capabilities. Applying CR-WBAN can reduce electromagnetic interference and ensure QoS enhancement.

2.1.4. UWB Approach

In a UWB-based WBAN, multiple access interference (MAI) may occur in the transmission between devices on a single person. In [47], a successive interference cancellation (SIC) algorithm is implemented to cancel the interference and the UWB/MIMO (multiple input/multiple output) system model is introduced. In the UWB/MIMO WBAN system, a zero correlation duration code (ZCD) is used to spread the transmitted UWB signals. SIC orders the relative signals between the users according to the strongest signal. In order to achieve the desired signal, SIC finds the strongest signal to cancel and repeat until it gets the signal with low probability of error. In this scheme, the receiver estimates the transmitted signal by using the interference cancellation scheme. At the receiver, zero forcing algorithm and minimum mean-square error algorithm are used to counteract the interference.

In another study, the interference mitigating scheme in a UWB body area network use a single hybrid hermit pulse to cancel the narrowband interference [48]. The hybrid hermit pulse is created by shifting and modulating the hermit pulse. Because the hybrid pulses are designed to have notches at the desired bands, the narrowband interference is cancelled at the notches.

2.1.5. Signal Processing Approach

In the interference scenario of multiple WBANs, the signal processing of sensors only needs to rebuild the original signal and remove both noise and electromagnetic interference (EMI) from power lines. In the first approach, the waveform of respiratory signals was reconstructed by processing single-channel ECG [49]. The empirical mode decomposition (EMD) in [49] aims to sum the components that approximates the original ECG signal. The EMD algorithm determines intrinsic oscillations by using the characteristics of data. The ECG and EEG signals are combined in the scenario of healthcare service [50].

In the presence of interference in WBANs, each receiver can remove interference from other systems by either applying the detectors or changing the structure of the receiver. In [51], the interference in CDMA-based WBAN systems is rejected by using multiuser detection. The multiuser detectors include two different structures which are the minimum mean square error (MMSE) receivers and the decorrelator. The MMSE receiver minimizes the mean square error between the transmitted bits and the outputs of the transformation, and the decorrelator has a decision metric to remove correlation. The system is modeled by both an interference source from other WBANs and the belt-head on-body transmission. In the result of simulation, the detectors with match filters outperform the conventional receiver.

On the other hand, an ultra-low power wake-up receiver (WUR) [52] is implemented in WBANs which consumes low power and avoids interference from other wireless devices. In WUR, the transmission modes depend on the type of transmission which can be explained as follows: the data transmission uses the transceiver's Gaussian frequency shift keying (GFSK) and the wake up transmission uses Gaussian on-off keying (OOK) modulated by pulse width. The WUR filters interference by using the preamble detector.

2.2. Comparison of Interference Mitigation Approach

As shown in Figure 2 earlier, the interference mitigation schemes have been categorized into five categories which are power control approach, MAC approach, cognitive radio approach, UWB approach, and signal processing approach. The five approaches are compared with each other with regard to the robustness to mobility, lossy channel support, self-learning ability, effectiveness, and cost as shown in Table 6. The robustness to mobility is taken into account as the ability of a mitigation scheme in mobile and densely network deployment of WBANs. The lossy channel support is investigated with respect to high fading channels. Effectiveness can be analyzed whether the technique is robust to the interference. Cost is evaluated on the basis of channel parameters, convergence time, and acceptable performance.

Table 6. Comparison of the five interference mitigation schemes

Interference Mitigation Approach	Robustness to Mobility	Lossy Channel Support	Self-Learning Ability	Effectiveness	Cost
Power control approach	Yes	No	Yes	Medium	High
MAC approach	Yes	No	Yes	High	High
Cognitive radio approach	Yes	Yes	Yes	High	Low
UWB approach	Yes	Yes	No	High	Medium
Signal processing approach	No	Yes	No	Medium	High

2.3. Open Issues and Challenges

2.3.1. System Throughput

In order to evaluate system performance, the system throughput is evaluated in terms of data rate and packet delivery ratio. The more reliable communication of the network is considered by the system throughput in the interference scenario. In addition, mobile and high-density WBANs adversely affect bandwidth utilization. Because main application of WBANs is healthcare service in which each sensor conveys vital signal from a human body to the medical service center, signal loss can cause a dangerous situation for patients. Therefore, the first requirement of mitigation scheme is to maximize system throughput in the multiple WBANs scenario.

2.3.2. Power Consumption

In order to ensure a long lifespan for the sensor nodes, energy efficiency or low power consumption becomes the main goals in any WBAN application. Because of the small size of the batteries, the power capacities of sensor nodes are limited, so that the batteries cannot be replaced or recharged. Moreover, in interference scenarios, power consumption of a WBAN is high because of the idle listening channel, contention to access the channel, and retransmission. Some algorithms consider the minimization power in a WBAN as a main objective. However, an effective interference mitigation scheme can be considered if it has a good tradeoff between performance and power consumption.

2.3.3. QoS and Reliability

WBANs have specific QoS requirements which are depended on type of sensor or application [4-7, 13]. Specifically, the QoS constraint focuses on bit error rate (BER) or the priority of a transmitted signal. In the interference scenario in a hospital or waiting line in a public place, WBANs with a high QoS constraint should have a high priority to access the channel because they may carry vital data about a chronic illness such as a heart disease.

Reliability can be investigated by the latency and probability of packet loss. The latency of the received data depends on the WBAN application; for example, the delays for an ECG signal and a video signal must be below 250 ms and 20 ms, respectively [13]. Furthermore, in the case of interference among WBANs, the convergence time can be considered as the time which WBANs return to normal operation or stable status. In addition, the convergence time also affects packet latency. For example, interference mitigation scheme is more effective if convergence time is short; WBAN quickly returns to the normal transmission leading to low end-to-end delay. In addition, the probability of packet loss defines the extent to which the packet drop rate affects the reliability of a WBAN in terms of BER or packet error rate.

2.3.4. Dynamic Environment

The mitigation scheme must work in a dense deployment of mobile WBANs. WBANs have the ability to avoid interference by working independently without exchanging their information with other neighbor WBANs. In the case of negotiation methods, WBAN needs to exchange information to others that may result in a long delay or slow convergence, but WBANs perform better if they have knowledge of the whole network system. In the case of non-negotiation methods, a WBAN needs to improve its performance, converge quickly, and learn about the network system by itself.

2.3.5. Impact of Wireless Communication on the Human Body

Because the biomedical sensors are placed in or on the human body, the radio frequency (RF) radiation may affect adversely to the tissues of the body. The RF radiation in interaction with biological systems has been examined in terms of thermal and non-thermal bioeffect [53]. Average specific absorption rate (SAR) limitation in the whole human body is 0.08 W/kg and 0.4 W/kg in uncontrolled and controlled environments, respectively; local SAR is 1.6 W/kg in any gram tissue in the shape of a cube [54]. The thermal mechanisms result in temperature increase of the biological system; e.g., a continuous wave RF field of 30 V/m at 1 GHz produces SAR of about 1 W/kg [53]. One example of the non-thermal mechanisms is membrane excitation; i.e., a very short pulse can make membrane breakdown. In [55], the non-thermal mechanisms are not fully understood but they do not cause the biological effects. Therefore, the human body may be involved with the safety problem in both short term and long term.

More specifically, in [56], the impact of RF radiation on the human body has been classified with respect to the radiation sources, impacts, and factors. The radiation impacts are divided into the extremely low frequency and radio frequency groups. The factors that affect RF absorption are classified into biological parameters, physical parameters, artifacts, and environmental parameters. Therefore, some open research areas for passive wireless technologies have been introduced for healthcare environments. Another research has been summarized in three-dimensional wireless sensor networks in [57], in which the aspect of radiation awareness is examined in three-dimensional environments. The main idea is to find the minimum radiation path for a person moving from one place to another place.

In WBANs, the coordinator node is a body-placed device which can forward the vital signals to the gateway. In [58], the new antenna structure which can decrease SAR is used in a body-worn communication device, for example, applied to the coordinator node. The new antenna is one type of an artificial magnetic conductor (AMC), which has the slotted periodic structure. This type of antennas can work at a wideband code division multiple access as well. In [59], an AMC-intergrated antenna is another type of AMC which is designed for WBANs to operate in the ISM bands. In [58, 59], the simulation results show that using the AMC antenna can reduce the SAR on the human body.

However, a path with low SAR in WBANs can be found by using an optimization algorithm as in [60]. One node will become the relay node which forwards signals from other sensor nodes to a hub by using the low SAR path.

3. Interference-aware Traffic-priority-based Link Scheduling Algorithm

3.1. Introduction

In order to improve the health monitoring, the wireless wearable sensors have been deployed to collect the biological signals of the human body, thanks to the development of new technology in wireless networks and sensors [61]. In current researches, WBANs are relevant to the medical or non-medical applications which usually occur in the public places such as hospital or bus station [9, 62-64]. In those environments, the number of co-located WBANs are densely deployed which depend on the number of patients, e.g, in the hospital. Therefore, the reliability and network performance becomes critical in the multiple WBANs scenario [65]. The coexistence environment of WBANs is unpredictable in time and spatial domain due to the number of traffic flows, the mobility of WBANs, and the dynamic of network topology [4]. When many WBANs move around in the same place, the transmission range of WBANs may overlap that results in the degradation of network performance in terms of low packet delivery and long latency [14]. On the other hand, the sensor nodes that attached to human body carry different vital signals with respect to different WBAN applications. The quality of service (QoS) of WBAN depends on the generated traffic of sensor nodes which can be categorized into on-demand, emergency, and normal traffic for medical and non-medical applications [63]. The typical values of the important parameters such as data rate and latency for various biomedical sensors are summarized in Table 1. In the IEEE 802.15.6 standard, QoS is mapped into the traffic priority according to the application type of sensor nodes as in Table 7. Hence, it is necessary to ensure the quality and reliability of signals at each WBAN by mitigating inter-network interference. Furthermore, some MAC protocols assign the packet transmission of multiple WBANs based on QoS and traffic priority, which overcome the performance degradation caused by interference as well as ensure the requirement of traffic priority [66, 67].

Table 7. Traffic priority in WBANs according to IEEE 802.15.6 standard [4]

Traffic Priority (TP)	Traffic Designation
0 (Lowest)	Background (BK)
1	Best effort (BE)
2	Excellent effort (EE)
3	Video (VI)

4	Voice (VO)
5	Medical data or network control
6	High-priority medical data or network control
7 (Highest)	Emergency or medical implant event report

As mentioned in Chapter 1, the inter-WBAN interference can be mitigated by scheduling the working channel in time or frequency domain. In addition, some medium access schemes can be used such as time division multiple access (TDMA), spatial-time division multiple access (STDMA), or frequency division multiple access (FDMA). Due to the vital signals of human body, the scheduling protocol should take the traffic priority and reliability into account to improve the network performance in the multiple WBANs environment.

In this chapter, the scheduling algorithm is deployed for multiple WBANs which allocate the transmission of each WBAN in the space–time domain as well as maximize network throughput with lower delay. The sensor node's transmission will be assigned into a specific time slot by the coordinator using TDMA-based MAC protocol. The interference level is defined by the number of interfered sensor nodes in each WBAN as well as packet length and the traffic priority of each type of traffic. The proposed interference-aware traffic-priority-based link scheduling (ITLS) algorithm can deal with inter-WBAN interference in dense deployment WBANs, thus results in high spatial reuse. According to the results of simulation, ITLS significantly improves the network performance such as high spatial reuse and network throughput, lower delay while mitigating inter-WBAN interference.

The contributions of this work are as follows: first, an interference graph represents to the multi-WBAN network where the edges describe the interference links and the vertices represent WBANs. Each WBAN consists of one coordinator and multiple sensor nodes. The interference level of WBAN is defined by the number of interfering WBANs, signal-to-interference-plus-noise ratio (SINR), and traffic priority of each sensor node. Second, the scheduling problem is formulated as an optimization problem that aims to maximize the number of simultaneous transmissions in multiple WBANs in each timeslot. Finally, the ITLS algorithm schedules the transmission of sensor nodes based on the optimization problem. The transmission of nodes is assigned to channel or timeslot based on a condition of the interference level of each WBAN. The transmission of each WBAN is scheduled with regards to the interference level without interfering with its neighbors. As a result, the proposed ITLS algorithm can reduce inter-WBAN interference and achieve higher performance.

3.2. Reviews of Interference Graph Background and WBAN Scheduling Algorithms

In general, the interference problems of wireless networks have been investigated and modeled as an interference graph [67]. The vertices represent terminals of a network and the edge model the relationship between two vertices. To model the interference graph, SINR at a node can be used to indicate the probability of interference. In wireless sensor networks, the scheduling algorithm can mitigate the interference as explained in the two examples of the link schedule optimization in reference [68] and TDMA scheduling algorithm in reference [69].

Currently, the IEEE 802.15.6 standard provides the mechanisms for coexistence and interference between WBANs [4]. In the standard, the three mechanisms of channel hopping, beacon shifting, and active superframe interleaving can be used to mitigate interference between WBANs. In current literature, the channel scheduling algorithm is investigated as the most effective technique for reducing inter-WBAN interference with respect to system throughput. Some channel scheduling at MAC layer can be listed as DRA [31], RIC [35], CBWS [38], cluster-coloring [39], AIM [40]. Moreover, some MAC protocols were also introduced to mitigate interference in healthcare monitoring. For example, QoS MAC protocol for multiple WBANs [70], interference-aware MAC [71], cognitive radio MAC protocol [72]. Nonetheless, there exist some limitations in the existing schemes. The existing link scheduling algorithms for WBANs focus on the channel status and the interference at each WBAN [31, 35, 38]. Because the interfered nodes can cause data loss at the coordinator, some scheduling algorithms adopt the number of interfering WBANs as well as the number of interfered nodes. Some works have focused on scheduling or shifting the transmission time but they do not take the traffic priority into account [31, 35, 38-39]. In fact, the traffic priority of sensor nodes is important because of different type of data at the on-body sensor nodes. Data of sensor nodes can be characterized in accordance with packet length, data rate, and transmission time [61]. Therefore, according to the traffic priority, the transmission links from sensor nodes to the coordinator need to be scheduled to the superframe as follows: if both high and low priority nodes need to transmit at the same time, the scheduling algorithm assigns the high priority node to use the link to the coordinator to access the medium, whereas the low priority node has to wait.

3.3. Interference-aware Traffic-priority-based Link Scheduling

In this section, we explain our proposed link scheduling algorithm for a multiple-WBANs network. At first, the network model is introduced, and the problem of link scheduling in multiple WBANs is formulated according to the network model. Next, the proposed algorithm is analyzed with examples, and it is compared to conventional algorithms qualitatively.

3.3.1. Network Model and Interference Graph Generation

In multiple WBANs, if sensor nodes exist in the overlapped transmission range of two WBANs, the transmission of those sensor nodes may be interfered by each other in a duration time or a timeslot. In our algorithm, the transmission of all WBANs is successfully scheduled into the superframe with T timeslots. Assume that each WBAN consists of one coordinator and a group of wireless sensor nodes in which is stable during one superframe.

We deploy a network with n WBANs labeled B_1, B_2, …,B_n that exist within the interference range of each other. The transmission range of each WBAN is modeled as a circle of radius r, where the coordinator is located at the center and m sensor nodes are located within the circle. The sensor nodes transmit the vital signals of the human body to the coordinator before aggregated at the gateway for a specific application. The data of sensor nodes are classified into eight different categories as defined in the IEEE 802.15.6 standard [4], as listed in Table 5. The sensors in each WBAN can be listed with different traffic priority. Therefore, the j-th sensor in B_i is represented as $s_{i,j}$, and the traffic priority of the j-th sensor in B_i is denoted as $p_{i,j}$, where $1 \leq j \leq m$. Assume that for each type of traffic priority, the length of the generated packets is different for each type of traffic; therefore, the transmission time of sensor node $s_{i,j}$ at priority $p_{i,j}$ is represented as $t_{i,j} = u(p_{i,j})/b(p_{i,j})$, where $u(p_{i,j})$ is the packet length and $b(p_{i,j})$ is the data rate of priority $p_{i,j}$. For intra-WBAN transmission, the coordinator assigns the transmission of the sensor nodes using the TDMA scheme. The sensor nodes transmit the vital signals according to the TDMA schedule after receiving the beacon message from its coordinator.

As given in reference [73], we consider that body-to-body links are modeled by free space path loss model without shadowing, with the path loss exponent of 2. This path loss is exponentially increased with the increased distance between WBANs. The channel gain of body-to-body links is modeled as gamma distribution as in reference [74].

At every WBAN, the coordinator finds its neighbors using distance-based interference: if the distance between two coordinators is less than the transmission range, two WBANs interfere with each other. The list of WBANs interfering with B_i is represented by $L_i = \{j|d_{i,j} < r\}$, where $d_{i,j}$ is the distance between B_i and B_j and r is the transmission range. Given n WBANs, the interference graph is represented by graph $G = (V, E)$; $V(G)$ is the set of WBANs, i.e., $V(G) = \{B_1, B_2, \ldots, B_n\}$, and $E(G)$ is the set of interfered links between WBANs, i.e., $E(G) = \{(i, j)|i \in L_j, j \in L_i\}$. If there is no interference between WBANs, $E(G) = \phi$.

