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Mutual Interference Mitigation Schemes on Wireless Body Area Networks (WBANs): A Survey

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Abstract: WBANs consist of a number of miniaturized sensors that are primarily used to monitor the patient's vital parameters over a long period of time. Those wirelessly connected sensors and actuators placed inside or around the body to introduce a continuous, effective, and unobtrusive monitoring of physiological signs to support medical applications, lifestyle, and entertainment. However, because of the coexistence of other wireless technologies as well as the presence of many WBANs in the same area, interference can occur. Since WBAN networks are used in health care applications, loss of data because of interference will be particularly dangerous for critical medical applications. Therefore, it is extremely important to mitigate this interference to ensure reliable data communication. This survey will firstly provide an up-to-date view of WBAN interference. Then, it will introduce a comparative study on the mutual interference mitigation schemes with considering the taken approach either MAC or power control.

Keywords: *WBAN, Coexistence, Interference, Mitigation, MAC, Power control.*

1. Introduction

According to the World Health Organization, population of aging has become a major problem. At the same time, the new lifestyle of millions of people is causing obesity or chronic diseases every day. Therefore, it is reasonable to expect that, those circumstances will only contribute to the continued decline in the quality of services (QoS) provided by the already burdened healthcare systems. These reasons make providing healthcare everywhere crucial which will increase efficiency, accuracy and availability of medical treatment and will provide continuous patient health monitoring without any restrictions on normal daily life activities [1], [2].

WBAN networks consist of a number of inexpensive, lightweight, miniature, and heterogeneous biological sensors. These miniaturized sensors could be placed on the body as tiny intelligent patches, integrated into clothing, or implanted below the skin or muscles. Each of them has specific requirements and is used for specific missions. These devices are used to measure changes in the patient's vital signs such as electrocardiographs (ECGs), electromyography (EMGs), electroencephalographs

(EEGs), and to detect emotions or human conditions, such as fear, stress, happiness, etc. Those sensors communicate with a specially coordinated node, which is generally less resource constrained and has greater processing capacity. It is responsible for sending the patient's biological signals to the doctor in order to provide real-time medical diagnosis and to allow him to make the right decisions[1], [2].

In fact, WBAN applications cover many areas in order to improve the quality of users' lives. These applications can be classified mainly according to whether they are used in medical fields or non-medical fields. **Non-medical applications** include motion and gestures detection for interactive game control applications, interactive fitness, cognitive and emotional recognition to assist in driving or social interactions. **Medical applications** mainly include health care solutions for aging and diseases' populations. Typical examples include early detection, prevention, and control of diseases, elderly home assistance, postoperative rehabilitation, and biofeedback applications which control emotional and assisted living applications that improve the quality of life of persons with disabilities[1], [2]. However, the concept of WBAN applications should take into consideration many technical requirements, such as motion, temperature of the body, node location, node lower power and processing capabilities. Other restrictions that are strongly related to wireless technologies used in body-to-body communications, such as short space, data rate, etc., should also be considered [1].

The factors that motivate the development of WBAN are the increased use of wireless networks and the developments in wireless communication technologies, new advances in the provision of lightweight, low-energy, ultra-low-energy, intelligent sensors that can be used, placed or implanted in the body, and the recent developments in the embedded computing area [1], [2].

However, because of the coexistence of other wireless technologies as well as the presence of many WBANs in the same area, the interference can occur. As WBANs are used in healthcare applications, loss of data will be dangerous particularly for critical medical applications and the use of WBAN for healthcare applications will no longer persist. Therefore, it is very important to mitigate this interference in order to be assured of a reliable data communication. The main objective of using WBAN mitigation plans is to improve the accuracy of data sent while maintaining low power consumption and high productivity. Beside interference some other parameters also affect performance. Therefore, the mitigation technique has to be designed to take certain factors into consideration such as mobility, QoS, spatial reuse, and latency [3].

In this survey, interference of WBAN has been surveyed and studied. Existing interference mitigation schemes for WBANs are analyzed and discussed. The interference mitigation schemes are categorized depending on the taken approach into MAC and power control. Different interference mitigation schemes are then reviewed and compared.

This paper is organized as follows: In section 2 the communications architecture in WBAN will be addressed. section 3 will discuss the hardware and devices of WBAN. Interference issues of WBAN will be discussed in section 4. Section 5 will provide detailed reviews of MAC and power control interference mitigation approaches and they will be qualitatively compared and discussed in Section 6. In section 7 open research issues and challenges are discussed. Finally, conclusion summarized in Section 8.

2. Communication Architecture in WBAN

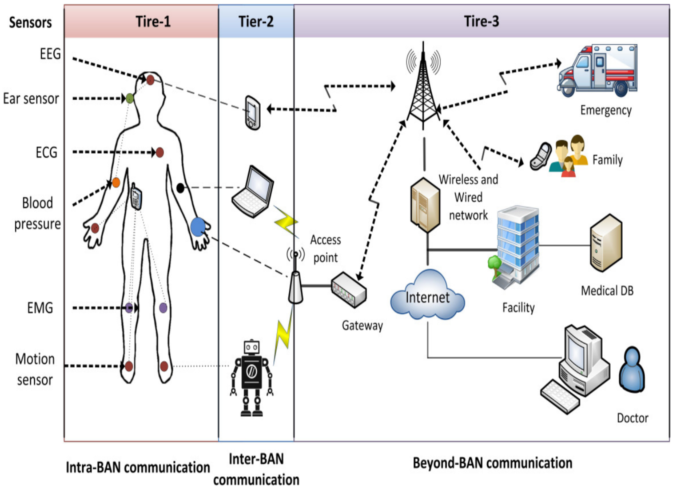

Fig. 1: Three tier communication architecture in WBAN

The WBAN general architecture consists of three tiers of communication: Tier-1-Communication design (intra-BAN communications), Tier-2-Communication design (inter-BAN communications) and Tier-3-Communication design (beyond-BAN communications). Intra-BAN connections indicate connections between wireless body sensors and the coordinator (master node or hub). Inter-BAN connections include connections between the coordinator and personal devices such as Mobile phone, laptops, home service, robots, and so on. The beyond-BAN connects the personal device to the Internet [2]. The architecture is shown in Fig.1.

3. Hardware and devices

The body sensor node consists mainly of two parts: the **physiological signal sensors** and the **radio platform**, to which multiple body sensors can be connected. The general function of body sensors is to collect analog signals that are compatible with human physiological activities or body actions. Sensors and actuators are the basic components of WBANs. They collect the body vital signs and send that information to the coordinator. Because these sensors / actuators work in direct contact with human body or even implanted, their size and physical compatibility with human tissues are crucial. This stimulates the research and synthesis of new materials [2]. Table1 shows the most commonly used sensors in WBAN and their typical data rate.

Table 1: Sensors in WBAN and their typical data rate [2]

Sensor	***Topology***	***Data rate***
Accelerometer/gyroscope	Star	High
Blood glucose	Star	High
Blood pressure	Star	Low
CO2 gas sensor	Star	Very low
ECG sensor	Star	High
EEG sensor	Star	High
EMG sensor	Star	Very high
Pulse oximetry	Star	Low
Humidity	Star	Very low
Temperature	Star	Very low

Image/video sensor	P2P	Very high

There are many wireless technologies that were implemented in WBAN as the following:

3.1. IEEE 802.15.1 (Bluetooth) standard

IEEE 802.15.1 (Bluetooth) standard was adopted in the implementation of many telemedicine and e-health applications. But, some of the characteristics of this standard unsuitable for WBAN applications such as the higher power consumption[2], [3].

3.2. Bluetooth low energy

The Bluetooth-derived option is the low-power Bluetooth technology that was introduced as a more convenient option for WBAN applications where power consumption can be reduced by using a low duty cycle process. But, this an exaggerated low power duty cycles unsuitable for health monitoring applications as they frequently require repeated data reporting. In addition, this technology is still not supported by many devices on the market[2], [3].

3.3. IEEE 802.15.4 (ZigBee) standard

IEEE 802.15.4 (ZigBee) is widely used to implement WSNs, providing a greater coverage area and better performance under interference when compared to Bluetooth technology. Both Bluetooth and ZigBee work within the 2.4 GHz ISM range. Moreover, power consumption in ZigBee is about half to one third of the Bluetooth device. However, the ZigBee data rate is low, resulting in higher data delivery delays due to the decline of the longer channel which is critical in medical applications with urgent data. Therefore, ZigBee does not support QoS for all WBAN applications and cannot be scalable in terms of power consumption[2], [3].

3.4. IEEE 802.15.6 standard

Due to the limitations stated in Bluetooth and ZigBee, a new standard is needed to work properly with WBAN applications. Thus, IEEE 802.15.6 WBAN has recently been proposed as a promising wireless technology for low-power devices that used in the human body. This technology is specifically designed for the WBAN operating environment and it's a suitable choice for different applications in medicine, entertainment, and other fields. IEEE 802.15.6 uses different frequency bands for data transmission, including: The Narrowband (NB), which includes 400, 800,900 MHz, and 2.3 and 2.4 GHz bands; Ultra Wideband (UWB) using 3.1–11.2 GHz; However, some bands are not suitable for WBAN applications where they cannot support video or audio transmission or only are eligible for use by authorized users (such as UWB). Therefore, the researchers agreed that the 2.4 GHz band is the most attractive spectrum to be used in medical applications as well as its ability to protect adjacent channel interference[2], [3].

3.5. Low-power Wi-Fi

Another wireless technology, recently investigated in WSN applications, is low-power Wi-Fi (modified from the original IEEE 802.11 standard). The modified version includes less transmission power, recycling operation, and other power saving options. IEEE 802.11 has well-tested security and high QoS. In addition, devices that use Wi-Fi are pervasive at home, hospitals, banks, smartphones, etc. Thus, the integration of low-power Wi-Fi devices with surrounding networks is easy and their infrastructure already exists. Furthermore, low-power Wi-Fi is characterized by high data transfer rates which reduce transmission time for example units can switch to low-power sleep mode faster. Moreover, low-power Wi-Fi enables heavy traffic applications such as live video and audio monitoring. The use of Wi-Fi networks in WSN networks is to enable the IoT concept, which is also a promising technology for WBAN applications[2], [3].

4. Interference issues in WBAN

Due to the specialization of WBAN topology and applications, some problems need thoughtful considerations while designing WBAN systems. First, WBAN is sensitive to power consumption on regard that sensors operate with batteries. Since the sensor is deployed in the body surface or implanted inside the body there is a difficulty to replace the battery. It is therefore strongly recommended to improve energy efficiency. Second, as a major application of WBAN, the task of health monitoring is to obtain and transmit vital physiological signals, guaranteeing QoS in WBAN is important when trying to reduce energy consumption. Furthermore, the diverse requirements for applications, the heterogeneity of sensor nodes should also be considered [3]–[5].

However, things became more complicated when many people wearing WBANs come into a range of each other. In such a case there is no natural way to choose a network coordinator (hub). As a result of human mobility, network interference is a critical problem in WBANs. Equipped on human body, WBAN can move with the user. A number of WBANs may remain close to each other, causing inter-WBAN interference. Because there is no central coordinator between the WBAN units on the site, two sensor nodes from different WBANs may sent simultaneously. When working in the same channel, WBANs may suffer from packet collisions. Thus interference from WBAN (inter-WBAN interference) will become an inevitable issue[4], [6].

In addition, a common problem in all the wireless technologies used so far is the coexistence with other wireless systems. For example, as WBAN networks are used, such as in hospitals, home, and public areas, other Wi-Fi devices may exist and interfere. Most WBAN wireless technologies work in the 2.4 GHz ISM band, which interferes with other nearby wireless technologies operating on the same band [3]. In order to improve network performance, mitigation techniques must be implemented in WBAN system design[4].