At WBAN B_i, the coordinator builds interfered sensor group ISG_i that consists of all the sensor nodes interfered by the neighbors. The coordinator always observes the SINR of its sensor nodes, $\gamma_{i,j}$, and compares the SINR with the threshold SINR, γ_{th}. In the IEEE 802.15.6 standard, the transmitted power is set as −20 dBm and the sensitivity of receiver is set at −90 dBm in the noisy environment. Because the free space path loss model is used for body-to-body links, we have evaluated the SINR of an intra-WBAN communication while increasing the number of nearby WBANs from 1 to 12. As a result, the SINR value is below 0 dBm. Therefore, we consider that the threshold SINR is 0 dBm. If SINR at a sensor is below the predetermined threshold, the sensor can be listed as an interfered sensor. SINR at sensor $s_{i,j}$ in Bi, $\gamma_{i,j}$, can be represented as:

$$\gamma_{i,j} = \frac{P_{i,j}}{\sigma^2 + \sum_{l \neq i} P_{l,j}} \tag{1}$$

where $P_{i,j}$ is the received signal power at $s_{i,j}$ (originates from the coordinator of B_i), $P_{l,j}$ is the interference power that originates from B_l (from the coordinator or any sensor) and received by the sensor $s_{i,j}$, and σ^2 is the power of additive noise. If $\gamma_{i,j} < \gamma_{th}$, sensor $s_{i,j}$ is added to the interfered sensor list ISG_i from the coordinator. That is, $ISG_i = \{s_{i,j}|\gamma_{i,j} < \gamma_{th}\}$, where $1 \leq j \leq m$. Otherwise, sensor $s_{i,j}$ is listed in the non-interfered sensor list $NISG_i$ from the coordinator. All WBANs build the interfered sensor list and exchange it with their neighbors at every superframe.

Because the sensor node is deployed with different traffic priority, we calculate the weighted interference of each sensor, $w_{i,j}$, as follows:

$$w_{i,j} = \frac{\gamma_{i,j}}{\gamma_{th}} \cdot p_{i,j}, j \in ISG_i \tag{2}$$

The weighted interference is used not only for calculating the interference level of each sensor but also for defining the weight constraint of each WBAN at each timeslot. Each coordinator examines its interference level by adding the weighted interference of the sensors in ISG_i, as follows:

$$ww_i = \sum_{j \in ISG_i} w_{i,j} \tag{3}$$

3.3.2. Problem Formulation

In a network with n WBANs, each WBAN comprises of m sensor nodes, there are $m \times n$ orthogonal transmissions in one superframe that contains T timeslots. The maximum number of required timeslots is $T = m \times n$. The number of received packets of $s_{i,j}$ at the coordinator of B_i is $u_{i,j}$. The total network throughput is calculated as:

$$BW = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} u_{i,j}}{T} \tag{4}$$

The network throughput can be increased by increasing the number of simultaneous transmission of nodes. Therefore, the objective of the problem is to maximize the number of nodes that can transmit in the same timeslot or maximize the shared timeslots among WBANs. The number of transmissions in n WBANs is $m \times n$, and $|T|$ is the set of timeslots in one superframe. At the k-th timeslot of the superframe, there are up to n transmissions in n WBANs that go from the sensor nodes to their coordinators; the scheduling decision can be represented by a vector $z_k = [z_{i,j,k}, z_{l,h,k}, \ldots, z_{m,n,k}]$, where $z_{i,j,k} = 1$ if the j-th sensor in B_i is scheduled in the k-th timeslot; otherwise, $z_{i,j,k} = 0$. Two WBANs can share the same timeslot if they do not share the same edge (interference link) in the interference graph. Because nodes have different traffic priority levels as well as different packet lengths, the required transmission time of each priority can be different from the others. Given the traffic priority level of each sensor node, we suppose that the WBAN with high priority can occupy the channel until its transmission finishes. In order to find the maximum number of WBANs that can be assigned in one timeslot, we formulate the scheduling problem as an optimization problem:

$$\max \sum_{i=0}^{n} \sum_{j=1}^{m} \sum_{k=1}^{T} z_{i,j,k} t_k \tag{5}$$

In this formulation, the scheduling algorithm attempts to maximize the number of sensors that can transmit in the k-th timeslot. However, the network throughput is measured in data packets per second, and the objective Equation (5) is rewritten as follows:

$$\max \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{T} \frac{z_{i,j,k} u(p_{i,j})}{t_k} \tag{6}$$

subject to:

$$z_{i,j,k} + z_{l,h,k} \leq 1 \mid j \in ISG_i, h \in ISG_l, l \in L_i \tag{6a}$$

$$1 < z_{i,j,k} + \sum_{\substack{l \notin L_i \\ h \in NISG_l}} z_{l,h,k} \leq T \tag{6b}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} z_{i,j,k} \leq n \tag{6c}$$

$$z_{i,j,k} = [0,1] \tag{6d}$$

$$t_k = \max_{i \in V} t_{i,j,k} z_{i,j,k} \mid z_{i,j,k} = 1,\ t_{i,j,k} = \frac{u(p_{i,j})}{b(p_{i,j})} z_{i,j,k} \tag{6e}$$

The traffic-priority-based scheduling algorithm is presented in Equation (6). Because the scheduling problem has a slotted structure in the time domain, multiple transmissions from multiple WBANs can be allocated in one timeslot. The constraints in Equation (6) can be explained as follows: if more than two WBANs interfere with each other, only one sensor node that belongs to the *ISGs* of two neighbors can transmit at the *k*-th timeslot; this constraint is shown in Equation (6a). The non-interfered WBANs can transmit in the same timeslot, as indicated in Equation (6b). In order to avoid intra-WBAN interference, the constraint in Equation (6c) shows that only one sensor node of a WBAN can transmit at one timeslot. The *j*-th sensor node of the *i*-th WBAN is active at the *k*-th timeslot if $z_{i,j,k}$ = 1; otherwise, $z_{i,j,k}$= 0, as indicated in Equation (6d). In equation (6e), the length of the k-th timeslot is the longest transmission time of all the sensor nodes that are active in the k-th timeslot.

3.3.3. Scheduling Algorithm

The step-by-step operation of the proposed ITLS algorithm is given in Algorithm 1. This algorithm executes at the coordinator of each WBAN and solves the problem in Equation (6). We use a contention value (CV) to define the weight constraint of each WBAN at each timeslot, as follows:

$$CV(i,k) = \sum_{j} w_{i,j} \mid j \in I_{i,k} \tag{7}$$

where $I_{i,k}$ is the list of interfered sensors in the *i*-th WBAN at the *k*-th timeslot. The contention value of B_i is defined as $CV(i, k)$ which is used to content the timeslot indexed by *k* in the superframe. The coordinator of B_i calculates its contention value which is calculated by the summation of the weighted interference values of the sensors in the ISG_i as shown in Equation (7).

Algorithm 1: ITLS algorithm

Input: $G = (V, E)$, T

Output: $z_{i,j,k}$,t_k, and K

Each WBAN creates its L_i, ISG_i, and $NISG_i$;

Initialize a temporal vector for B_i: a temporal scheduling value for each j-th sensor in each B_i: $z_{i,j,1} = 0$; list of interfered sensor at first slot: $I_{i,1} = ISG_i$, list of non-interfered sensor at first slot: $NI_{i,1} = NISG_i$

1. while all WBANs are not scheduled
2.   if $k < T$
3.   calculate contention value $CV(i,k)|\forall i \in V$ as in (7)
4.   find CV_{max} = max($CV(i,k)$; return j-th sensor of i-th WBAN ($j \in I_{i,k}$)
5.   find required transmission time for $s_{i,j}$, which is $t_{i,j,k}$
6.   set $z_{i,j,k} = 1$; remove j of $I_{i,k}$
7.   update $t_k = t_{i,j,k}$ to network
8.   for each $B_l \in L_i$
9.   return h-th sensor of l-th WBAN ($h \in NI_{l,k}$) such that h-the sensor has the highest priority
10.   set $z_{l,h,k}$= 1; remove h of $I_{l,k}$
11.   end for
12.   for each $B_x \notin L_i$
13.   return y-th sensor of x-th WBAN ($y \in I_{x,k}$) such that y-th sensor has the highest priority
14.   set $z_{x,y,k} = 1$; remove y of $I_{x,k}$
15.   end for
16.   update $k = k + 1$
17.   end if
18. end while
19. update $K = k$

Each WBAN is assigned to the scheduling vector of each superframe; the scheduling vector comprises the timeslot index for each sensor node in the superframe. In Algorithm 1, at each timeslot, all WBANs estimate their contention value, as shown in line 3. If other WBANs interfere with a given WBAN, the latter exchanges its scheduling message with its neighbors before starting transmission. The superframe structure for multiple WBANs is shown in Figure 4, where the coordinators of WBANs will exchange the message with their neighbors before starting intra-WBAN communication. The interfered WBAN compares its contention value with that of the interfering WBANs (line 4). The winner in this step is the WBAN with the highest CV. The active sensor with the highest priority is chosen for scheduling (lines 5 to 7). In lines 8 to 11, the winner's neighbors choose the sensor node to transmit at the *k*-th timeslot. In lines 12 to 15, the non-neighbors of the winner choose the sensor node to transmit at the *k*-th timeslot.

In order to ensure the continuity of transmission, the high priority sensor node can occupy the channel in one timeslot, and more than one WBAN can transmit via the channel with low interference. When the coordinator reports any changes to the SINR of its sensor node, the coordinator updates scheduling for the new transmission at the end of the existing superframe. Otherwise, the scheduling is kept the same.

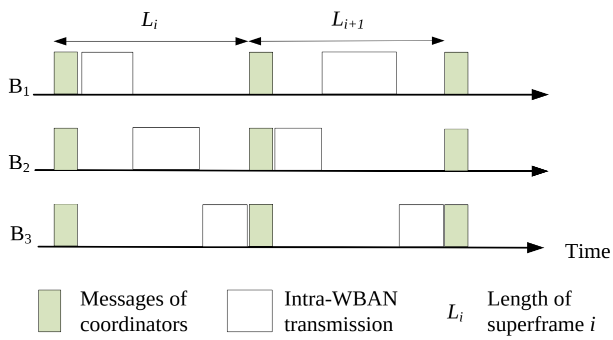
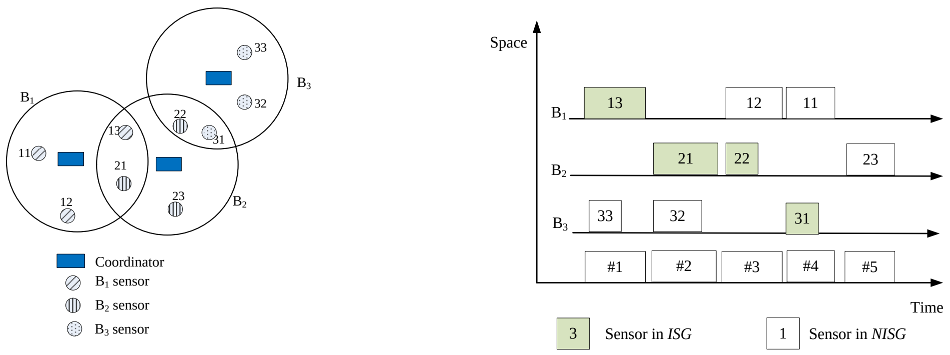


Figure 4. Superframe structure for WBANs showing messages of coordinators and intra-WBAN transmissions

3.3.4. Scheduling Example

A scheduling example is shown in Figure 5. Assume that there are three WBANs, B_1, B_2, and B_3 that work at the same time and at the same place. Three WBANs and their interference areas are shown in Figure 5(a). The sensor list of each WBAN with traffic priority written in parenthesis is as follows: B_1 = {11(1), 12(4), 13(5)}, B_2 = {21(2), 22(1), 23(2)}, and B_3 = {31(1), 32(2), 33(3)}. The interference areas of the WBANs consist of the sensor nodes {13, 21, 22, 31} as shown in Figure 5(a). Each WBAN creates its *ISG* and *NISG* as listed in Table 8.

At the first timeslot, B_1 has the highest CV (because of the priority of the interfered sensors) and *ISG*(1) = {13}; therefore, B_1 occupies the channel and sensor "13" is the highest priority sensor node in *ISG*(1) that transmits data; while *NISG*(3) is {32, 33}, B_3 can choose one of the sensors in its *NISG* to transmit. The scheduling decision at the first timeslot is B_1(13) and B_3(33). At the second timeslot, B_2 has the highest CV; therefore, one of the sensor nodes in *ISG*(2) can transmit data; because B_3 does not share the same edge, B_3 can transmit. The scheduling decision at the second timeslot is B_2(21) and B_3(32). The final scheduling among WBANs is shown in Figure 5(b). The total required timeslot for three WBANs is nine orthogonal transmissions, but the proposed algorithm requires five timeslots. Therefore, the spatial reuse is 9/5, and up to two sensor nodes can share the same timeslot.



(a) (b)

Figure 5. Interference-aware traffic-priority-based link scheduling example: (a) Three WBANs and their interference areas; (b) Timeslot assignment for network

Table 8. Example list of ISG and NISG (ITLS algorithm)

WBAN	ISG	NISG
B_1	{13}	{11, 12}
B_2	{21, 22}	{23}
B_3	{31}	{32, 33}

3.4. Analysis of ITLS

In this section, we analyze the average system throughput and the spatial reuse factor of the network under study. The system throughput is determined as the effective transmission per slot that counts the data transmission of all sensor nodes actually received by all the coordinators in the network. The spatial reuse factor is determined as the average number of sensor nodes that share the same timeslot.

Given a network with n WBANs, $V(G) = \{B_1, B_2, \ldots, B_n\}$ is the set of WBANs. The total number of sensor nodes in the network is $m \times n$. Let *BW* indicate the system throughput in the network, which is the sum of data rates received by all the coordinators. Throughput is calculated as follows:

$$BW = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{i,j}}{T} \tag{8}$$

where $u_{i,j}$ is the number of received packets of $s_{i,j}$ in B_i.

The required transmission time for the network is calculated as follows:

$$T = \sum_{i=1}^{n} T_i \tag{9}$$

where T_i is the required transmission time of B_i.

The probability that k WBANs are interfering is denoted by:

$$P_k = \binom{n}{k} p^k (1-p)^{n-k} \tag{10}$$

where p is the probability that other WBANs interfere with k WBANs.

In a group of k WBANs, each WBAN creates its ISG by considering the SINR of the sensor nodes. The set of interfered sensors in k interfering WBANs is:

$$SI_k = ISG_i \cup ISG_l \mid i \in L_l, l \in L_i, 1 \le i, l \le k \tag{11}$$

Therefore, the required transmission time of SI_k is given by:

$$TS_k = \sum_{i \in SI_k} \sum_{j \in ISG_i} t_{i,j} \tag{12}$$

Assume that the maximum degree of the network is k, and the required transmission time for k interfered WBANs is T_k. Because the non-interfered nodes and two-hop neighbors can share the same timeslot, the required transmission time for the non-interfered nodes is T_{nk}.

There exists the i-th WBAN with the maximum degree of the network. The required transmission time for this WBAN can be calculated by:

$$T_i = \sum_{x \in SI_k} \sum_{j \in ISG_x} t_{x,j} + \sum_{j \in NISG_i} t_{i,j} \tag{13}$$

The transmission time for k interfered WBANs is:

$$T_k = T_i \tag{14}$$

The total transmission time of the network is calculated by:

$$T = \max\{T_k, T_{nk}\} \tag{15a}$$

and

$$T = T_k \text{, if } k > \frac{n}{2} \tag{15b}$$

The waiting time of the *i*-th WBAN is calculated as follows:

$$WT_i = T - T_i \tag{16}$$

For each timeslot, the length of a timeslot is the length of the highest traffic data to finish its transmission. Therefore, it can be calculated as in Equation (6e):

$$t = \max_{i \in V} t_{i,j} z_{i,j,a} \mid z_{i,j,a} = 1, t_{i,j} = \frac{u(p_{i,j})}{b(p_{i,j})} \tag{17}$$

The spatial reuse factor is defined as the average number of sensor nodes that share the same timeslot, which is calculated as follows:

$$\sigma = \frac{m \times n \times t_s}{T} = \frac{m \times n}{T_k} \tag{18}$$

The average network throughput is defined as the effective transmission per slot that counts the data transmission of all sensor nodes actually received by all the network coordinators. Therefore, it can be calculated as follows:

$$BW = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{i,j}}{T_k} \tag{19}$$

3.5. Performance Evaluation

In this section, the performance of the proposed ITLS is evaluated via MATLAB simulation and compared with the conventional algorithm AIM [40]. Similar to ITLS, AIM considers traffic priority while allocating sensor nodes for each interfered WBAN; therefore, AIM is selected for comparison.

3.5.1. Simulation Environment

In the real scenario, inter-WBAN interference may occur because data can be transmitted and received by multiple WBANs at the same time. In order to reflect the scenario with the practical WBAN applications, we consider a network within a hospital where there are many patients wearing a WBAN for healthcare monitoring as in [64, 65]. The network consists of several mobile WBANs which each WBAN has some biomedical sensor nodes [64, 65].