As shown in figures 2 and 3, WBAN interference can be divided into two types that are intra-interference and inter-interference. An intra-network interference occurs between sensor nodes within the same WBAN due to the overlapping of data transmission. The effect of intra-interference is not greater than inter-interference and can be suppressed by improving MAC protocols [4]. Whereas an inter-network interference occurs between two WBANs close to each other called **mutual interference**, or between WBAN and other 2.4 GHz wireless networks such as Bluetooth, ZigBee or Wi-Fi called **cross interference**. Actually, the Wi-Fi effect on WBANs' performance, among the wireless technologies listed before, is the most crucial one. Next two subsections explain these two interference in IEEE 802.15.6 WBANs and Low power Wi-Fi.

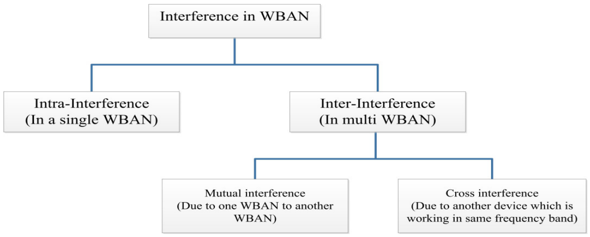

Figure 2: Interference taxonomy in WBAN [4]

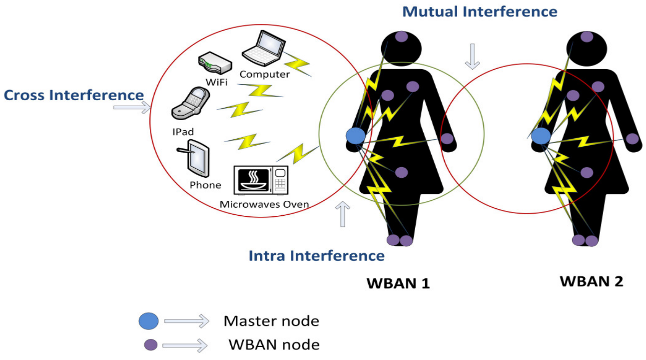

Fig3. Different interferences in WBAN

WBAN plays a key role in the future of e-health. To standardize WBAN schemas, IEEE creates 802.15.6 workgroup. WBAN sensors operate primarily on the 2.4 GHz free industrial, scientific and Medical (ISM) frequency. This feature makes this system not only easily applicable, but also susceptible to intrusion and interference by other devices operating in this range such as Wi-Fi and microwave oven. In addition, in some application scenarios, many WBANs may exist in near to each other and cause high mutual interference. Over-interference can lead to a severe degradation of network performance, which is too crucial to e-health applications. It is essential to fully understand the problem of network coexistence to ensure efficient WBAN networks. Since WBAN applications are often life critical, people are particularly interested in reliability, especially reliability in coexistence[7], [8].

4.1. Mutual interference

Mutual interference occurs between adjacent WBANs and it mainly affects the performance of the WBANs. The source of interference is from multiple sensors sending data to single personal data assistant (PDA) and multiple adjacent WBANs that are based on the same wireless technology [4].

4.1.1.1. Mathematical and analytical method

Wang X. and Cai L. [7] presented an analytical and mathematical study. They have analyzed and investigated the network mutual interference and the problem of coexistence with the network with densely deployed WBANs scenarios. They used the advanced Geometrical Probability approach to develop a probability distribution model for interference between coexisting WBANs. Also, they used a simple gamma distribution to give the approximate Probability Density Function (PDF) of the entire interference. The PDF is a tool for understanding the performance of the entire system for effective network planning and resource management. Moreover, they demonstrated their results using simulations. The interference model was used to find the minimum distance between nodes in any WBAN that maintains an acceptable Signal to Interference ratio (SIR) value. The simulated results demonstrated the validity of the model and verified its efficiency.

Pradnya H. et al [9], addressed the interference issue in WBAN via quantitative analysis and also they demonstrated the simulation based results using MATLAB. Analysis showed that the number of WBANs, transmission power of sensors as well as path loss exponent have a great impact on the level of interference. It appeared that for distances up to 2 m, the interference level is very high even for few number of coexisting WBANs.

Zhang A. and et al, [10] have presented a mathematical model for collision probability and mean SIR interference in the co-channel in WBAN networks. The researchers take into consideration three traditional access technologies in the media access control (MAC) layer including TDMA, FDMA and CDMA for Piconet coexistence while changing on both frequency channels number and interfering nodes number. They made the comparison while taking in mind the Collision Probability, signal to interference and noise ratio (SINR) statistics, and bit error rate (BER). They first made theoretical analysis of these schemas, and then simulate each diagram using real-world interference measurements. The results, in terms of bit error rate (BER) and Packet Loss Ratio (PLR), showed that interference in the same channel can significantly degrade system performance if left unchecked, and that TDMA and FDMA are better options than CDMA in terms of interference mitigation in the same channel. However, FDMA networks in synchronized networks have shown the best performance with respect to interference cancellation.

Hanlen L. W. et al, [11] considered WBAN interference analysis when people move randomly in an indoor office environment. The Distance-to-interferer was a weak estimate of the power of instantaneous interference and a less reliable estimate of the instantaneous SIR. Random signal fluctuations, even when the targets are stationary, dominate the loss of energy due to the distance because the direction of energy loss over 3 meters is steeped in the random variation in signal capacity. This paper has provided statistical and deterministic best-fits results for describing the effect of interference and stimulated the use of the median and statistical models of SIR. However, the time required to observe this trend is much longer than the typical runtime of the network, for example, packet length, or speed of motion, and thus limited value for a practical system.

4.1.1.2. Testbed and experimental model

An experimental, beside analytical study mentioned before, of the interference between several WBAN networks due to human movements in an indoor/outdoor environment carried out in [11] by Hanlen L. W. et al, at the offices of NICTA (National Information and Communications Limited Australia Ltd). The test consists of five people, each representing WBAN, who were moving within an office on a 6 m 9 m 6 grid, marked out on the carpet floor, with grid points at 1 m intervals. A dedicated device uses a channel design to measure the power received. The effect of distance between the nodes and their orientation on interference were investigated. It was stated that distance did not always have a significant effect on interference, especially for mobile WBAN, which was not the case in fixed WBAN networks. Transceivers' orientation had a significant impact on SIR, which was found to be larger for outdoor environments because of the shortage of multipath and reflections effects that typically found in indoor environments.

Hanlen L. W. et al also presented the same experiment, in another paper [12], at the offices of NICTA year before the paper [11]. The interference strength of multiple WBANs is compared when a group of people moves randomly within an indoor area, taking into account the distance between the moving persons. Signal-to-interference ratio (SIR) and interfering power levels are measured in five BAN units and compared in a closed environment. They found that a linear direction could be applied to the signal strength of the interference signal, but the direction was controlled by non-distance factors, which include subject movement - whether local such arm waving or universal like walking - and orientation. It has shown that the SIR may be low or even negative throughout the experiment.

Davenport D. M. et al, [13] presented an empirical test , beside a simulation. The researchers presented their study on three main components of the WBAN: On-body wireless link (to distinguish the RF channel of the worn wireless devices), coupling between bodies (to distinguish RF interaction between objects) and coexistence between WBAN in the RF spectrum. Also, they measured signal attenuation with different types of antennas on the nodes that were distributed in different places on the human body. To study the mutual interference caused by other WBAN interfering networks, a 10-person testbed unit was created with WBANs moving in an office, while there was no interference from other devices such as Wi-Fi or Bluetooth. PLR was calculated using simulations of various communication techniques, including Listen Before Talk (LBT), frequency hopping, and Automatic Repeat Request (ARQ). The results showed that the combination of LBT and ARQ gives the best performance on TDMA technology.

4.1.1.3. Simulation model

Igor Dotlic [14] analyzed mutual interference using simulation. The researcher evaluated the performance of the proposed physical layer, Impulse–Radio Ultra–Wideband (DPSK) physical layer, by exploring the operability of the IEEE 802.15.6 standard in different types of interference: Frequency Modulated Ultra–Wideband (FM-UWB), WiMAX and other co–located IEEE 802.15.6 Impulse–Radio Ultra–Wideband (IR-UWB) devices. In addition, different types of receivers were kept into account duty-cycled sampling receiver and chirp receiver that were being monitored to explore the probability of error at various stages of packet reception. Three co-existed WBAN networks were configured at the site to operate at different transmission power (TP) levels, two at the same levels and the third at a higher level. The results showed that under high traffic density, the chirp receiver was more immune to interference than the sampling receiver where the PLR was about 1% for up to 10 users at the same site. The chirp receiver showed much better performance in multiple BAN environments compared to the sampling receiver. However, the sampling receiver shows better performance in the IEEE 802.15.6 framework of FM-UWB and WiMAX interference types. However, both receiver architectures, chirp and sampling, were able to maintain relatively high levels of all interference types considered.

Igor Dutlitz, the author of [14], do similar work with another researcher in [15] .They analyzed the performance of the lowest data rates impulse-radio ultra-wideband (IR-UWB) DPSK physical layer in the IEEE 802.15.6 standard. The same two receiver architectures were introduced in this paper, sampling receiver and chirp receiver. The performance of these receiving architectures were analyzed by the probability of error at different stages of packet reception. The analysis was carried out in the presence of different types of interference frequency modulated ultra-wideband, WiMAX and, other co-located IEEE 802.15.6 impulse-radio ultra-wideband devices.

Simulation-based method to study the performance of multiple WBAN networks coexisting with collaborative communications using TDMA scheme was investigated in [16]. D. Jie and S. David investigated the coexistence performance of multiple WBAN networks. TDMA is used in inter-network, as well as intra-network, as multiple access scheme. Collaborative communications in WBAN-of-interest can be used to significantly reduce interference by providing up to 12 dB improvement in SINR. This optimization is maintained with a change in the coordinator location. However, different coordinator sites affect the overall performance of co-existence with on-body WBAN. There is a better SINR breakout performance when the coordinator was placed in the chest than when it is placed either in the left or right hips. Moreover, the movement of the body affects the reliability of WBAN performance significantly when there are many networks are located nearby. The simulation has shown that shadowing of the body helps WBAN to coexist when taking diversity into account.

Domenicali D. and Benedetto M. [17] examined WBAN performance under interference with BER as a function of a number of nodes and the level of synchronization between the nodes. It is used to provide useful thresholds for specific parameters to test the performance of the network architecture. This work analyzed the WBAN behavior of IEEE 802.15.4a UWB sensors. The BAN structure is proposed and investigated by simulation.

The mutual interference between UWB-BANs has been analyzed by simulation in [18]. The researchers analyzed the interference between two different BAN systems in a UWB-based system in terms of the acceptable interference ratio between the BANs Processing Gain (PG) providing the required QoS for each BAN. The first BAN is used as a healthcare device (e.g. EEG, ECG, etc.) with a relatively longer spreading sequence and the second BAN is used in entertainment application (for example, a wireless headset, a wireless game pad, etc.) with a shorter spreading code. Taking bandwidth usage and the used spreading sequence into account, the acceptable ratio of interference between these BANs should be between 0.05 and 0.5 to improve the spreading sequence used and, at the same time, to meet the quality of service required for these applications. In addition, they suggested that they need to analyze the system using the full channel capacity and the maximum number of users allowed in different applications.

4.1.2. Cross interference

The cross interference occurs when networks rely on different wireless technologies operating in the same frequency bands. The cross-interference scenario is very complex to deal with in real-time because there are different wireless standards that use different protocols, power settings, and packet sizes [4].