We consider a simulation area of 10 m × 10 m while varying the number of WBANs as in reference [71]. Initially, all WBANs are uniformly deployed. Each WBAN use star topology, in which six biomedical sensor nodes are wirelessly connected to one coordinator as in reference [11]. In our simulation, the coordinator is located at the center of a WBAN and the sensor nodes are randomly deployed within the transmission range of 2 m [11]. The transmit power and receiver sensitivity are set as −20 dBm and −90 dBm, respectively, as specified in the IEEE 802.15.6 standard. The channel for intra-WBAN communication is modeled by the free space path loss model with a path loss exponent of 2. In medical applications, the WBAN traffic generated at sensor nodes is categorized into different levels of priority [63]. More specifically, the traffic priority at each sensor is set according to the IEEE 802.15.6 standard as in Table 1. For satisfying the requirement of different types of WBAN applications, the packet size can be varied according to the traffic priority shown in Table 7. In the simulation, we assume that the packet size is linearly increased with the increased priority level from50 bytes (at priority level 1) to 350 bytes (at priority level 7). In order to control the traffic, the packet outgoing rate of each node is varied, which is 1, 2, 3, 4, 8, and 16 packets per second. The transmission rate is set as 240 kbps according to IEEE 802.15.6. The mobility of WBAN is modeled as the typical random waypoint model in which the node speed is less than 2 m/s and pause time is 30 s [71]. Therefore, the inter-WBAN connectivity is dynamically varied during the simulation time. We consider two factors which are the number of WBANs and packet outgoing rate at each sensor node. We obtained the average results of the simulation after 20 iterations. The detailed settings of simulation parameters are listed in Table 9.

Table 9. Simulation parameters (ITLS algorithm)

Parameter	Value
Simulation area	10 m × 10 m
WBAN topology	Star topology consisting of one coordinator and six sensor nodes
Number of WBANs	4, 6, 8, 10, 12
Transmission range	2 m
Priority level	1 to 7
Transmission rate	240 kbps
Receiver sensitivity	−90 dBm
Transmit power	−20 dBm
Mobility model	Random waypoint model (speed 0~2 m/s, pause time 30 s)
Packet size	50 bytes (at priority level 1) 350 bytes (at priority level 7)
Channel model	Free space path loss model with path loss component of 2
Simulation time	600 s

Number of iterations	20
Frequency	2.4 GHz

3.5.2. Results

At each WBAN, the packet delivery ratio (PDR) is the ratio of successfully received packets at the coordinator to the total number of generated packets at the sensors of the *i*-th WBAN. Figure 6 shows the PDR of the proposed algorithm and compares it with that of the conventional AIM. In both AIM and ITLS, PDR declines in the dense deployment as well as the high traffic rate scenario. However, the proposed ITLS always achieves higher PDR than AIM. This can be explained as follows. In ITLS, the schedule of a superframe is share among WBANs, as a consequence, the first available timeslot is assigned to only the sensor node with the highest priority or the longest packet size. Some packets generated by sensor nodes may be dropped inevitably because of long waiting time. In addition, the two-hop neighbors can reuse the same timeslot, resulting in increased network throughput.

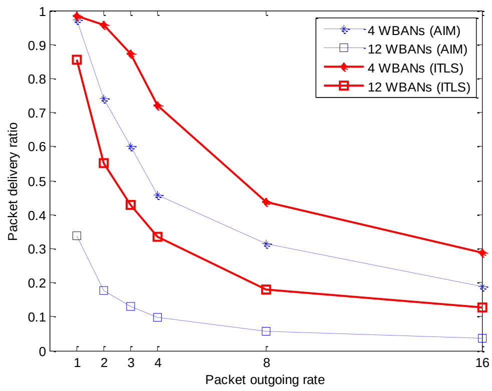


Figure 6. Packet delivery ratio (ITLS)

In our study, the spatial reuse factor is defined as the average number of sensor nodes that share the same timeslot. Figure 7 shows that the proposed ITLS achieves higher spatial reuse than AIM. In general, network has high spatial reuse if the algorithm increases the number of simultaneously transmission from the sensor nodes to their coordinator in the same timeslot without interfering with their neighbors. For both algorithms, the spatial reuse factor depends on the number of WBANs for both algorithms. In our proposed ITLS, the schedule of a superframe which is shared among WBANs allows the nodes in NISG of non-interfered WBANs can be transmitted at the same timeslot of *ISG*. Therefore, the two-hop neighboring WBANs can reuse the timeslot, thus increasing the spatial reuse factor.

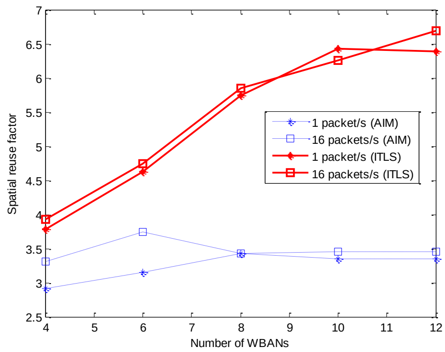
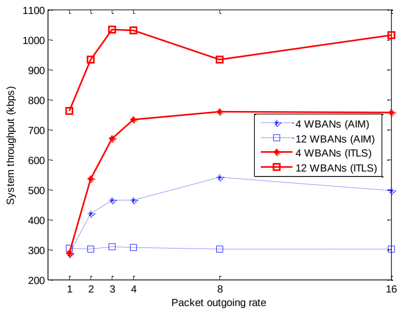


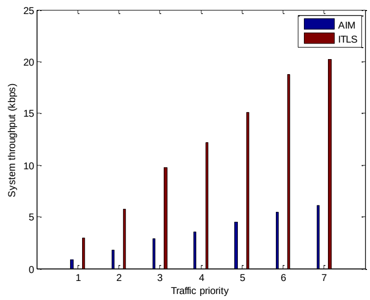
Figure 7. Spatial reuse factor (ITLS)

System throughput is defined as the effective transmission per slot that counts the data transmission of all sensor nodes actually received by all network coordinators. This metric is measured in bps (bit per second). However, the system throughput can be reflected by the spatial reuse factor; if the simultaneously transmission is high, the system throughput is also high. The system throughput is shown in Figure 8. Due to the higher spatial reuse of ITLS, ITLS achieves higher system throughput than AIM. It should be noted that the first available timeslot is assigned to only the sensor node with the highest priority or the longest packet size in the schedule of a superframe shared among WBANs.

In addition, we also consider the throughput of each type of traffic priority in the case of densely network deployment and high traffic, 12 WBANs and 16 packets per second, respectively. The results shown in Figure 8(a) indicate that the traffic priority of our proposed ITLS depends on traffic priority. Because the nodes with the highest traffic priority can access the channel, the throughput is higher than that of the lower traffic priority. Figure 8(b) shows the throughput in the same interference scenario for different traffic types, the nodes with high priority traffic have higher system throughput than the ones with low priority traffic due to the assumption of longer packet size for higher traffic priority.



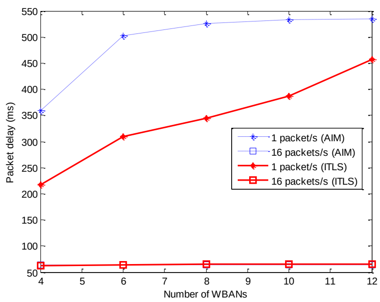
(a)



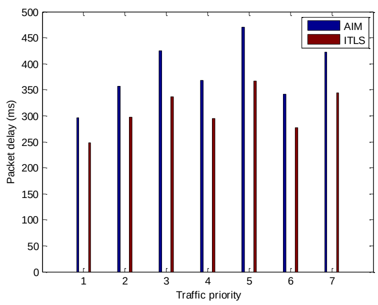
(b)

Figure 8. (a) System throughput (ITLS); (b) System throughput with regards to traffic priority.

Average packet delay is the time between the generation of a packet at a sensor node and the reception of the packet at the coordinator. In Figure 9, network traffic and node density affect to the average packet delay. More particular, the average packet delay increase in the high traffic scenario and densely network, 16 packets per second and 12 WBANs, respectively. The average packet delay in ITLS is lower than that of AIM in case of low packet outgoing rate or low network traffic. However, with high traffic, the results of both algorithms become similar, as shown in Figure 9(a). Figure 9(b) shows that our algorithm has lower delay then AIM for every type of traffic priority. This is mainly due to the fact that, in the proposed ITLS, the schedule of a superframe is shared among WBANs and the first available timeslot is assigned to only the sensor with the highest priority or the longest packet size. Moreover, the two-hop neighbors can reuse the timeslot in our algorithm. As a result, the packet delay is decreased.



(a)



(b)

Figure 9. (a) Average packet delay (ITLS); (b) Average packet delay in terms of traffic priority.

3.6. Conclusion

In this chapter, a novel link scheduling algorithm for multiple WBANs has been proposed not only to mitigate inter-WBAN interference but also to increase the spatial reuse of channels. ITLS use TDMA-based MAC superframe taking traffic priority, packet length, and the number of interfered sensor nodes into consideration. ITLS ensures the continuity of the highest priority nodes which has long packet size by scheduling its transmission in the first available timeslot of superframe. As a consequence, high traffic priority has more opportunities to access the channel. By applying the interference graph with the negotiation steps, both of the two-hop neighbors can transmit at the same timeslot. It results in the high spatial reuse and high throughput. Our extensive performance study shows that the proposed ITLS significantly increases spatial reuse and network throughput with lower delay by mitigating inter-WBAN interference. For our future work, we will consider transmission power control and human mobility in the scenarios of densely deployed WBANs, such as environments for healthcare applications.

4. Link Scheduling Algorithm with Interference Prediction for Multiple Mobile WBANs

4.1. Introduction

WBAN can be developed for medical and non-medical applications for e-health monitoring [75]. With the development of wireless sensors, the patients who wear WBAN can freely move inside a hospital or can even do daily activities at home. Unlike wireless sensor networks, WBANs are mobile due to the unpredictable movement of human in public places such as hospitals, bus stations, or schools. In those scenarios, the overlapped transmission range of WBANs can cause collision to the concurrent transmission of WBANs [15, 19]. The network performance of WBAN may be affected by the number of interference sources, packet size, and the number of packets [76]. The network performance can be degraded by the mobile WBANs which cause the significant loss of data or low quality transmission. For example, in the hospital scenario, if the coordinator cannot receive any emergency signals from on-body sensors, there is a loss in the feed of vital signals. Therefore, it is necessary to avoid interference to ensure the continuity and quality of the transmission.

In the IEEE 802.15.6 standard, the coexistence of multiple WBANs includes static, dynamic, and semi-dynamic environments as shown in Table 3 [4]. In addition, mobility support in WBAN can be investigated in depth because the network topology changes frequently, according to the mobility of the human [77]. Investigation into the problem of mobility WBANs, the main factors may be the distance between WBANs, the topology change according to human movement, and the received power. In [8], the coexistence state of multiple mobile WBAN is predicted by applying the Bayesian inference classifier which uses signal to interference plus noise ratio (SINR) values and the value of the packet delivery ratio at the current state. In addition, the interaction between WBANs has been investigated with regards to the probability of interference by taking into account the distance between coordinators in cyber-physical WBANs based on Bluetooth technology [24]. Currently, the new paradigm of body-to-body networks focuses on energy efficiency, quality of service (QoS), interference coexistence, and mobility prediction [78]. In addition, the coexistence of mmWave WBANs has been examined at 60 GHz using the game-theoretic approach of power control to maximize the signal-to-noise-plus-interference-ratio at each WBAN [79]. Many interference mitigation schemes and MAC protocols have been designed to mitigate node-level interference and WBAN-level interference [79-81]. Some existing works have predicted the coexistence environment while overcome the inter-WBAN interference, the interference prediction remains a challenge issue. That is because the mobility of WBANs is modeled as group mobility which is different from that of in mobile ad hoc networks (MANETs). Therefore, it is necessary to develop an interference aware algorithm while considering the unexpected mobility in multiple WBANs network.

In this chapter, a link scheduling algorithm with interference prediction (LSIP) for multiple mobile WBANs is proposed. First, the interference prediction mechanism based on the Bayesian inference classifier is developed using SINR values and the number of neighboring WBANs. Then, the link scheduling algorithm is proposed by exploiting superframe structure, common scheduling, and negotiation. In LSIP, some coexisting mobile WBANs can transmit simultaneously due to the common scheduling of the superframe. The superframe includes a contention access phase (CAP) and a scheduled phase (SP) for two different types of medium access mechanisms. More specific, the CAP of a superframe is used for the transmission of signals for non-interfering sensors using carrier sense multiple access with collision avoidance (CSMA/CA), whereas the SP of a superframe is used for the transmission of signals of interfering sensors using time division multiple access (TDMA). The simulation results show that LSIP improves the packet delivery ratio and network throughput with acceptable delay compared to that of the conventional scheme.

4.2. Review of Works based on Mobility Prediction for WBANs and Interference Mitigation Algorithms

The link scheduling algorithm can reduce the inter-WBAN interference which results in the improvement of network performance metrics such as packet delivery ratio, latency, and QoS [81]. However, some newly interference mitigation techniques have been deployed for multiple co-located WBANs which achieve acceptable results in terms of packet delivery ratio and latency. The ITLS also consider the priority of the sensed data in the scheduling algorithm [82]. In [33], the channel sensing is applied at the coordinator of WBAN while using a hybrid MAC superframe comprised of CSMA/CA and TDMA. This technique aims to avoid the concurrent transmission from nearby WBANs. In medical environment such as hospital, WBANs may coexist with other devices of wireless local area networks (WLANs) which may cause loss of packets in WBANs and WLANs [83]. In [84], the set of the channel states of sensor nodes to the coordinator is defined as the collective channel state which is used as a factor in designing a scheduling algorithm. In addition, the scheduling algorithm also selects the collective buffer state, and the time index to determine the transmission of the next superframe by sensor nodes to ensure QoS in medical environments. In [85], cooperative scheduling for WBANs applies horse racing scheduling for a single WBAN and considers multi-WBAN concurrent transmissions as a game.

In the real scenario, the movement of people wearing WBAN can cause interference to others in the same vicinity, and vice versa. Even though the movement behavior is random, it is necessary to estimate the coexistence for WBANs. The work in [18] developed an algorithm for coexistence prediction in WBANs, which considers the current status according to the defined coexistence environment in the IEEE 802.15.6 standard. Another work in [24] detects the presence of nearby WBANs. In MANETs, the duration that two nodes stay connected is estimated to predict the mobility [86, 87]. In contrast, the mobility of WBANs depends on the typically random group mobility of the sensors in the human body. Hence, the mobility prediction techniques of MANETs cannot be applied to predict the mobility of WBANs. The requirement of QoS for WBAN is critical, a QoS-based MAC protocol for WBANs detects the interference for mobile WBANs before starting intra-WBAN transmission [67]. In [88], the adaptive CSMA/CA mechanism is applied at the coordinator to avoid collision, and it achieves good performance in terms of high throughput and low collision rates. Thus, it is necessary to consider the group mobility of WBANs in the interference mitigation algorithm.

4.3. Interference Prediction for Mobile WBANs

4.3.1. Network Model

A multi-WBAN network consists of n mobile WBANs, denoted as B_i, $1 < i < n$, where each WBAN consists of one coordinator and m sensor nodes. For intra-BAN communication, the sensor nodes receive the control signal or beacon from the coordinator, then send the sensed data to the coordinator. The transmission range of a WBAN is modeled as a circle with radius R for simplicity. If the transmission range of two nearby WBANs overlaps, the interference can occur in the intra-WBAN communication of each WBAN. In this case, these WBANs are called neighbors of each other. The term neighbor is used to describe the interfering source of a WBAN. The free space path loss model is assumed for intra-WBAN and inter-WBAN links. The channel gain of body-to-body links is modeled as gamma distribution as in [74].

The mobile WBAN is moving within the deployment area with a random velocity. The operating time can be divided into a set of T epochs. At time t, the SINR at the coordinator of B_i when sensor s transmit data is defined as

$$\gamma_{i,s}(t) = \frac{P_{i,s}(t)}{N_0 + \sum_{j \neq i} P_{i,j}(t)} \tag{20}$$

where $P_{i,s}(t)$ and $P_{i,j}(t)$ are the received signal power at the coordinator of B_i for the signals that originate at sensor s in B_i and the received signal power from the coordinator of B_j, respectively.

The free space path loss model uses the path loss exponent of 2 and is proportional to the distance between transmitter and receiver. The received power at the coordinator of B_i, P_{rx} is represented as

$$P_{rx}(t) = P_{tx} \times Gain_{tx} \times Gain_{rx} \times \left(\frac{\lambda}{4\pi d(t)} \right)^{\eta}, \tag{21}$$

where P_{tx} is the transmit power, η is the path loss exponent, and $d(t)$ is the distance from the source to the coordinator of B_i; $d(t)$ can be $d_{i,s}(t)$ or $d_{i,j}(t)$ for intra- or inter-WBAN transmission, respectively.