4.1.2.1. Mathematical and analytical method

Analytical-Based modeling of coexistence of IEEE 802.15.6 WBANs UWB has been studied mathematically in [19]. The researchers studied the interference effect of both IEEE 802.15.4a (pico-nets) and IEEE 802.15.4f (RFID) on IEEE 802.15.6 WBAN devices. Analytical models were presented for the transmitted signals, antenna power, and signal-to-interference-plus noise ratio (SINR). Nevertheless, the dynamic nature of the UWB has made finding a closed form of BER or PLR unrealistic, therefore, simulations have been used to obtain numerical results on the interference effect. It was found that the mutual interference between up to 10 interfering WBAN networks could be tolerated, for example the Bit Error Rate (BER) was not affected. Moreover, interference from IEEE 802.15.4f devices was higher compared with IEEE 802.15.4a.

Mucchi L. and Carpini A. [20] performed a mathematical method on different environments such as the hospital, home, and office based on WBAN power distortion due to interference. The best suitable Probability Density Functions (PDFs) were developed for each case. Moreover, in this paper, a measurement was conducted to collect the interference power levels of the modern city's hospital, office and, home. Data was collected at various locations during a typical busy day. The data was used to show typical interference levels in the ISM band. The best distributions for each frequency and place were derived. For each distribution the main parameters of the best PDF were derived. Interference behavior can therefore be reproduced to test and design the use of wireless body area networks at the main sites where the monitored patient stayed most of the time such as home, office, and hospital. They concluded that interference is not dramatic in hospital, home and office environments to justify additional intelligence, and hence complexity, in WBAN transceivers. Of course, this was true in Italy, other countries can experience different levels of interference in the ISM band in those environments.

4.1.2.2. Testbed and experimental model

Mucchi L. and Carpini A. [20] also conducted an experiment to analyze the cross network interference, beside an analytical model as stated before, due to the unexpected impact of other networks on WBAN networks. The authors of this paper have conducted experiments in different environments such as hospital, home, and office. The experiment was based on WBAN power distortion caused by interference. The best PDFs are optimized for each case.

4.1.2.3. Simulation method

Cross-interference in IEEE 802.15.6 WBANs with other technologies in both the UWB and ISM bands were studied using simulations. Thaier Hayajneh et al [3] made a comprehensive study and in depth analysis of coexistence issues and interference mitigation solutions. They introduced a mathematical analysis of coexistence to find the probability of successful channel access for different wireless technologies on the interfering network. To evaluate the coexistence between wireless technologies, they made an extensive simulation using OPNET with real life scenarios. They considered three main WBAN wireless technologies: IEEE 802.15.6, IEEE 802.15.4, and low-power Wi-Fi. The results showed that an interfering network (e.g., standard Wi-Fi) has an impact on the performance of WBAN and may disrupt its operation.

In addition to studying mutual interference in IEEE 802.15.6 WBAN, Igor Dotlic [14] also explored coexistence with WiMAX devices in the UWB. The interfering WiMAX network was operating in a small and large bandwidth. Sampling and chirp receivers experienced a higher proportion of PLR than only on mutual interference. Nevertheless, the chirp receiver showed much better performance in multiple BAN environments compared to the sampling receiver. On the other hand, the sampling receiver showed better performance under IEEE 802.15.6 FM-UWB and WiMAX interference. However, both receiver architectures were able to maintain relatively high levels of all the considered interference types.

WBANs coexistence issues at the 2.45 GHz ISM band with both IEEE 802.11 (Wi-Fi) and IEEE 802.15.4 (ZigBee) was investigated in [21]. The simulated environment contained different node types that were deployed in a single room. Five WBAN nodes distributed on the human body, two Wi-Fi nodes, and five ZigBee nodes. The authors looked at a channel model that contributes to both body proliferation and mobility effects. Moreover, they studied the performance of various modulation schemes and medium access techniques. An analytical model for BER was derived for all physical modeling techniques for calculating PLR during simulation. Under MSK (Minimum Shift Keying) modulation, the MAC of IEEE 802.15.6 performed better than the MAC of ZigBee. The modified MSK and Gaussian MSK (GMSK) modulation had similar PLR values regardless of the interference. This is because the loss of packets due to the high sensitivity of the receiver in these schematics rather than interference. Packets delay and energy consumption of nodes increased slightly with interference compared with PLR which increased significantly. IEEE 802.15.6 MAC showed a better delay than the IEEE 802.15.4 MAC but consumes more power due to a longer medium listening time. The performance of WBAN system based on IEEE 802.15.6 was evaluated for three different physical layers and two different Carrier Sense Multiple Access with Collision Avoidance algorithms.

Wang and Wang [8] have evaluated the performance of the 2.4GHz of 802.15.6 WBAN under the interference of Wi-Fi and Bluetooth in the context of multi-parameter medical surveillance. The simulated network consists of a monitor and four ECG electrodes that send data to the monitor. An interfering mobile station, initially set up as a Wi-Fi station then replaced with a Bluetooth station, exchanged FTP traffic with the Access Point. The distance between the mobile station and WBAN varied, and PLR was calculated in addition to Mean Time To Fail (MTTF), the time the network failed to correctly move any packet. As expected, PLR increased and MTTF decreased as the distance increased. Performance degradation was larger when a Wi-Fi station was used instead of a Bluetooth station because Wi-Fi has a higher signal power and occupies larger bandwidth.

WBAN performance was examined in a home environment due to microwave radiation and Wi-Fi interference in [22]. The authors considered three genetic algorithms for interference analysis through simulations: SPEA-II, NSGA-II, and OMOPSO. They examined energy efficiency and throughput which were important issues in such systems. These issues are affected by an important factor such as the packet error rate (PER) parameter that indicates the number of incorrectly received packets divided by the number of all packets received. This factor increases when interference, attenuation, and noise occur by other devices on the network. The results showed that the NSGA-II algorithm outperforms the OMOPSO and SPEA-II algorithms for performance measures.

Hernandez M. and Miura R. [23] have studied the coexistence of UWB devices of IEEE Std 802.15.6-2012 with other UWB systems especially IEEE Std 802.15.4a-2007(pico-nets) and IEEE 802.15.4f-2012 (RFID) devices. The recently published IEEE Std 802.15.6TM-2012 includes IR-UWB and FM-UWB technologies. The IR-UWB transceivers for BANs are based on transmission of a single and relative long pulse per symbol, new paradigm in UWB, or a series of short pulses per symbol (legacy), whereas FM-UWB transmitters and receivers are based on the CP-2FSK and a broadband FM signal. Thus, the coexistence of UWB devices becomes very important for reliable operation in medical applications. They concluded that the BAN, which contains UWB 15.6 devices in the default mode, will not be affected by at least 10 FM-UWB interference devices in the same BAN during the competition period. On the other hand, 15.6 UWB devices are not likely to be affected by the default method in band 6 by at least 10 15.4a or 15.4f interference devices unless there is an approximate degradation of 15 dB m in S.

4.2. Interference in Low power Wi-Fi

The original operation of the Wi-Fi technology has been modified to suit the requirements of sensor networks. These include low transmission power, cycling process, etc. This is done to meet one of the basic design requirements for WSN networks, that is, the maximum lifetime of the battery. Many Wi-Fi enabled devices / sensors found on the market which makes the use of low power Wi-Fi more beneficial[3]. There has been no careful study of the use of low-power Wi-Fi networks for WBAN and WSN in previous research. Thaier Hayajneh et al [3] investigated using low-power Wi-Fi for WBANs in comparison to other wireless technologies such as IEEE 802.15.6 and IEEE 802.15.4. Low-power Wi-Fi has been proved to be a feasible option.

Coexistence with the experimental of heavy-duty Wi-Fi network was studied in [24]. Evaluation of power consumption of Wi-Fi enabled devices for each scenario, checking for interference impact, and measurement of range performance were conducted. Two different scenarios were considered; on the first one, low-power Wi-Fi and Wi-Fi standard nodes were associated with different access points, while on the second scenario they were connected to the same access point. Network performance is reported in terms of Packet Delivery Ratio (PDR) and Round Trip Time (RTT) for different packet sizes and data rates. A low-power Wi-Fi nodes were found to perform better in the first scenario, when it was associated with its own access point. However, they have experienced more packet loss and greater packet delay when working with standard Wi-Fi nodes on the same access point. Furthermore, it was found that PDR and RTT in this case had better values when the nodes used a low data rate, i.e. 1 Mbps, and small packet sizes. In addition, using a low data rate extends the range of communication in low-power Wi-Fi nodes.

5. Interference mitigation schemes

To improve WBAN system performance, mitigation techniques should be considered. Interference mitigation schemes’ goal is reducing the average transmission power using link adaptation mechanisms while maintaining link quality at the cost of low data rate throughput. However, interference mitigation methods in WSNs and MANETs cannot be used in WBAN. Also, since WBAN networks are limited in cost, size and power consumption, the function of each sensor node must be very simple. Thus, advanced antenna techniques cannot be used to mitigate interference in WBAN networks. [25].

5.1. Mutual interference mitigation

5.1.1. MAC Approach

MAC sub-layer is responsible of a number of functions including control of access to the physical transmission medium, frame delimiting and recognition, conveyance of source station addressing information and protection against errors[26]. Interference between WBAN networks can be mitigated by switching their work channel or manually scheduling superframe. In this method, the MAC protocol is explored to increase throughput and reduce transmission power while mitigating interference[27].

Cheng S. H. and Huang C. Y. [28] proposed a Random incomplete coloring (RIC) to reduce interference between WBAN coexisting networks. The suggested method is designed as a graph coloring problem. In the higher interference environment, the proposed method outperforms conventional coloring methods by obtaining higher spatial reuse, fast convergence, and higher throughput. It is a less complex coloring method designed for fast inter-WBAN scheduling (IWS). The authors have made mathematical analysis and conducted extensive simulations to prove the effectiveness of the proposed solution. The RIC algorithm was proposed to achieve rapid and high spatial-reuse inter-WBAN scheduling. In order to improve spatial reuse in each channel usage, the RIC algorithm chooses a subset of WBANs that share a location that does not interfere with each other to be active. Incomplete coloring is performed periodically to allow a fair share of the spectrum resource among all WBAN networks. However, they take into account scheduling among WBANs but not the node level interference, so spatial reuse is not used optimally.

An improvement of the Random incomplete coloring (RIC) introduced in [25], the researchers have taken a step forward and consider node-level interference mitigation to maximize the spatial reuse. More specifically, they allow nodes from different WBANs with lower interference levels to transmit on the same channel while high interference nodes to transmit orthogonally. They have proposed a dynamic resource allocation scheme to avoid interference amongst coexisting WBANs. In the proposed schema, each WBAN creates a table containing interfering nodes from nearby WBAN networks. Each WBAN then broadcasts this table to its neighbors, allowing for an effective interpretation of the Interference Region (IR) between each WBAN pair. The nodes in the IR are later allocated orthogonal sub-channels; while the nodes that are not in the IR can transmit in the same time period. Moreover, the proposed scheme did not add any complexity to the sensor nodes because all calculations are performed by the coordinators (master nodes). Also, there is a tradeoff between the SINR level and the spatial reuse value which helps in choosing the interference threshold in an adaptation to the lower interference level. This means that a lower interference threshold is selected when the minimum interference level is relatively low. Otherwise, higher values should be specified for the interference threshold. The proposed scheme has been evaluated by simulation showing 20 times higher spatial reuse than conventional orthogonal channel assignment amongst all nodes in WBANs and 16 times higher spatial reuse than the color based approach in [28].