However, in the practical scenarios of multiple WBANs network, the SINR is estimated as in [89] even though there are some estimation errors. In our study, it is assumed that the SINR value is estimated at the physical layer of the receiver as in [89] by using the RSSI (Received Signal Strength Indicator) measurements in dBm as in the following equation:

$$SINR(t) = 10^{RSSI(t) - \eta_0 - C - 30)/10}, \quad (22)$$

where η_0 is the thermal noise, the constant C is the measurement offset which is empirically measured in [89] using Chipcon CC2420 on the Telos motes (C = 45 dB), and the value of 30 is the conversion of dBm to dB.

The network of multiple mobile WBANs can be considered as a graph $G(t) = (V(t), E(t))$, in which $V(t)$ is the set of WBANs at time t and $E(t)$ is the set of interfering links between WBANs at time t. An interference link is defined if the transmission ranges of two nearby WBANs overlap. If the distance between two WBANs is less than the interference range, they interfere with one another. A WBAN B_i is interfered with if any sensor interferes with other WBANs, or $\gamma_i(t) < \gamma_{th} \mid \gamma_i(t) = min\{\gamma_{i,s}(t), 1 \leq s \leq m\}$. The interference links at B_i can be represented as $d_{i,j}(t) < R \mid i,j \in V(t)$. The set of neighbors that interferes with B_i is denoted as $NB_i(t) = \{NB_i(t) \cup B_j \mid \gamma(t) < \gamma_{th}, d_{i,j}(t) < R\}$.

The set of all interfering WBANs in the network is denoted as $S(t) = \{NB_i(t) \cup (NB_j(t) \mid i,j \in V(t)\}$. The maximum degree of $S(t)$ is denoted as $\Delta S(t) = \max\{\Delta(B_i) \mid i \in V(t)\}$ in which $\Delta(B_i)$ is the degree of B_i. Each B_i creates interfered sensor groups and non-interfered sensor groups: $I_i = \{s \mid \gamma_{s,i} < \gamma_{th}, 1 \leq s \leq m\}$, $NI_i = \{s \mid \gamma_{s,i} > \gamma_{th}, 1 \leq s \leq m\}$, respectively.

The mobility of WBAN is different to that of WSN, therefore, the reference point group mobility model (RPGM) [87] can be used to represent WBAN movement behavior. In the RPGM for each WBAN, the coordinator of B_i is considered as the reference point moving with a constant speed $v_i(t)$ in each epoch, all the sensor nodes of B_i follow the coordinator's motion behavior. The group motion vector of the coordinator will map the location of the coordinator whereas all sensor nodes add the node-dependent random motion vectors to the group motion vector. At time t, the location of the sensor node $Y_s(t)$ in a WBAN is given by the following: $Y_s(t) = Y_c(t) + RV_{s,c}(t)$, where $RV_{s,c}(t)$ is a node-dependent local displacement or random motion vector of the sensor nodes, and $Y_c(t)$ is the location of the coordinator at time t.

In a real-world scenario, people wearing a WBAN can move either close to or far away from another WBAN. Interference duration at a WBAN is defined as the duration that the WBAN is interfered by the concurrent transmission of other WBANs. The interference duration depends on the duration that the transmission ranges of WBANs overlap. If the two WBANs stay near each other more than the threshold time, the interference duration is long. Otherwise, if one WBAN may move away from the overlapped transmission range or the duration is less than the threshold time, the interference duration is short.

The number of neighbors can be estimated on the basis of overhearing control and data packets in the same way used as in wireless ad hoc networks. The beacon signal of other WBANs are also received and detected. Because WBANs send the beacon after sensing the idle channel, a WBAN lists the source of the beacon signal into its neighbors when it receives the beacon. In this case, the network consists of n WBANs, each WBAN sends a beacon signal with length $t_B(s)$ after sensing idle channel t_{sense}, the total time for transmitting and receiving beacon packets can be estimated $t_{neg,\max} = n \times t_B + t_{sense}$.

After detecting the neighbors, the coordinators of interfered WBANs start the negotiation steps for interference avoidance as follows: the coordinators will exchange the schedule during the negotiation time before starting a new superframe. Because the WBANs need to exchange information with their neigbors, we assume that all the coordinators are synchronized so that the superframe can start at the same time for all coordinators. Figure 10 shows the framework of interference prediction and avoidance at each WBAN coordinator. In the LSIP, depending on the results of interference prediction steps, the interference avoidance step will use two different types of MAC superframe for intra-WBAN transmission. In the case of long time interference, the number of neighbors may not change immediately. Hence, the schedule of multiple WBANs can be kept the same. If the number of neighbors is either increased or decreased, the schedule in the superframe may be changed. Because the WBANs are synchronized with the negotiation steps and scheduling algorithm, the transmission of signal from sensor nodes to the coordinator is ensured. However, the delay is constrained by the negotiation time between a WBAN and its neighbors, which must be below a given threshold. We propose a scheduling algorithm for multiple WBANs, which uses a hybrid MAC superframe structure based on the hybrid carrier multiple access of CSMA/CA and a scheduled part with TDMA. The transmission of nodes will be assigned to the TDMA part after negotiation steps of the coordinators. By applying TDMA in the MAC superframe, the two-hop WBANs can reuse the time slot, which will increase the network throughput.

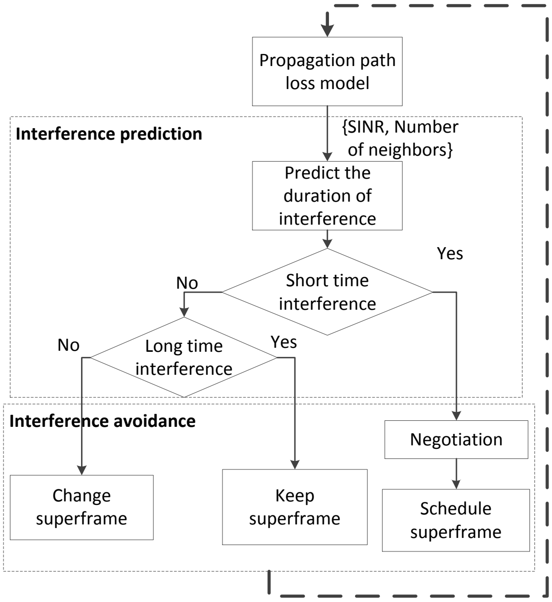


Figure 10. Interference prediction and avoidance at each WBAN coordinator.

4.3.2. Bayesian Inference Classifier for Interference Prediction

The IEEE standard 802.15.6 has defined the coexistence environment of multiple WBANs in Table 3 which covers four coexistence states as follows: none (no interference), static, semi-dynamic, and dynamic. The coexistence condition is defined by the mobility level (i.e., slowly moving or fast moving) and the traffic data rate. However, the specific parameters for differentiating between the states are not clearly defined in the standard.

In LSIP, the operation time is divided into T epochs, the duration of interference is obtained by the number of neighbors and the SINR at each epoch time t. The duration of interference is represented as T_{IF}, which can be divided into two cases: short-time interference (*ShortIF*), if the interference duration is shorter than a given threshold value T_{thr}, and long-time interference (*LongIF*), if the interfered duration is longer than T_{thr}. Depending on the duration of interference, the state of the WBAN can be classified as: no interference (*None*), *ShortIF*, and *LongIF*. The inference model of the Bayesian inference classifier in [90] is applied to the interference prediction process to determine the next state of a WBAN. The Bayesian inference model is chosen because of low complexity, so that it can be easily applied to WBANs with high accuracy.

The Bayesian inference classifier in [90] which operates as an inference system is used to predict the next state of a WBAN. The Bayesian inference classifier has two input values: the number of interfering neighbors and the SINR value. These are represented as x_{NI} and x_{SINR}, respectively. The possible state is defined as $State = \{None, ShortIF, LongIF\}$. The classifier will choose the most probable value among the possible values according to the input training values by using the maximum a posteriori (MAP) method. The probability of predicting the next state uses naïve Bayesian prediction. Hence, the state using MAP, s_{MAP}, can be represented as

$$s_{MAP} = \arg\max_{s_i \in State} p(s_i \mid x_{SINR}, x_{NI}) \cdot \tag{23}$$

where s_i indicates the class within the possible states $\{State\}$, and x_{NI} and x_{SINR} represent the input values. By applying the Bayes' theorem, we have

$$s_{MAP} = \arg\max_{s_i \in State} \frac{p(x_{SINR}, x_{NI} \mid s_i)}{p(x_{SINR}, x_{NI})} = \arg\max_{s_i \in State} p(x_{SINR}, x_{NI} \mid s_i) p(s_i) \cdot \tag{24}$$

Assuming that the input values are conditionally independent, the outcome of the classifier, s_{MAP}, can be calculated as

$$s_{MAP} = \arg\max_{s_i \in \{None, ShortIF, LongIF\}} p(s_i) p(x_{SINR} \mid s_i) p(x_{NI} \mid s_i), \tag{25}$$

where $p(x_{SINR} \mid s_i)$ and $p(x_{NI} \mid s_i)$ can be obtained by observing the training data set.

The network with multiple WBANs is deployed for the duration of 100 s for verifying the training value of the prediction algorithm. The group mobility of each WBAN can be given as follows. The coordinator of each WBAN will follow the random waypoint model [91] to choose a destination at the next epoch time and move with a given speed. The sensor nodes follow the group velocity model. In order to reflect the real scenario, the deployment for multiple mobile WBANs is quite similar to the scenario for hospital applications in [65]. The network deployment of five WBANs is illustrated in Figure 11. Each WBAN is denoted with different color and shape which follows the arrow line. Based on the deployment, we have extracted the average SINR and the average number of neighbors for a WBAN as shown in Figure 12 and Figure 13, respectively. From the extracted data, we have classified the inputs of the Bayesian inference classifier in Table 10. As a result, a training table is set up in Table 11 to predict the next state of the tagged WBAN. The threshold value (T_{thr}) of interference duration is set as 10 s.

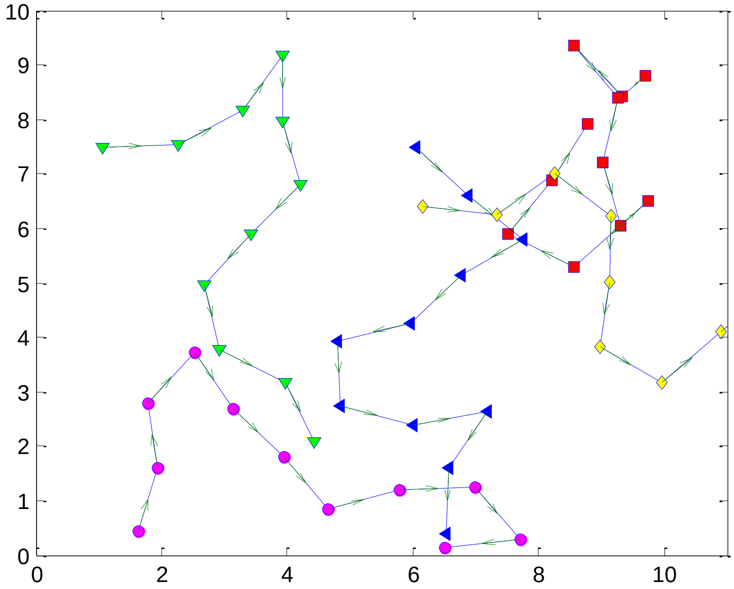


Figure 11. An example mobility scenario of five mobile WBANs.

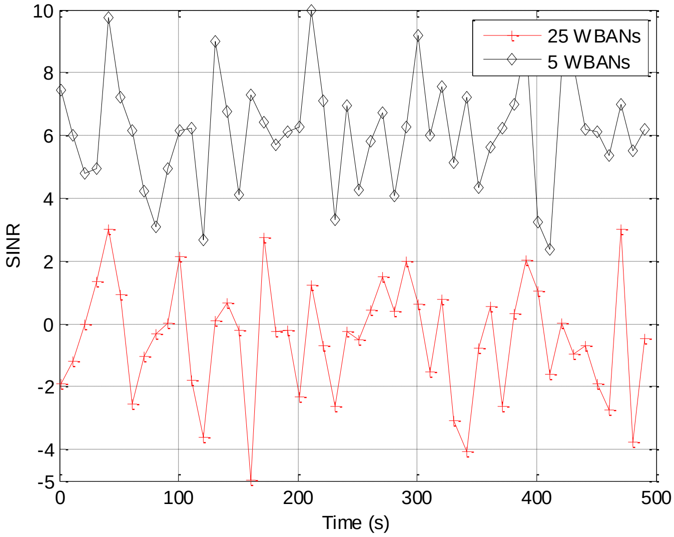


Figure 12. Average SINR in a WBAN for different numbers of WBANs in the deployment area.

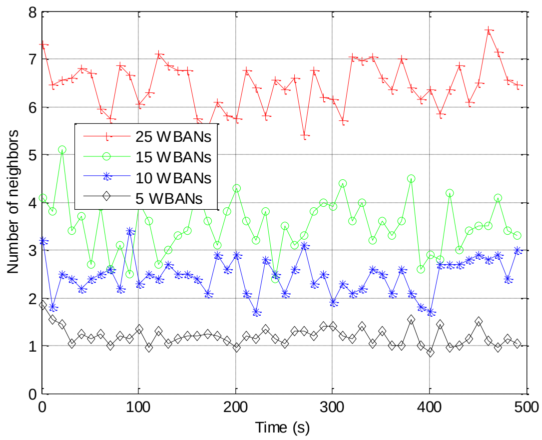


Figure 13. Average number of neighbors of a WBAN for different number of WBANs in the deployment area

Table 10. Classification table of interference prediction algorithm (LSIP)

Category	No Interference	Short Time	Long Time
Duration of interference	0	<10 s	>10 s
Number of neighbors	<2 neighbors	2–6 neighbors	>6 neighbors
SINR	>6 dB	1–6 dB	<1 dB

Table 11. Training table of interference prediction algorithm (LSIP)

SINR	Number of Neighbors	Previous State	Current State
1–6 dB	<2 neighbors	Short IF	No IF
1–6 dB	<2 neighbors	Long IF	Short IF
1–6 dB	2–6 neighbors	Short IF	Short IF
1–6 dB	2–6 neighbors	Long IF	Long IF
1–6 dB	>6 neighbors	Short IF	Long IF
1–6 dB	>6 neighbors	Long IF	Long IF
>6 dB	2–6 neighbors	No IF	No IF
>6 dB	2–6 neighbors	Short IF	No IF
>6 dB	2–6 neighbors	Long IF	Short IF
>6 dB	>6 neighbors	No IF	Short IF
>6 dB	>6 neighbors	Shor IF	Long IF
>6 dB	>6 neighbors	Long IF	Long IF

As referred in [18, 65], the walking speed of people can be low or high in between 0-2 m/s. Therefore, the result of the interference prediction is taken from the scenario of 25

WBANs moving with the speed of 0-2 m/s. For a single WBAN, the results of interference prediction are shown in Table 12.

Table 12. Results of interference prediction

Scenario	Current State	Next State
SNIR = 2.0735; Deg = 5; Previous_state = noIF	Short IF	Short IF
SNIR = 0.65; Deg = 6; Previous_state = ShortIF	Long IF	Long IF
SNIR = −2.6; Deg = 5; Previous_state = LongIF	Long IF	Long IF
SNIR = −4; Deg = 9; Previous_state = ShortIF	Long IF	Long IF
SNIR = 11; Deg = 7; Previous_state = LongIF	Short IF	Short IF

4.4. Link Scheduling Algorithm Avoiding Interference in Multiple Mobile WBANs

Because the operation time is divided into T epochs, the coordinator predicts the interference state for the next epoch based on the SINR, current status, and the number of neighbors. If the next status of a WBAN is *ShortIF*, the coordinator will broadcast a negotiation message to the network. Upon receipt of the messages from the neighbors, the coordinators exchange the TDMA schedule in the superframe for sharing the transmission channel in the interference avoidance process. Figure 10 shows the interference steps at the coordinator that can be explained as follows. At first, the coordinator negotiates with its neighbors at the *ShortIF* state. Assume that the tagged WBAN B_i is interfered with by a mobile WBAN B_j. When B_j moves into the interference range of B_i, the coordinators of both WBANs require all the sensors to stop transmitting data. The coordinator of B_i starts to negotiation for a shared superframe by broadcasting a HELLO signal. The coordinator of B_j will send a REPLY signal because B_j is in the transmission range of B_i. The result of this step is to create a neighbor set $NB_i(t)$ for each WBAN. Then, the coordinators of B_i and B_j run the scheduling algorithm to allocate their data into fixed slots of the shared superframe.

4.4.1. MAC Superframe for Multiple WBANs

The scheduling algorithm is run on the WBAN B_i subject to interference and its neighbors. The WBANs share the superframe structure shown in Figure 14. A superframe consists of five parts: the beacon signal (B), the CAP, the SP, T_{pre}, and T_{avo}. In the CAP, the nodes in NI_i perform CSMA/CA for intra-WBAN communication, which can be considered as the simple version of the exclusive access phase (EAP), random access phase (RAP), and CAP in an IEEE 802.15.6 MAC superframe. In the SP, the nodes in I_i use TDMA for transmitting data to the coordinator, which is similar to the managed access phase (MAP) in an IEEE 802.15.6 MAC superframe. The lengths of the CAP and the SP in our proposed superframe are adjusted to adapt to the number of interfered WBANs in

$NB_i(t)$. T_{pre} is the short duration for which B_i predicts the next state based on the value of the SINR and the number of members in $NB_i(t)$. T_{avo} is the short duration during which B_i negotiates with every member in $NB_i(t)$ before starting the new superframe.