Similar to [25], Mohamad Ali et al in [29] proposed a distributed orthogonal code allocation scheme to avoid interference between WBAN coexisting networks. They considered interference at the sensor and time-slot levels. First, they proposed distributed orthogonal code allocation scheme called OCAIM, where each WBAN generates sensor interference lists (SIL), and then all the sensors belonging to these lists are allocated orthogonal codes. Second, it proposed a distributed time reference correlation scheme (DTRC), which is used as a core block of OCAIM. DTRC is a scheme used to determine which superframes and corresponding times slots interfere with each other. DTRC enables each WBAN to create a virtual time-based pattern to connect different super-frames. Finally, they analyze further the probability of success and collision of frames transmissions when the number of co-existence WBAN networks increases. Simulation results and theoretical analysis showed that the proposed approach can significantly increase the minimum signal to interference plus noise ratio (SINR) and energy savings per WBAN. In addition, the proposed scheme significantly reduces the level of interference between WBAN and adds no complexity to the sensors as the coordinators (master nodes) are only required to calculate and negotiate for orthogonal code assignment.

While all the previous approaches used centralized controlled multiple access mechanism, W. Huang and T. Q. S. Quek proposed two-layer MAC (2L-MAC) [5] which makes use of CSMA/CA technique for a higher flexibility to better cope with the dynamics/mobility of the WBAN networks. The 2L-MAC interference mitigation scheme is proposed to avoid both intra- and inter-WBAN interferences. The protocol is presented with two algorithms, polling with the back off mechanism and channel switching. To coordinate the inter-BAN transmissions, polling is implemented and to reduce the inter-BAN interference, a carrier sensing mechanism is adopted. Before polling a carrier sensing is performed, the data is transmitted only if channel state is idle else it holds the polling and performs back off. It means that in the polling with backoff mechanism, the hub performs carrier-sensing to check the channel state before sending an intra-WBAN poll frame. If the channel is idle, the hub sends a polling frame to the sensor nodes. When nodes receive the polling frame, they send data to the hub within the SIFS (short interframe space) period. If the channel is busy, the hub performs the backoff procedure and waits until the channel is idle. This reduces the packet collisions with the constraints of QoS requirements by implementing sensor priorities. By implementing channel switching in the proposed method, the performance has notably improved.

The 2L-MAC outperforms beacon shifting, channel hopping, and B2IRS in terms of delivery performance and energy efficiency. It resolves collisions well with multiple wireless channels, but the polling frame for each packet introduces extra overhead, which limits the network throughput and increases packet delivery latency. Also, the scheme is non-adaptive in the sense that at each polling the coordinator only schedule one node for transmission regardless of the interference level. Such design is appropriate when the number of coexisting WBANs is relatively large; but when the interference level is low, this might lead to a low throughput and delay performance. Moreover, this paper did not specify any sensing or sleeping mechanism for the sensor nodes. It only assumes that the nodes will be awake whenever the coordinator sends the polling message. Nevertheless, since the coordinators adopt random backoff timers, it is impossible to accurately predict the sleeping and wakeup time for the sensor nodes.

Huang W. and Quek Q. S. T. [6] have solved the problems with 2L-MAC. First, they make the length of each polling period/MAC frame adaptive to the interference level. That is, if the coordinator senses significant interference from the surrounding WBAN networks, this will reduce the length of the MAC frame to allow other WBANs to have a shorter transmission delay; otherwise, it will increase the length of the MAC frame to allow more transmissions from nodes. Second, they propose a practical sleeping and sensing mechanism for the sensor nodes as well as an equivalent polling technique using a busy tune for the coordinators. Compared to 2L-MAC, the proposed protocol is more flexible and adaptive and works efficiently in both sparse and dense scenarios. It provides a higher throughput independent of a number of WBAN networks that coexist with low power consumption which makes it meet WBAN sensor QoS requirements. Also, the proposed method achieved an increase in performance of approximately 14% greater than 2L-MAC. Moreover, they proposed an adaptive CSMA/CA (A-CSMA/CA) MAC protocol. Similar to 2L-MAC, they combined polling with carrier sensing to avoid inter-WBAN interference. Before each polling, the coordinator will randomly choose backoff timer based on its contention window size (CWS) to reduce the probability of collision of the polling message from several WBAN networks. The coordinator then makes clear channel assessment (CCA) for a backoff slot time to ensure that no other WBANs have ongoing transmissions. If the channel is busy, the coordinator will hold the backoff timer; otherwise, it reduces its backoff by 1. Once the backoff timer reaches zero, the coordinator will send its polling message / beacon to its sensor nodes. Following the beacon will be the rest of the frame that contains all the scheduled intra- WBAN transmissions.

Yuan B. et al, [30], proposed a decentralized interference mitigation scheme called DIM for inter-WBAN. Instead of using public information or exchanging information between WBAN networks at a regular time interval, which offers an additional overhead that limits the network throughput and increases packet delivery latency, as in 2L-MAC, they used only the network performance information that each node will receive within its WBAN domain. Also, they considered interference mitigation at the node-level to improve the channel utility as an improvement to RIC mentioned previously. Their work is based on the superframe with beacon mode, the most widely used method by researchers and developers. The superframe is divided into Beacon period, scheduling phase (SP) and contention access phase (CAP), where DIM uses CSMA / CA for CAP and scheduling for SP. The coordinator (hub) will dynamically adjust the length between SP and CAP according to its recent network performance. Specifically, the SP length will be reduced when channel utilization is low in SP, and will be expanded on the contrary. DIM combines SINR and interference performance. The nodes in the overlapping region tends to be interfered and will get lower access priority. The coordinator allocates slots for nodes based on the DIM algorithm. The simulation results show that the DIM algorithm establishes much higher throughput and lower latency under the interference scenario.

5.1.2. Power Control Approach

WBAN sensor power consumption is an important factor that affect battery lifespan along with the network. Since sensors are implanted in or placed on the human body, it is crucial to minimize energy consumption and save energy especially for implanted sensors. As a result, interference mitigation schemes have to focus on energy consumption as well as on quality and throughput in the interference environment [27].