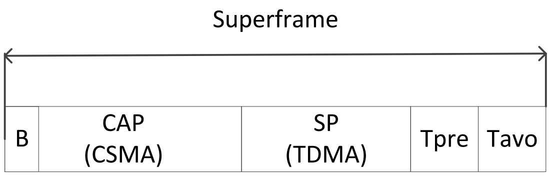


Figure 14. Superframe of LSIP

As shown in Figure 14, for intra-WBAN communication, the sensor nodes wait for the beacon signal from the coordinator; the node will transmit data in the CAP if the node is not interfered, otherwise, the node will transmit data via the scheduled timeslot in the SP.

An example of intra-WBAN communication for an interfering WBANs is shown in Figure 15. The non-interfered sensors who will send data within the CAP start scanning idle channel; then transmit data if the channel is idle. On the other hand, the interfered sensor node only transmits at the assigned timeslot in the TDMA portion.

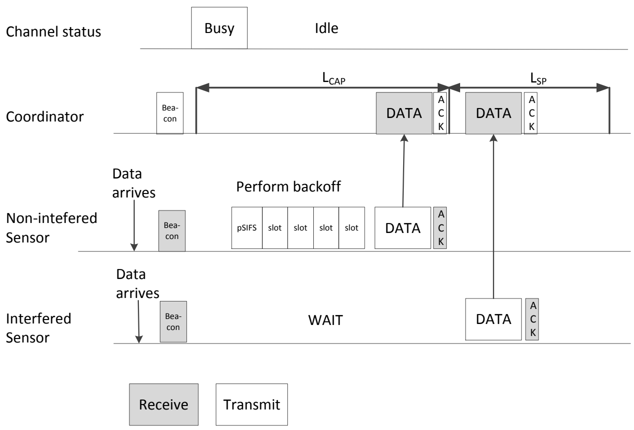


Figure 15. An example of intra-WBAN communication of interfered WBANs.

For inter-WBAN transmission, the Figure 16(a) shows an example of two interfering WBANs who their transmission ranges are overlapped, resulting in the interference at sensor 13 and 21. The transmissions of sensors 13 and 21 are scheduled into the SP, which is called *common scheduling* among WBANs, as shown in Figure 16(b). The transmission of the other non-interfering sensors can occur in the CAP using CSMA/CA without a common scheduling.

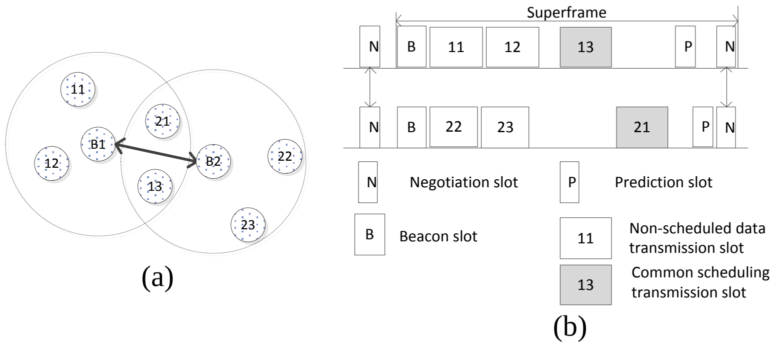


Figure 16. An example of inter-WBAN communication in two interfering WBANs: (a) negotiation between two WBANs; and (b) data transmission

4.4.2. Common Scheduling

At each WBAN, the lengths of the CAP and the SP are calculated for every epoch T because the number of members in $NB_i(t)$ changes. The length of the CAP is calculated by

$$L_{CAP} = t_s \times \max_{i \in NB_i(t)} |NI_i|, \; NI_i = \{ j \,|\, \gamma_i > \gamma_{th}, d_{i,j} > R \} . \tag{26}$$

Likewise, the length of the SP is calculated by

$$L_{SP} = t_s \times \sum_{i \in NB_i(t)} |I_i|, I_i = \{ j \,|\, \gamma_i < \gamma_{th}, d_{i,j} < R \} . \tag{27}$$

The required transmission time for a WBAN is calculated as

$$T_i = \sum_{s=1}^{m} t_s = \sum_{s \in I_i} t_s + \sum_{s \in NI_i} t_s , \tag{28}$$

where t_s is the transmission time of a sensor node. Assuming that there are k neighbors of B_i, so that $|NB_i| = k$, the required transmission time, $T(k)$, for B_i and $NB_i(t)$ is calculated as follows:

$$T(k) = \sum_{i=1}^{k} T_i = \sum_{i=1}^{k} \sum_{s \in I_i} t_s + \max_{1 \le i \le k} \sum_{s \in NI_i} t_s \cdot \tag{29}$$

The length of a superframe for k interfering WBANs can be given as

$$T_{ISF} = T(k) \cdot \tag{30}$$

Let SF_m be the longest superframe that is acceptable for the latency of a vital signal. As in [67], if T_{ISF} is longer than SF_m, each coordinator will calculate the average number of slots for each WBAN.

The average number of time slots for each WBAN in the SP is calculated as

$$T_i = \frac{T_{SPm}}{n}, \quad (31)$$

where T_{SPm} is the acceptable length of the SP that is calculated as

$$T_{SPm} = SF_m - \sum_{i=1}^{n} \max_{s \in NB_i} \{t_s\} \cdot \quad (32)$$

4.4.3. Negotiation and Scheduling Algorithm

As shown in Figure 10, the coordinators will schedule the transmission after the prediction state. Each coordinator of $V(t)$ runs the link scheduling algorithm as in Algorithm 2. The inputs include the network topology, neighbor set, and resources of channels such as the maximum length of the superframe. The output of the algorithm is the schedule for each WBAN into a hybrid MAC superframe. For the TDMA part, the interfering sensors will transmit data in the assigned timeslot without contention to other nodes. For the CAP part, the non-interfering sensors will sense the channel and perform backoff before transmitting data to the coordinator.

The algorithm proceeds in two phases. The first phase is to calculate the length of the CAP and the SP. The second phase is to assign the timeslot by using a greedy algorithm into the TDMA portion. Because the sensor nodes collect the different type of traffic and each WBAN has the different number of neighbors, each WBAN calculates a contention value for scheduling as follows. The contention value $s_i(t)$ is represented by the total number of interfering sensors and the number of neighbors as follows:

$$s_i(t) = \frac{\sum I_i}{M} \times \frac{\sum NB_i(t)}{\sum NB_i(t-1)} \quad (33)$$

In the link scheduling algorithm shown in Algorithm 1, at the first phase, each coordinator will broadcast the list of interfering sensor nodes to its neighbors (line 1). After sending and receiving this list, the coordinators create two common lists of sensor nodes which are the interfering and non-interfering sensor nodes at the current time t, denoted as $CI(t)$ and $CNI(t)$, respectively (lines 2 to 5). Each coordinator will calculate the length of L_{CAP}, L_{SP}, and T_{ISF} (line 6). The total length of the superframe is calculated (line 7). In the case the length of the superframe exceeds the acceptable length SF_m, the lengths of SP and CAP are calculated as in lines 8–12. At the second phase, the first available time slot is assigned to the sensor node with the highest priority in $CI(t)$ (line 15). Therefore, all the sensors in $CI(t)$ will be assigned to a time slot in the superframe.

Algorithm 2: LSIP algorithm

Input: $NB_i(t)$, SF_m , I_i, NI_i, t_s

Output: scheduled superframe

Initialize: $t = 0$

// Phase 1: Calculate length of superframe

1. B_i broadcasts $\{I_i, NI_i\}$ to all members in $NB_i(t)$
2. For each $C_j \in NB_i(t)$
3.   Receive $\{I_j, NI_j\}$
4.   Create a common list of neighbors: $CI(t) = \{s_j(t) \cup s_i(t), I_i \cup I_j \mid j \in NB_i(t), i \in NB_j(t)\}$, $CNI(t) = \{NI_i \cup NI_j \mid j \in NB_i(t), i \in NB_j(t)\}$
5. End For
6. Calculate L_{CAP} and L_{SP} as in (26) and (27), respectively
7. $T_{ISF} = L_{SP} + L_{CAP}$
8. If $T_{ISF} > SF_m$
9.   Calculate TSP_m as in (32)
10.   Calculate T_i as in (31)
11.   Update $L_{SP} = T_{SPm}$
12. End If

// Phase 2: TDMA scheduling by using greedy algorithm

13. For each sensor $s \in CI(t)$
14.   Return the sensor s_x with the highest contention value in $CI(t)$
15.   Assign time slot to s_x with length t_s (t_s is transmission time of s_x)
16.   Update $t = t + t_s$
17.   Remove s of $CI(t)$
18.   If $t > L_{SP}$
19.   break
20.   End If
21. End For

4.5. Performance Evaluation

In this section, we conduct a performance evaluation via Matlab simulations for our proposed LSIP. We also compare this performance with the A-CSMA/CA system in [88]. The interference mitigation algorithm in [88] reduces inter-WBAN interference by using CSMA at the coordinator and a hybrid superframe for intra-WBAN transmission.

4.5.1. Simulation Environment

In our simulation, the multiple WBAN scenario is setup for health monitoring as in [65]. To evaluate the mobility scenario, the WBANs movement is similar to the mobility scenario in Figure 2 in Section 2. The velocity of WBANs is set as 0–1.5 m/s, according to [18, 65]. We executed the simulations for 500 s with different sets of parameters to evaluate the density of the network and the traffic load in each WBAN. The dense deployment of the network is represented by the number of WBANs and the number of sensors per WBAN. Each WBAN consists of one coordinator and several sensors nodes with the transmission range of 2 m [11]. The traffic load is represented by the the number of packets generated by sensor nodes which can be varied to estimate the high or low traffic for each WBAN. The power consumption at the coordinator is set as 31.2 mW for transmission and 27.3 mW for reception as in [67]. Simulation parameters and their values used in the simulation are shown in Table 13. We only consider the flexibility and reliability of our scheduling algorithm in the mobile scenario so that we do not consider the priority of sensor nodes. However, the scheduling algorithm is evaluated in the worst case where all the sensor nodes are in the overlapped area with neighboring WBANs. For that matter, the CAP in a superframe is not implemented in the simulation; the proposed scheduling algorithm assigns the transmissions from sensor nodes to the coordinator in the SP.

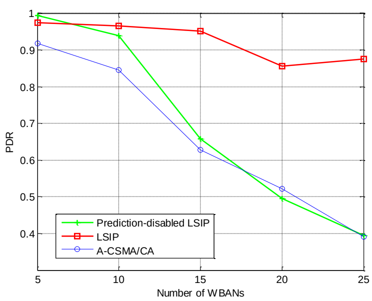
We also simulate two scenarios: LSIP with and without interference prediction. With interference prediction, each WBAN will transmit and schedule according to the proposed algorithm in Figure 10. Without interference prediction, the coordinator broadcasts the negotiation message at the end of each epoch time. The performance is evaluated by four metrics: packet delivery ratio, end-to-end delay, network throughput, and energy consumption per bit by varying three different parameters. First, the network density is evaluated by varying the number of WBANs in the network, in which each WBAN consists of 10 sensor nodes and each sensor node generates two packets per second. Next, we vary the number of generated packets per sensor node, in which there are 10 WBANs in the network area and each WBAN consists of 10 sensor nodes. Lastly, we vary the number of sensor nodes per WBAN, in which the number of WBANs is 10 and each sensor node generates two packets per second.

Table 13. Simulation parameters (LSIP)

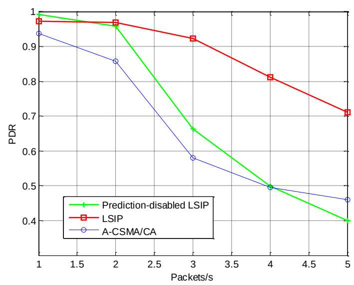
Parameters	Value
Number of WBANs	5–25 (default: 10)
Number of sensors per WBAN	5–25 (default: 10)
Simulation area	10 m × 10 m
Transmission range	2 m
Velocity of each WBAN	0–1.5 m/s
Direction of motion vector	Random
Simulation time	500 s
Slot allocation length	10 s
Negotiation time	10 ms to N × 10 ms
Packet size	100 bytes
Packet transmission rate	1–5 packets/s (default: 2)
Tx power consumption	31.2 mW
Rx power consumption	27.3 mW
Data rate	250 kbps

4.5.2. Results

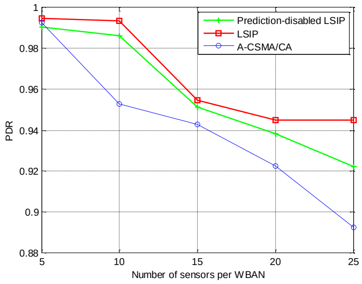
Packet delivery ratio (PDR) is calculated as the number of successfully received data packets at the coordinator over the number of actual generated packets at the sensor nodes. It is shown in Figure 17 that the proposed algorithm with interference prediction achieves better performance than the other methods. For all three algorithm, PDR decreases in dense networks and/or with high traffic load. However, our proposed algorithm outperforms the others for all cases. Because the coordinator predicts the interference duration then negotiates for the common scheduling, the sensor nodes transmit data during the allocated time slot without interference. Therefore, the number of the data packets received at the coordinator is increased in the LSIP. In the prediction-disabled LSIP, however, the common scheduling is not updated when a new neighboring WBAN moves closer. It results in interference with the new neighboring WBAN.



(a)



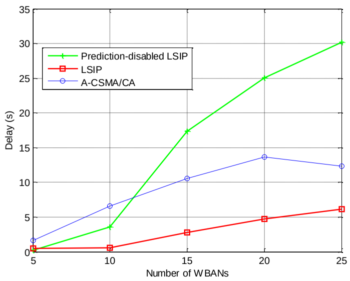
(b)



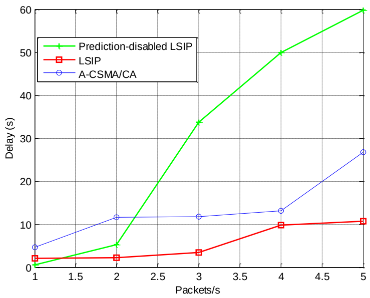
(c)

Figure 17. Packet delivery ratio (LSIP): (a) varying the number of WBANs; (b) varying traffic load at each sensor node; and (c) varying the number of sensors per WBAN

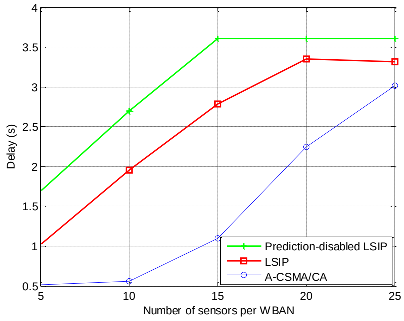
End-to-end delay is calculated as the average duration from the time when a packet is generated at a sender node to the time when the packet is received at the coordinator. The simulation results of the end-to-end delay are shown in Figure 18. In three scenarios, the end-to-end delay also increases when the traffic load or network density increases. More specifically, because of the prediction and negotiation steps, the end-to-end delay of our proposed algorithm is higher than A-CSMA/CA when increasing the number of sensors per WBAN. However, in the worst case for high density and high traffic load, our proposed algorithm achieves lower end-to-end delay. In the case without interference prediction, a WBAN takes more time for negotiation because the neighbor set of WBANs changes over time. In the case with interference prediction, however, a WBAN only negotiates with the specific neighbors, which results in lower delay.



(a)



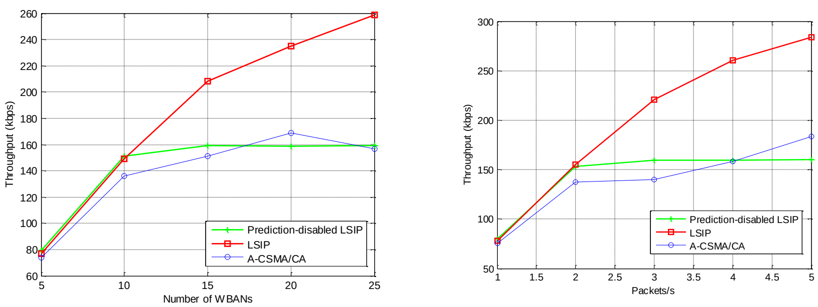
(b)

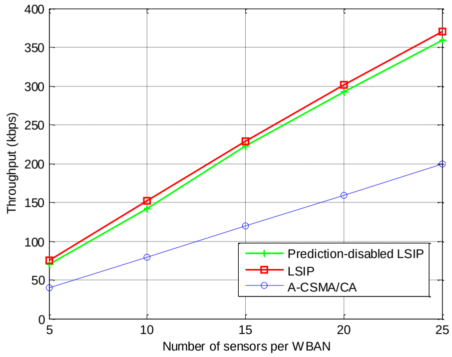


(c)

Figure 18. End-to-end delay (LSIP): (a) varying the number of WBANs; (b) varying traffic load at each sensor node; and (c) varying the number of sensors per WBAN

Network throughput is the average rate of successful packet deliveries at the receiver, which is usually measured in bits per second or packets per second. In our evaluation, the network throughput is calculated in kilobits per second (kbps) for the data packets received at the coordinator which is shown in Figure 19. LSIP outperforms the other methods in three scenarios. The network throughput depends on the density of the network or the traffic load of the sensor node. However, if LSIP works without interference prediction, the network throughput is similar to that of A-CSMA/CA as in Figure 19(a, b). In case of prediction-disabled LSIP, the coordinator takes more time slots for finding the neighbors for negotiation even though multiple WBANs can transmit at the same time by using the shared superframe, it results in the low network throughput as in Figure 19(a, b). With interference prediction, the superframe can be kept a long time because the neighbor set of a WBAN may not change, resulting in higher throughput for the LSIP.





(c)

Figure 19. Network throughput (LSIP): (a) varying the number of WBANs; (b) varying traffic load at each sensor node; and (c) varying the number of sensors per WBAN.

Energy consumption of a coordinator is calculated in Joules per bit. At the coordinator, power consumption is the amount of power consumed at different states, which are: (a) the transmitting state, where the coordinator transmits the beacon and negotiation messages; (b) the receiving state, where the coordinator receives data packets from sensor nodes and negotiation messages; and (c) the interference prediction states. It should be noted that, after receiving the beacon from the coordinator, the sensor nodes transmit the sensed data according to the information included in the beacon and then enter the sleep mode. As shown in Figure 20, the power consumption of the proposed algorithm depends on the traffic load and the network density where as that of A-CSMA/CA varies in a range, but does not depend on the traffic load or the network density. In the proposed algorithm, however, the power consumption also depends on the duration and negotiation messages where the coordinator negotiates the schedule with its neighbors. Therefore, the coordinator consumes more energy when the network density or the traffic load increases. It should be noticed that the energy consumption in our simulation study contains the energy consumed at the coordinators of multiple WBANs and, in a WBAN, the coordinator consumes much more energy than sensor nodes. Typically, the coordinator is equipped with high-capacity battery in comparison to the sensor nodes. Therefore, even though the proposed algorithm consumes more energy, the energy consumption is not a critical issue in the most applications of multiple mobile WBANs. Instead, both the reliability and the throughput, which are very important and sometimes critical in the target applications of health monitoring, are significantly improved in comparison to the other algorithms as shown earlier. On the other hand, the proposed algorithm without interference prediction consumes less energy than A-CSMA/CA because the coordinator does not perform sensing channel and back off for channel contention.

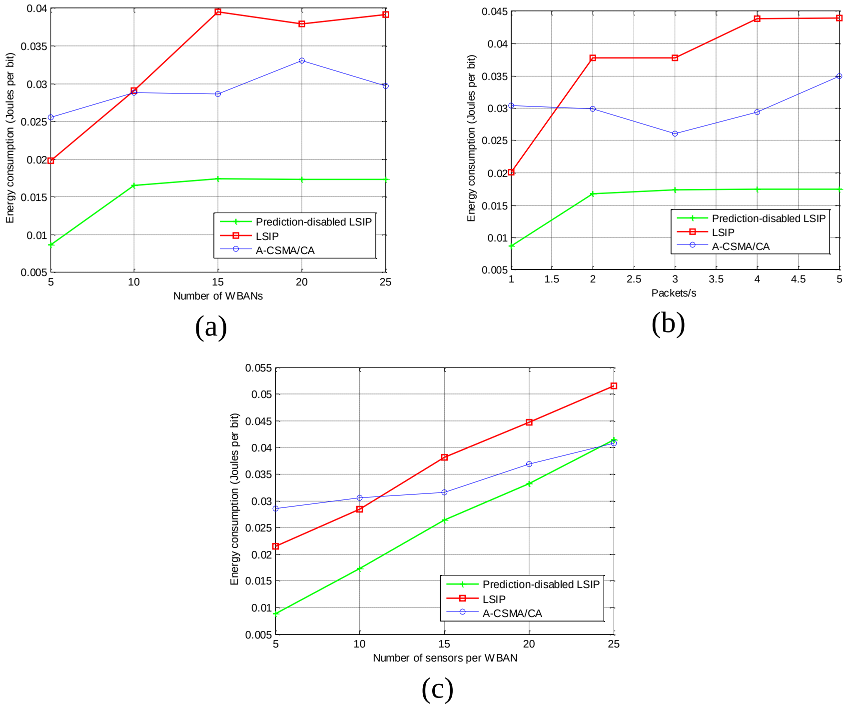


Figure 20. Energy consumption at the coordinator (LSIP): (a) varying the number of WBANs; (b) varying traffic load at each sensor node; and (c) varying the number of sensors per WBAN.

4.5. Conclusion

In this chapter, the link scheduling algorithm with interference prediction for multiple mobile WBANs shows its performance in the dense network and high traffic load which is outperform the conventional algorithm. The Bayesian inference classifier which is simple and has a low computational complexity, can be easily deployed to predict the interference state of WBANs. With interference prediction, a WBAN can estimate its current state and its neighbor set, which results in a short link schedule amongst nearby WBANs. In addition, the superframe with common scheduling allows for multiple concurrent intra-WBAN transmissions without interference. In order to schedule the WBANs, the contention value has been defined based on the interference level of WBANs, enabling the signal transmission of a WBAN even with interference. The proposed LSIP improves the packet delivery ratio and network throughput remarkably with acceptable delay by overcoming the inter-WBAN interference in comparison to the conventional scheme. Nonetheless, the negotiation between the WBAN coordinators requires additional energy consumption. As a future work, we will investigate the development of more energy-efficient negotiation mechanisms.

5. A Hybrid Multi-channel MAC Protocol for WBANs with Inter-WBAN Interference Mitigation

5.1. Introduction

In the IEEE 802.15.6 standard, the coexistence strategies have been introduced to deal with the dense deployment network of WBANs which include beacon shifting, active superframe, and hopping channel [4]. The hopping channel strategy allows a WBAN to avoid interference on the same channel by selecting a new channel according to the channel hopping sequence. The coordinator will generate channel hopping sequence which is not being used by its neighbors. The channel hopping sequence is a random value which is based on the maximum-length Galois linear feedback shift register [4]. Because the intra-WBAN transmissions occupy a single channel during the operation time, the coordinator will announce the new channel for the sensor nodes on the beacon signal. The coordinator and the sensor nodes change the working channel according to the beacon signal. However, the new channel is taken by the coordinator without performing sensing channels, and it may lead to the channel collision with another WBAN that will also select the same channel. In addition, the single channel MAC protocol may cause collision in case of high load traffic at sensor nodes, resulting in the degradation of network throughput. In the present, to handle the need of higher network throughput, multi-channel MAC protocols are taken into account to increase the network throughput in various wireless networks such as wireless sensor networks, ad hoc networks, cognitive radio networks, and WBANs [92-96].

In this chapter, taking motivation from the above challenges of inter-WBAN interference mitigation and multi-channel access, we propose a hybrid multi-channel MAC (HM-MAC) protocol to improve the network performance while mitigating the inter-WBAN interference. In the proposed protocol, a superframe consists of carrier sensing multiple access with collision avoidance (CSMA/CA) phase and time division multiple access (TDMA) phase. The CSMA/CA phase allows both higher priority users to transmit data packets with low latency and high reliability. The periodic data are transmitted in the TDMA phase, resulting in no contention and high reliability. The channel selection algorithm at the coordinator is also proposed to avoid the collision between neighboring WBANs. The analysis and simulation results show that the proposed multi-channel MAC protocol allows many sensor nodes transmit to the coordinator simultaneously on different channels causing no collision to neighboring WBANs. The higher priority users using CSMA/CA achieve higher packet delivery ratio and lower delay than the low priority users using TDMA. In addition, the sensor nodes listen to the beacon signal before switching to a new idle channel, which reduces the energy consumption of channel scanning.

The major contributions of our work are as follows:

- Hybrid medium access: The hybrid MAC superframe consists of random access CSMA/CA phase and scheduled TDMA phase. It is used to adapt with the transmission of different priority levels of traffic as well as allow the sensor to retransmit data packets.
- Framework of interference mitigation: The framework consists of inter-WBAN message exchange and intra-WBAN transmission. The inter-WBAN message exchange allows the coordinator to reserve idle channels for intra-WBAN transmission by selecting different idle channels to its neighbors.
- Channel selection algorithm: A channel selection algorithm amongst the neighboring WBANs is proposed, which allows each WBAN to select more than one channel for data transmission. We assume that the probability of selecting the data channel is the same in all WBANs in the network.
- Efficient use of multiple channels: To improve the network throughput, a coordinator will choose more than one channel for data transmission and one channel for control signal transmission. The multi-channel MAC improves the network throughput and reliability while avoiding the inter-WBAN interference and collision from neighboring WBANs.

5.2. Review of Related Works for Multi-channel MAC Protocols

In general, an efficient algorithm to reduce the inter-WBAN interference is to schedule the transmission of either nodes or WBANs in the time domain or frequency domain [15-18]. However, if multiple WBANs share the common scheduling, the increasing in the latency may adversely affect the quality of healthcare monitoring system. On the other hand, MAC protocol for WBAN has been widely researched to achieve better network performance of the vital signal as well as avoid the inter-WBAN interference. Despite of that, the existing MAC protocol allows the intra-WBAN transmission in single channel which may lead to collision amongst the sensor nodes while accessing the medium. To improve the bandwidth capacity and network performance, the multi-channel MAC schemes has been applied to various wireless networks including WBAN. The multi-channel MAC protocol in [94] has been introduced for intra-WBAN transmission where the coordinator selects the idle channels before broadcasting the list of idle channel to its sensor nodes in the beacon signal. While receiving the beacon signal, the sensor nodes will obtain the channel for transmitting data packets to the coordinator. In [95], the coordinators use channel hopping techniques to allocate the transmission of sensor nodes into a specific channel and time-slot. The collision from other neighboring WBANs is minimized as well as the energy consumption. The channel hopping technique is applied to increase the coexistence capacity by allocating multiple WBANs into the same channel. Moreover, the transmission of WBAN may be at risk under the cross-technology interference from other devices in the real scenario. In [96], the joint of control routing and transmitting power is applied by selecting the good-quality links to reduce the interference at WBAN. Furthermore, the cognitive radio technique is implemented in WBAN to reduce interference, the coordinator of WBAN detects the level of interference in the working channel and switch to another channel [43]. In [97], the multi-channel MAC protocol applies to WBANs working in Medical Implant Communication Service (MICS) band of IEEE 802.15.6 standard, which only consider the inter-WBAN interference of the same band in a public place. The multi-channel MAC protocol maintains the historical table of channel states and adaptively selects the available channel for data transmission. The energy-delay efficiency MAC for WBAN deploys multi-channel for intra-WBAN communication which used two separate channels for control and data signal [98]. The nodes will contend the data channel for transmission after receiving beacon via the control channel.

In summary, MAC protocols can operate in single channel or multiple channels to avoid intra-WBAN collision. In addition, those MAC protocols also reduce the inter-WBAN interference with the scheduling algorithm to allocate the transmission time and operating channel of each WBAN. On the contrary, there exist some limitations in the existing works. Firstly, the existing scheduling algorithm requires the synchronization amongst WBANs that will lead to long delay and high cost energy by transmitting the negotiation messages. However, the synchronization is a difficult task due to the mobility of WBAN in the real scenario. Furthermore, the current MAC protocols operate on a single channel which may cause the collision on accessing the medium. The density of nodes in the multiple WBAN will be increased so that results in increasing of interference. For example, the sensor node who is transmitting the emergency signal may collide with another signal from the neighbor WBANs in the same channel. In this case, if two sensor nodes can operate in different channel, it will reduce the collision. Therefore, based on the above limitation, our work focus on the MAC protocol operating on multiple channel while considering the interference signal from the other WBANs.

5.3. Hybrid Multi-channel MAC

5.3.1. Network Model

The network consists of N WBANs which is denoted as B_i, $1 \leq i \leq N$; each WBAN consists of one coordinator and M sensor nodes in which the sensor node is denoted as s_{ij}, $1 \leq j \leq M$. We assume that the sensor nodes of WBAN can either transmit or receive data via multiple channels. For simplicity, the transmission range of each WBAN is set as a circle with radius R. We assume that the path loss model for intra-WBAN and inter-WBAN follows free path loss space model. The received power is calculated as

$$P_{rx} = \frac{P_t G_t G_r \lambda^{\eta}}{(4\pi d)^{\eta}} \tag{34}$$

The signal-to-interference-noise-ratio (SINR) at the coordinator of B_i is denoted as $\gamma_{i,j}$ when any sensor node $s_{i,j}$ transmit data is calculated as follows

$$\gamma_{i,j} = \frac{P_{rx}(i,j)}{N_0 + \sum_{\substack{l \in (1,N) \\ l \neq j}} P_{rx}(i,l)} \tag{35}$$

where $P_{rx}(i, j)$ is the received power at B_i from sensor node $s_{i,j}$, $P_{rx}(i, l)$ is the received power at B_i from neighboring B_l. The SINR threshold value is denoted as γ_{th}, the coordinator adds the sensor node $s_{i,j}$ into the list of interfered nodes if $\gamma_{i,j} < \gamma_{th}$. If the coordinator detects any interfered nodes, the coordinator will start the interference mitigation algorithm.

We consider N WBANs working on a spectrum of K channels which denoted as C_k, $1 \leq k \leq K$. Among K channels, there is one common channel for inter-WBAN exchanging messages and K – 1 channels for intra-WBAN transmissions. For intra-WBAN, each WBAN occupies one control channel and M_{DATA} data channels which can be explained as follows. The control channel is used for transmission beacon, acknowledgement signal from the coordinator to the sensor nodes while data channel is used for data transmission from sensor nodes to the coordinator. The matrix of relationship between WBANs and channels is represented as

$$M_{DATA} = \begin{bmatrix} M_{1,1} & M_{1,k} & M_{1,K} \\ M_{i,1} & M_{i,k} & M_{i,K} \\ M_{N,1} & M_{N,k} & M_{N,K} \end{bmatrix} \tag{36}$$

where the rows represented for the index of WBAN and the column represented for the index of channel. The value of $M_{i,k}$ is set to 1 if B_i uses channel C_k, otherwise, $M_{i,k}$ is set to 0.

When B_i is interfered as in (34), we call the neighboring WBAN is the source of interference. The neighboring WBAN can either transmit or receive data at the same time over the same frequency channel or the neighboring WBAN transmission is in the transmission range of B_i. We call B_j as the one-hop neighbor of B_i if the transmission range of B_j and B_i is overlapped. Therefore, the interference condition can be obtained as: $I_{i,j} = 1$ if $d_{i,j} < \mathrm{R}$. Due to the overlapped transmission range, if the signal from B_i can be detected at B_j, it indicates the inter-WBAN interference occurs at the specific time and channel. The interference matrix is a matrix to identify the interfered WBAN where $I_{i,j} = 1$ denotes the interference between WBAN B_i and B_j as following

$$I = \begin{bmatrix} I_{1,1} & I_{1,j} & I_{1,N} \\ I_{i,1} & I_{i,j} & I_{i,N} \\ I_{N,1} & I_{N,j} & I_{N,N} \end{bmatrix} \quad (37)$$

We define the condition to avoid interference between two nearby WBANs is follows: $\{M_{DATA(j,:)} \cap M_{DATA(i,:)} = \varnothing \mid I_{i,j} = 1\}$. We define the common channel for inter-WBAN transmission as follows: the coordinator of WBANs can communicate through the first channel of set C_k. The intra-WBAN channel set is defined as follows: M sensor nodes can transmit data to the coordinator through C_M channels without collision, $C_M \leq M$.

We assume that the energy level of the sensor nodes is lower than that of the coordinator. Therefore, the channel sense is obtained only at the coordinator by using the energy level detection. The coordinator applies the channel sense by using energy level detection. The channel C_k is idle if the energy level detection is above a threshold E_{Thr}.

5.3.2. Interference Mitigation

We have developed a framework for interference mitigation algorithm which supports multi-WBANs as in Figure 21 which can be explained as follows. The coordinator will list the interfered sensor nodes by using SINR value. Then, the coordinator will sense the idle channel by the energy level detection. In the next step, the coordinator will exchange the list of idle channel to its one-hop neighbors. The received message from one-hop neighbors contains the list of idle channels from the neighbors. If there exist any neighbor B_j who has the same idle channel set as B_i, B_i and B_j will exchange messages to find a reasonable data channel set as in Algorithm 3. The total available idle channels at two WBANs is called $TotalAvaiCh_{i,j} = IdleCh(i) \cap IdleCh(j)$. When WBAN finds its own data channel set which does not interfere with the neighbor, the intra-WBAN communication starts as in Algorithm 4.

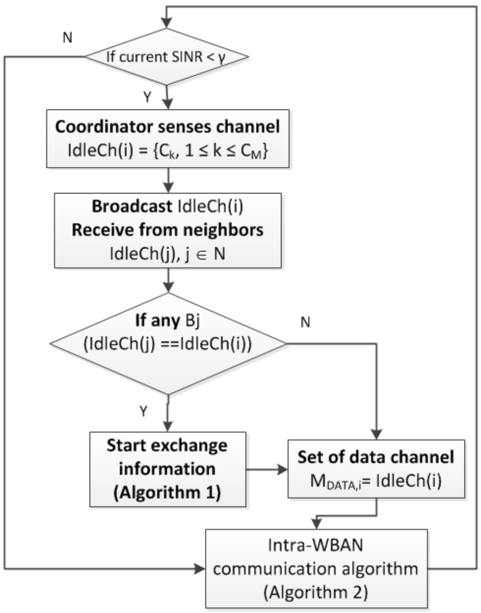


Figure 21. Framework of inter-WBAN interference mitigation for multichannel MAC

5.3.3. Inter-WBAN Communication and Channel Selection

The inter-WBAN communication process is taken amongst the WBANs with the same available idle channels. The inter-WBAN communication with the exchanging message steps is shown in Figure 22. The coordinators will send the “*REQCh*” message which contains the set of *IdleCh* to its one-hop neighbors. The coordinator also waits for the “*REP*” messages from its neighbors which contains the set of *IdleCh* and the priority value as in (37). Upon receiving the “*REP*” message from one-hop neighbors, the coordinator of WBAN will reselect its data channels by running Algorithm 3. After selecting the data channels, the coordinators will broadcast again the “*LISTCh*” message which contains the list of data channels for each WBAN. As a consequence, the channels in *TotalAvaiCh* will be occupied by two neighbors without interference.

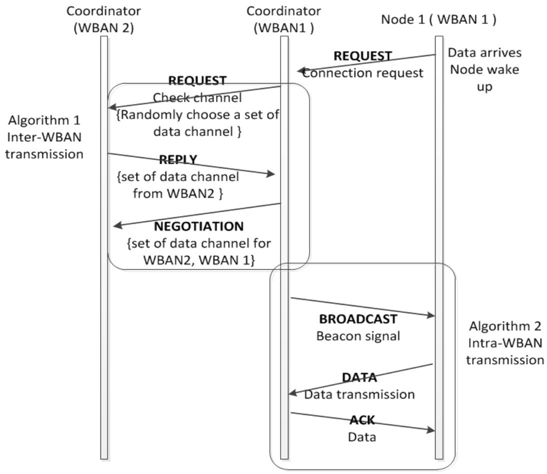


Figure 22. Inter-WBAN communication of HM-MAC

Algorithm 3. Channel selection algorithm.

Input: A set of available channels at neighbor Bj ($IdleCh(j)$, $j \in NI$, $M_{DATA,i} = \varnothing$)

Output: A set of data channels for each WBAN {$M_{DATA,i}$ }

1. Step 1. Calculate the total available channels for Bj and Bi :
2. $TotalAvaiCh = IdleCh(i) \cup IdleCh(j)$
3. Step 2. Calculate the priority value for each WBAN as in (5)
4. Step 3. The number of channels for WBAN(i) in $TotalAvaiCh$ with a higher $PVal_i$ calculated as follows
5. If $TotalAvaiCh > \Delta C_i$
6. $x = \max([TotalAvaiCh / 2], \Delta C_i)$
7. else
8. $x = \min([TotalAvaiCh / 2], \Delta C_i)$
9. end if
10. Step 4. The number of channels for the other WBAN is calculated as follows
11. $y = |TotalAvaiCh| - x$
12. Step 5. The intra-WBAN channel set at a WBAN
13. for cnt = 1: x
14. $M_{DATA,i} = M_{DATA,I} \cup TotalAvaiCh(cnt)$
15. end for
16. $M_{DATA,j} = TotalAvaiCh \cap M_{DATA,i}$

In Algorithm 3, the coordinator creates a set of total available channel as in Step 1. Then, in order to verify the interference level at WBAN, each WBAN will calculate the priority value which takes into account the operating time and the data channel set as follows

$$Pval_i = \frac{\Delta C_i}{C_{\max}} \times \frac{\Delta TI_i}{\Delta T} \quad (38)$$

where ΔT is the total operating time which is calculated by the number of superframe; ΔTI_i is the number of interfered-superframe which WBAN is interfered by other WBANs; ΔC_i is the average channel for intra-WBAN communication of WBAN during ΔT; ΔC_{max} is the total available channel.

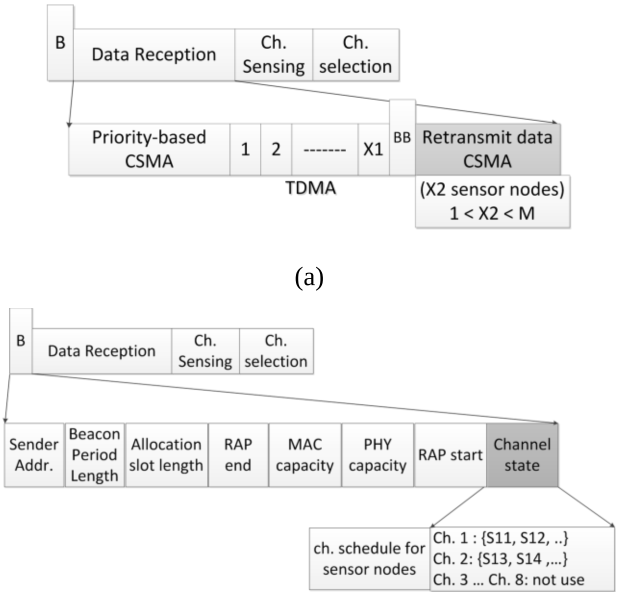
In Algorithm 3, the total available idle channel for B_i and B_j is calculated as the join of *IdleCh*(i) and *IdleCh*(j) in step 1. In step 2, the priority at each WBAN will be calculated as in (38). In the step 3, the WBAN with higher *Pval* will get higher priority to access the total available idle channel, or WBAN will get more idle channels than the WBAN with low *Pval*. At the WBAN B_i with higher *Pval*, the number of *TotalAvaiCh* is compared to the average channel ΔC_i, then the number of channels for B_i is calculated as in the Algorithm 3. The other WBAN will get the channel as in step 4. Finally, the data channel for each WBAN is calculated in step 5.

The separate channel is defined as in IEEE 802.15.6 [7] which is three channels to avoid interference from adjacent channels. To avoid the collision in time domain as well as synchronization, the coordinators will send beacon signal via the control channel as follows. Each coordinator will sense the idle channel before transmitting its beacon signal. The sensor node will stay awake to listen to the beacon signal of its WBAN. After receiving the beacon signal, the sensor nodes have the knowledge of the data channel and the TDMA schedule, then, it switches to the data channel and wait until its time slot. The radio will be turned off after transmission. At the end of data transmission, the sensor node turns on at the control channel to listen to the acknowledgement and the next beacon. Therefore, it reduces energy from the listening channel and sensing channel. This algorithm provides a strategy to support switching channel from control channel to data channel at the sensor nodes and the coordinator.

5.3.4. Intra-WBAN Communication

We assume that the priority of data generated at each sensor nodes can be categorized as in the standard IEEE 802.15.6. The sensor nodes have knowledge of C_M data channel by receiving the beacon signal, $1 \leq C_M \leq M$. Assume there is always a packet in the buffer at each sensor node. If the packet is failing to transmit to the coordinator, it will be re-transmitted in a future. The sensor nodes will contend the idle channel for packet transmission by using CSMA/CA with a specific *CW*. We also use the CW_{min} and CW_{max} as defined in standard IEEE 802.15.6. Let define CW_{avg} is the average *CW* of node during the operating time ΔT. At each sensor node, the new value of *CW* is calculated according to the average CW_{avg} as follows

$$CW_{new} = \begin{cases} \max(CW_{avg}, CW_{\max}/2) & if \quad CW_{avg} < CW_{\max}/2 \\ \min(CW_{\max}, CW_{avg}) & otherwise \end{cases} \tag{39}$$



(b)

Figure 23. HM-MAC superframe: (a) intra-WBAN transmission; (b) beacon signal.

The superframe for intra-WBAN transmission is shown in Figure 23(a). We have modified the superframe of standard IEEE 802.15.6 by using two beacon signal, the priority-based CSMA, TDMA part, and retransmitted CSMA part. In our superframe, the first beacon signal is sent by the coordinator at the beginning of the superframe which includes the control signal as shown in Figure 23(b). The coordinator will broadcast the list of data channel in field "*Channel_state*" in the beacon signal to the sensor nodes as well as the list of channel WBAN cannot use. In the data reception part, we use hybrid medium access techniques of both CSMA and TDMA. In the first CSMA part, only the high priority-based users can access the channel. The other sensor node will access the channel in the TDMA part. In case of lost packets from sensor nodes, the coordinator will broadcast a second beacon called *BB* after the TDMA part. The second beacon signal consists of the list of the sensor nodes who need to retransmit and the length of transmission.

Algorithm 4. Intra-WBAN communication algorithm.

Input: A set of data channel M_{DATA}
Output: A set of data channel for sensor nodes (by CSMA/CA)

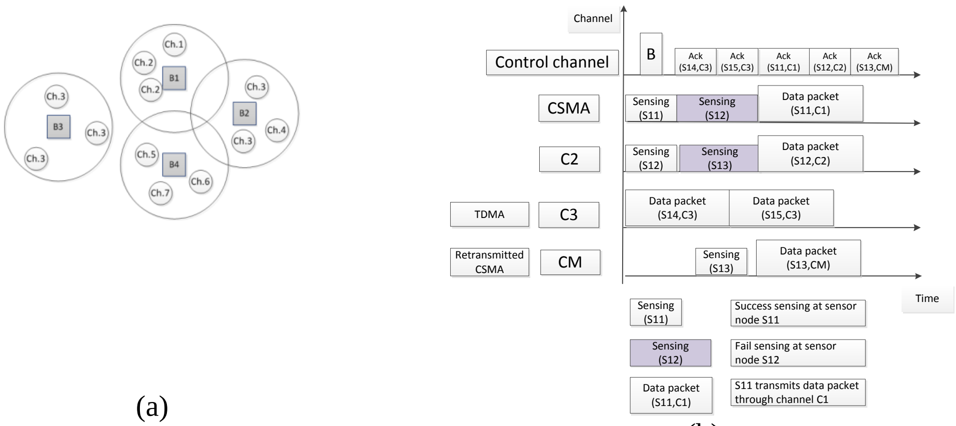
Step 1.
for each nodes
    receive Beacon
    gets the value of *CW*, *backoff_counter*
end for
Step 2.
if the priority of node is highest
    compare the current channel (*Ci*) to the set of data channel
        if *Ci* belongs to M_{DATA}, continue
        else,
            pick up a random channel (*Cr*) in M_{DATA},
            if *Cr* is idle, decrease *backoff_counter*
                if *backoff_counter* is zero, transmit data to coordinator
                else, lock *backoff_counter*
                end if
            else, choose another *CW* and pick up another channel
            end if
        end if
Step 3. // the priority of node is not the highest
else
    pick up a channel (*Cr*) for TDMA transmission in M_{DATA}, which is broadcasted in the beacon signal
    wait until its allocated time slot, transmit data to coordinator
end if

The TDMA transmission is scheduled in the superframe after the transmission length of priority-based CSMA. As a consequence, the high priority nodes can switch the channel to transmit in the priority-based CSMA portion after receiving beacon while the low priority nodes have to wait until end of CSMA portion. The CSMA protocol for intra-WBAN transmission algorithm is shown in the Algorithm 4. In the first step (Step 1), each node listens to the channel and receives the Beacon signal from the coordinator, then calculate the value of *CW* and *backoff_counter*. The highest priority node will get the channel as in Step 2. The *backoff_counter* is reduced when the channel is busy. In Step 3, the low priority node will transmit data in a allocated slots in a specific channel which is assigned by the coordinator. In case of failure transmission, the node will wait for the second beacon signal, repeat Step 2 in the retransmitted-CSMA part.

5.3.5. Multi-channel Multi-WBAN Example

An example of multi-channel multi-WBAN configuration is shown in Figure 24(a). Assume that there exist four WBANs in which each WBAN has one coordinator and several sensor nodes. The number is written in the small circle which indicates to the index of data channel. In Figure 24(a), B1, B2 and B4 share the same vicinity with the set of channel TotalAvaiCh = {1, 2, 3, 4, 5 ,6 , 7}; while B3 is not interfered with any WBAN, so that B3 can reuse channel {3} for intra-WBAN transmission.

The example in Figure 24(b) shows the intra-WBAN transmission. The high priority nodes {S11, S12, S13} will sense the channel C1 and C2, if there is no collision, the data packets are transmitted to the coordinator. Channel C3 is divided into slots for TDMA transmission for sensor node {S14, S15}. The sensor node {S13} will retransmit data through channel CM because of failure during priority-based CSMA. The acknowledgement of the successful transmission at the coordinator will be transmitted on the control channel.



(a) (b)

Figure 24. Multi-channel multi-WBAN example: (a) network configuration and (b) intra-WBAN transmission

5.4. Throughput and Delay Analysis

5.4.1. Probability of Successful Transmission

Throughput is measured by the number of successfully received packets by the given time. Assume there exist N WBANs in the network, each WBAN consists of M sensor nodes and one coordinator. The total number of channels for the network is K data channels, $1 \leq K<N$, each channel is divided into T data time slots and total generated packets during T time slots is G packets.

The number of successfully received packets is calculated as

$$P_s = G \times p_s \tag{40}$$

where p_s is the probability that a packet is successfully received at the coordinator.

In case of intra-WBAN transmission, at channel C_k, the data collision occurs when two sensors simultaneously transmit packets in C_k at slot t_i. Let $p_{s,i}$ be the probability of successful transmission at slot t_i when C_k is idle, $p_{s,i}$ is given by

$$p_{s,i}^{(k)} = p_{idle}^{(k)} \cdot p_s(t_i) \tag{41}$$

where $p_s(t_i)$ is the probability of successful transmission in slot t_i. The Bernoulli trial will be given to represent $p_s(t_i)$ when there is another node tries to transmit packets. We represent $p_s(t_i)$ as follows

$$p_s(t_i) = p_i \binom{M}{1} q(1-q)^{M-1} \tag{42}$$

where q is the probability that node performs successful channel sensing, and p_i is the probability that a packet will transmit in time slot t_i; q and p_i are shown as

$$q = \frac{1}{\overline{CW}} \tag{43}$$

where $\overline{CW}$ is the average value of contention window, and $p_i = \dfrac{1}{T}$.

The probability of successful transmission in C_k is given as

$$p_s^{(k)} = \sum_{i=1}^{T} p_{s,i}^{(k)} = \sum_{i=1}^{T} p_{idle}^{(k)} p_s(t_i) = \sum_{i=1}^{T} p_{idle}^{(k)} p_i \binom{M}{1} q(1-q)^{M-1} \tag{45}$$

The interference area between two nearby WBANs $\{B_i$ and $B_j\}$ is denoted as $L_{i,j}$ where locates the set of interfering sensor nodes of B_i and B_j, $\{S_i\}$ and $\{S_j\}$, respectively. In addition, the data channel set of B_i and B_j is given as $\{C_i\}$ and $\{C_j\}$, respectively. To calculate the probability that channel C_k is idle or $p_{idle}^{(k)}$, we also assume that the probability of selecting channel is equal. In addition, only the interference in the same channel is considered in this paper, so that the condition of interference is $\{C_i\} \cap \{C_j\} = C_k$. If B_i selects channel C_k, probability that B_j selects a random channel is $1/K$, and have a $(K\text{-}1/K)$ probability to select a channel not chosen by B_i. The probability that two WBANs take the same channel is given by

$$p_{col}^{(k)} = 1 - \frac{K}{K}\frac{K-1}{K} = 1 - \frac{K-1}{K} \tag{45}$$

Hence, the probability that C_k is idle is given by

$$p_{idle} = p_{idle}^{(k)} = 1 - p_{col}^{(k)} = \frac{K-1}{K} \tag{46}$$

Therefore, the probability of successful transmission over K channels is represented as

$$p_s = \sum_{k=1}^{K} p_s^{(k)} \tag{47}$$

5.4.2. Transmission Time and Throughput

Transmission time is defined as the total time to transmit a packet including sensing time T_s, time to transmit a data packet T_{data}, time to receive acknowledgement T_{ack}, time to receive beacon T_B and T_{B2}, delay due to retransmission $T_{d,R}$. Thus, transmission time T_i of packet i^{th} is given as

$$T_i = T_s + T_{data} + T_{ack} + T_B + T_{B2} + T_{d,R} \tag{48}$$

Sensing time T_s is the duration that a sensor node performs sensing idle channel. We divide T_s into two cases as follows. In case (1), if the sensor node performs idle channel, it will transmit data, so that T_s is calculated as

$$T_s = T_{bo} N_{bo} p_{s,i}^{k} \tag{49}$$

In case (2), if there is more than two nodes perform the same channel, the sensor node will lock the counter in a random time T_{rand} which take the random value between $[0, T_{data}]$ and perform sensing on another channel, so that T_s is given as

$$T_s = (1 - p_{s,i}^{k}) T_{rand} + T_{data} \tag{50}$$

Delay due to retransmission $T_{d,R}$ is simply given when a packet is transmitted in the *Retransmitted Data* part as in Figure 23(a). Thus, the delay due to retransmission is given by

$$T_{d,R} = T_W + T_{data} \tag{51}$$

where T_W is the duration of the priority-based CSMA and TDMA part in the superframe.

Therefore, the total transmission delay is calculated as

$$T_D = \sum_{i=1}^{G} T_i \tag{52}$$

The throughput at a WBAN is a fraction of total successful received packets at the coordinator to the total transmission delay, which is given as

$$Throughput = \frac{P_s}{T_D} \tag{53}$$

5.4.3. Channel Utilization

Channel utilization is defined as the average bandwidth for successful transmission to the given bandwidth. The average bandwidth for transmission of WBAN B_n is given as

$$E_{BW,n} = W \cdot E_{idle,n} \tag{54}$$

where W is the bandwidth of a channel, and $E_{idle,n}$ provides the average number of idle channels that a WBAN uses for data transmission in a given T.

The probability of x channels with successfully transmissions in K channels is denoted as

$$p_{idle} = \binom{K}{x} (p_{idle})^x (1 - p_{idle})^{K-x} \tag{55}$$

The average number of idle channels at WBAN B_n is calculated as follows:

$$E_{idle,n} = \sum_{k=1}^{K} p_{idle}^k \tag{56}$$

Therefore, the channel utilization at WBAN B_n is given as

$$\omega_n = \frac{E_{BW,n}}{K \cdot W} \tag{57}$$

5.5. Performance Evaluation

In this section, the performance of the proposed HM-MAC is evaluated via extensive computer simulation OMNET++ and then compared to that of conventional protocols. The conventional multi-channel MAC called MC-MAC [94] is selected for performance comparison because MC-MAC considers the multiple channels while using the beacon mode with superframe.

5.5.1 Simulation Environment

The network consists of *N* WBANs and *C* channels. In each WBAN, there exist *M* sensor nodes. We assume the total number of channels is 12 channels and each WBAN consists of one coordinator and 10 nodes. In each WBAN, we deploy four channels for intra-WBAN transmission [94]. The simulation parameters are summarized in Table 14. In order to evaluate the network performance, we aim to derive the packet delivery ratio, network throughput, latency, and energy consumption at each WBAN with respect to the network density. The network density is chosen as the number of neighboring WBANs who share the same vicinity. In HM-MAC, we assume that the traffic priority is categorized as in IEEE standard [7]. If nodes carry vital data such as emergency, they are considered as high priority traffic nodes that will transmit data through CSMA part of the superframe. On the other hand, the other nodes will transmit in the TDMA part of the superframe. In this simulation, the number of nodes with high priority is around 20%, the CDMA length is 4 slots.

Table 14. Simulation parameters (HM-MAC)

Parameter	Value
Number of WBANs	1 ~ 5
Number of sensors per WBAN	10
Traffic priority	20 % - high priority (CSMA) 80% - low priority (TDMA)
Number of channels per WBAN	4
Number of channels in the network	12 channels
Simulation area	10m x 10m
Transmission range	2m
Distance between coordinator and nodes	0.6 ~ 1.4 m
Data rate	250kbps
Packet length	50 ~ 150 bytes (depends on the traffic at the sensor nodes)

Parameter	Value
Beacon size	15 bytes
Negotiation size	5 bytes
Superframe length	100 ms
CCA time	0.01 ms
Number of TDMA slots per superfame	4 ~ 6 slots
Frequency	2.4 GHz
Traffic arrival rate	10 packets per second
Transmit current [23]	17.4mA
Receive current [23]	19.7 mA
Energy consumption per each channel switching [23]	2 mJ
Votage	3.3 V

5.5.2. Results

Packet delivery ratio (PDR) is calculated as the number of successfully received data at the coordinator to the number of total sent packets at the sensor nodes. As shown in Figure 25, HM-MAC achieves higher PDR than MC-MAC. It should be noted that, as

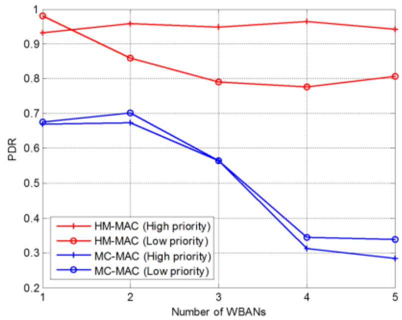


Figure 25. Packet delivery ratio (HM-MAC).

shown in Table 14, the average channels for intra-WBAN is four while the number of total data channel is 11. As a result, more than one WBAN need to reuse the channel which causes the dropped packet at the coordinator. For high priority traffic, HM-MAC achieves higher PDF due to the proposed channel selection algorithm and CSMA/CA based transmission. It is noted that the any failure transmission will be retransmitted in the retransmitted CSMA/CA portion. In consequence, even for low priority traffic, HM-MAC is better than MC-MAC.

End-to-end delay is calculated as the time when packet is received at the coordinator to the generated time at the sensor nodes. The end-to-end delay consists of duration of CSMA/CA for high priority traffic or waiting time for low priority traffic. Because of the high-density network and the reuse of idle channels, the sensor nodes need to perform CSMA/CA for longer duration that leads to high end-to-end delay. For high priority traffic, HM-MAC has shorter end-to-end delay than MC-MAC as shown in Figure 26. The intra-WBAN transmission algorithm allows high priority user to access the channel after receiving beacon signal and switch to other idle channel to ensure the continuity of transmission. On the other hand, the low priority users have to wait until end of CSMA/CA portion then transmit on the scheduled slot which causes higher delay.

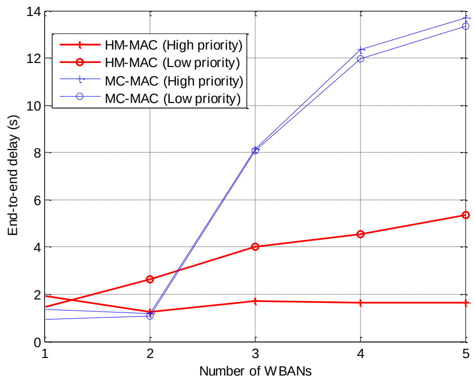


Figure 26. End-to-end delay (HM-MAC).

Throughput is the total successful received packets per total transmission time which can be measured by packets per second. In HM-MAC, the high priority node will send data in CSMA part of the superframe, if the channel is busy; node will switch to another channel. However, the low priority nodes only transmit data in TDMA part without switching the channel. If the number of WBANs increases, WBAN may reuse the channel due to the total number channels of the network. The average throughput per node is shown in Figure 27(a), the successfully received packets at the coordinator decrease while increasing the number of WBANs in both HM-MAC and MC-MAC. Despite of that, the average throughput per node of high priority traffic is higher than that of low priority traffic in case of HM-MAC. In Figure 27(b), the average throughput per WBAN is evaluated. In order to ensure the quality of high priority traffic in multiple WBANs environment, the average throughput of low priority traffic decrease with the slightly increasing of high priority traffic. Because any failure transmissions will be retransmitted in the CSMA part, the higher priority will occupy the channel for transmitting while the low priority nodes have to wait until end of transmission. The total throughput of network is shown in Figure 27(c), HM-MAC achieves higher network throughput then MC-MAC even though both algorithms show the increasing trends. However, the total throughput of high priority nodes is lower than that of low priority, this can be explained as follows. The number of high priority node is around 20% of the total nodes, each node generates the same amount of packets to transmit to the coordinator. Because of that, total generated packets of higher priority nodes are lower that that of high priority nodes.

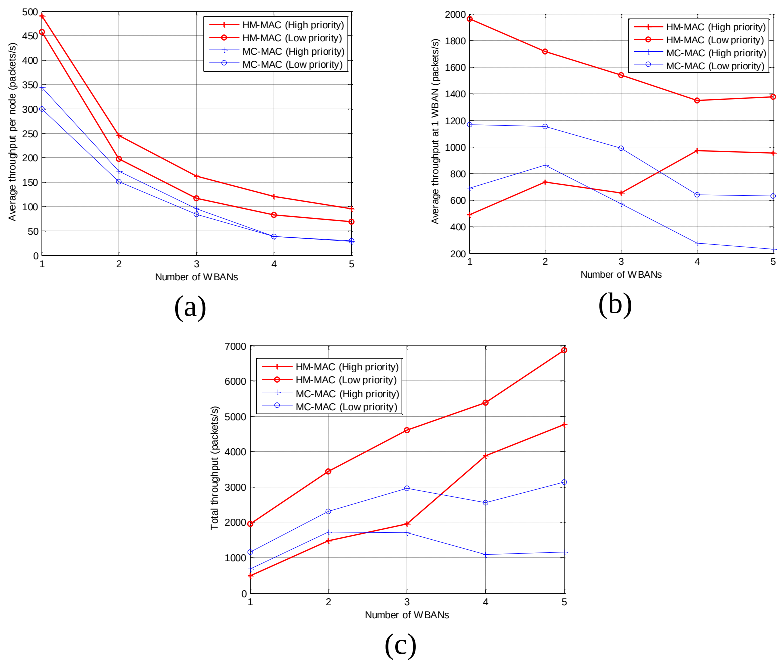
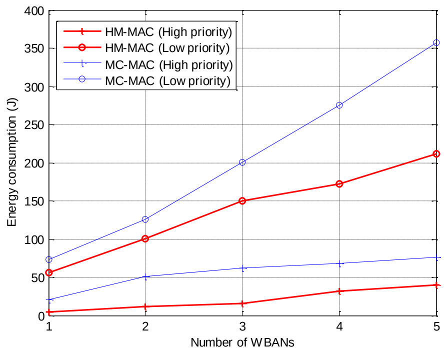


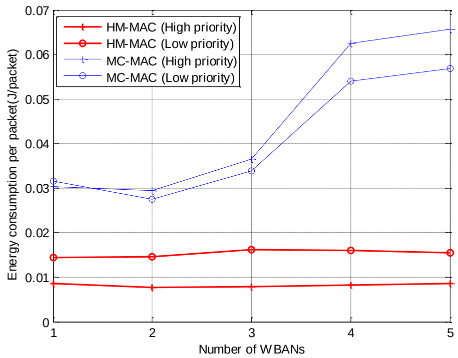
Figure 27. Network throughput (HM-MAC): (a) Average throughput per node; (b) Average throughput per WBAN; (c) Total network throughput

Energy consumption is calculated by the energy for transmitting and receiving control packets, data packets, negotiation packets and energy for switching channels. However, we do not consider the energy consumption for idle listening of nodes. Total energy consumption for transmitting and receiving increase while increasing the number of WBANs as in Figure 28(a). However, energy consumption for transmission of higher priority is lower in both cases even though HM-MAC consumes less energy than MC-MAC. In Figure 28(b), we consider the energy consumption of different tasks of both

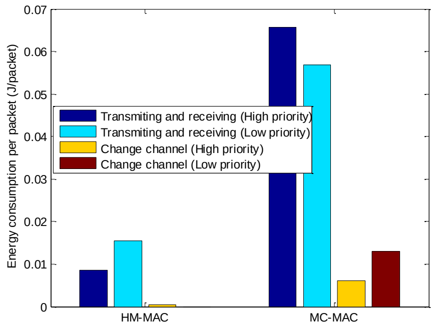
HM-MAC and MC-MAC. The energy consumes for transmitting and receiving high traffic priority is lower than that of low traffic priority in both cases. Nonetheless, the energy consumption for changing channel of HM-MAC is lower compared to MC-MAC, because only nodes with high priority traffic can change that working channel. The nodes transmitting in TDMA do not change working channel, therefore, it saves the energy. On the other hand, in MC-MAC, nodes with different priority traffic will occupy the channel by using CSMA/CA with different backoff value while be able to switch the working channel to avoid collision. Nonetheless, it may cause higher energy consumption in MC-MAC. In addition, the energy consumption per packet is calculated by the fraction of total energy consumption to the successfully received packets. In Figure 28(c), the average energy consumption per packet of HM-MAC is less than that of MC-MAC.



(a)



(b)



(c)

Figure 28. Energy consumption (HM-MAC): (a) Total energy consumption; (b) Energy consumption per packet; (c) Energy consumption per task per packet

5.6. Conclusion

In this chapter, we have proposed hybrid multi-channel medium access control called HM-MAC for WBANs in order to mitigate inter-WBAN interference significantly. In HM-MAC, a superframe consists of random access CSMA/CA phase and scheduled access TDMA phase. The CSMA/CA phase allows the higher priority users to transmit data packets with low latency and high reliability whereas the TDMA phase enables the periodic data to be transmitted with no contention and high reliability. The channel selection algorithm allows the coordinators to select the channels for intra-WBAN transmission to adapt the priority traffic conditions, by which the collision between neighboring WBANs is avoided. In addition, HM-MAC consumes low energy compared to the conventional protocols. The performance study shows that the HM-MAC protocol achieves higher network performance with lower energy consumption and lower delay than the conventional protocol. As a future work, we are going to investigate the energy efficiency of multi-channel MAC protocols without negotiation in multi-WBAN scenarios.

6. Conclusions and Future Works

6.1. Conclusions

In this thesis, the problem of inter-WBAN interference has been reviewed with regards to the network performance and the reliability of WBAN according to the real application. The inter-WBAN interference can be mitigated by applying some scheduling algorithms in time domain or frequency domain. The basic requirements of WBAN application mainly focus on the high delivery packets, low end-to-end delay, and low energy consumption. However, WBAN represents to the wireless network for human body (but not limited to human) which is dynamic and movable. Therefore, the task of interference mitigation needs to consider the mobility or interference prediction for high network performance. Based on those difficulties, our thesis aims to achieve high performance in the multiple mobile WBANs network.

At first, the inter-WBAN interference is modeled as an interference graph which two vertices or two WBANs share the same interference edge becoming the interfering source of each other. The scheduling algorithm ITLS applies the STDMA to allocate the transmission of different sensors into timeslot with regards to their priority levels. More particular, ITLS allows two non-interference nodes can share the same timeslot which increase the network throughput. Nodes with high priority level have more chance to be scheduled into the first available timeslot, therefore, increasing the reliability of traffic. As shown by the simulation results, the packet loss rate is reduced while comparing to the other conventional algorithm. In addition, the network throughput and delay depends on the traffic priority, the high priority traffic achieves higher network throughput with low delay compared to the low priority traffic.

LSIP is another scheduling algorithm which also works in single channel for intra-WBAN transmission as the ITLS. LSIP considers the mobility of WBANs by predicting the interference duration of WBAN based on Bayesian inference classifier. The superframe of LSIP consists of two different portions which are CSMA and TDMA for the transmission of non-interfered sensor nodes and interfered sensor nodes, respectively. The length of TDMA portion is calculated so that multiple sensor nodes of the neighboring WBANs can access the channel with acceptable delay. However, the non-interfered nodes can access the channel in the CSMA portion which decrease the latency. In the simulation results, the LSIP achieves high network throughput with low latency compared to the other existing work. However, due to the prediction steps and negotiation steps among WBANs, the energy consumption is considerably higher than the existing work.

Lastly, we consider the multiple channel for intra-WBAN transmission while negotiating with the neighbor WBANs for channel selection. In HM-MAC, the hybrid superframe consists of two portions which are CSMA/CA and TDMA. The nodes with high priority traffic who will transmit in the CSMA/CA portions can change to another channel if the channel is busy. On the contrary, the nodes with low priority traffic will transmit in the assigned timeslot in the TDMA portion in the specific channel. The multiple WBANs network is considered which allow the coordinator to negotiate with others; in a result, the idle channel may be reused at multiple WBAN. The multiple channels MAC algorithm increases the network throughput as well as ensuring the low latency for the high priority traffic. The simulation results show that HM-MAC obtains higher performance than conventional multichannel MAC protocol in terms of the packet delivery ratio and end-to-end delay. Therefore, the multichannel MAC protocol works well for intra-WBAN transmission which shows in the higher packet delivery ratio with low energy consumption for high priority traffic.

6.2. Future Works

In WBANs, the energy consumption is the main issue because the low-energy sensors are attached in-, on-, or around the human body. High energy consumption at WBANs may lead to a short lifetime of sensor nodes, which may interrupt the process of collecting data at the health monitoring center. Therefore, the energy-efficient design of an interference mitigation algorithm will be a promising work. In addition, an energy-efficient MAC protocol is highly required as well.

Furthermore, the cognitive radio technology is capable of adaptation features which can be applied to WBANs in medical applications. The cognitive radio WBANs (CR-WBANs) can be considered as the secondary users who can change the working channel according to the application. However, it is necessary to find the new channel selection algorithm for WBANs in the licensed and unlicensed bands. The application for multiple CR-WBANs can be at the hospital. As a consequence, the link scheduling for multiple CR-WBANs should be taken into account.

Last but not least, the protocol for UWB-WBANs is needed to consider in both intra- and inter-WBAN communications. UWB-WBANs can obtain high data rate with low power consumption which can be recommended for the medical applications in the future.

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