Yong Xu et al, [31], proposed a non-cooperative, distributed, and self-adaptive power-control algorithm based on game theory to solve interference from nearby WBAN networks called Optimal Response Iteration Strategy (ORI). This algorithm considered the effect of the wireless channel status, the QoS required, and the power threshold. The paper analyzed and demonstrated the presence and uniqueness of the Nash equilibrium (NE) and then suggested an ORI strategy to reach the NE point. They compare the ORI algorithm with the K-G [32] and PAPU [33] algorithms and show that ORI can effectively reduce the impact of inter-network interference by selecting the appropriate channel and transmitting power. The ORI algorithm outperforms K-G and PAPU on terms of total utility, power consumption, and speed of convergence. In addition, simulation results showed the effect of proposed energy prices on utilities, energy consumption, and convergence.

Zou L. et al, [34] used Bayesian Game based power control scheme. The Bayesian game model reflects the diversity of links within intra-WBAN and the independence of WBAN connections. The proposed scheme can also achieve a trade-off between throughput and energy consumption. Taking into account the multi-link functionality within the WBAN network in the Bayesian Game, WBANs are considered as players and active links are types of players. It also established a Bayesian balance and derives a sufficient operational condition for Bayesian equilibrium (BE). To approximate BE in a non-cooperative manner, they proposed a distributed algorithm that did not need to pass messages between WBAN networks which makes it a fully distributed scheme. This harmonic algorithm is proposed on an average basis to obtain the approximate BE value.

Simulation shows that the algorithm approximates the BE point effectively. They have accomplished maximum benefit while reducing energy consumption, but whether WBAN is satisfied with the performance of the obtained throughput has not been considered in the literature. WBAN may receive redundant throughput performance and cause unnecessary energy waste.

By focusing on a more practical WBAN model, Zhao X. [35] et al, proposed a non-cooperative power control game to mitigate WBAN interference, where the cost function is well designed by considering both QoS and power consumption constraint requirements. The utility function is well designed so that the QoS requirements can be addressed with a small power consumption for each WBAN. At least one Nash equilibrium (NE) of the game has been demonstrated, and enough NE has been derived. The exact value of the NE point cannot be easily obtained due to lack of cooperation between WBAN networks. To overcome this problem, they proposed a non-cooperative interference segmentation estimate (ISE) based on the historical interference information received to approximate the NE point, ensuring that the information is not shared between the WBAN network coordinator. Simulation results showed the effectiveness of the proposed ISE algorithm. Lee C. and Lee J. [36] proposed a transmission power adjustment algorithm (FTPC-U algorithm) which addresses interference problems and ensures QoS fairness among users. First of all, the function of the tool is defined, which indicates how closely the current data rate matches the required data rate. Second, based on information from neighboring WBAN networks, each network concludes the necessary transmission power for QoS value to the average QoS satisfaction value of the neighboring WBANs. They used the Cucker-Smale model to calculate the appropriate transmission power per user. The Cucker-Smale model is typically used to simulate the phenomena in which organisms move in groups using limited information. The model is therefore suitable for the WBAN environment where transmission power must be controlled in a distributed manner. Moreover, the Cucker-Smale model can be applied to solve the problem of fair distribution of satisfactory QoS in all adjacent WBAN networks because it synchronizes the variables specified for each entity with the same value. Simulation results showed that the proposed algorithm performs better than existing algorithms with considering QoS fairness and energy efficiency.

Table2: Comparison of the mutual interference mitigation schemes in the MAC approach

Interference Mitigation Scheme	*Throughput*	*Spatial Reuse*	*Collaborative Method*	*Mobility Support*	*QoS Guarantees*	*Channel Access*	*End-to End delay*	*Number of WBANs*	*Mathematical*	*Simulation*
RIC[28]	Medium	Medium	Yes	No	No	TDMA	High	High	Yes	Yes
Smart Spectrum[25]	Medium	High	Yes	No	No	TDMA	High	High	Yes	Yes
OCAIM, DTRC[29]	Medium	High	Yes	No	No	TDMA	Medium	Medium	Yes	Yes
2L-MAC[5]	High	No	No	Yes	Yes	TDMA	High	Medium	No	Yes
Adaptive CSMA/CA[6]	High	Low	Yes	Yes	Yes	TDMA	Medium	Medium	No	Yes
DIM[30]	High	No	No	No	Yes	TDMA	Low	Low	Yes	Yes

Table3: Comparison of the mutual interference mitigation schemes in the power control approach

Interference mitigation scheme	*Throughput*	*Energy consumption*	*Mobility Support*	*QoS Guarantees*	*Tradeoff*	*Cooperative*	*Game Theory*	*Mathematical*	*Simulation*
A Self-Adaptive Power Control[31]	Medium	Low	Yes	Yes	High	No	Yes	Yes	Yes
Bayesian Game Power Control[34]	High	Medium	Yes	Yes	High	No	Yes	Yes	Yes
QoS-Driven Power Control[35]	Medium	Low	No	Yes (High)	High	No	Yes	Yes	yes
QoS-based[36]	Medium	Low	No	Yes (High)	Low	No	No	Yes	Yes

6. Comparison and discussion

6.1. Mac Approach

The coloring method proposed in [28] supports medium throughput and medium spatial reuse in WBANs while supporting lower power consumption because a beacon is transmitted by the coordinators to indicate which sensor can transmit. When a transmission is suspended, wasted energy is low. Despite these advantages, RIC does not consider the mobility of WBANs or the QoS requirement of the vital signal in the superframe. The priority of each sensor in WBANs is not considered because this algorithm colors nodes randomly. The node that transmits a vital signal may not be colored and therefore may not transmit, which could cause a dangerous situation in healthcare service scenarios [27]. The researchers take into account scheduling among WBANs but not the node level interference, so spatial reuse is not used optimally. Smart spectrum allocation in [25], aimed to increase the channel reuse as well as maintaining a tolerable interference level. Smart spectrum supports medium throughput and high spatial reuse because the researchers have taken a step forward by considering node-level interference mitigation to maximize the spatial reuse. More specifically, the nodes from different WBANs with lower interference levels can transmit on the same channel while high interference nodes transmit orthogonally. Thus, limited resources in WBANs are used much more efficiently, which results in a higher network lifetime and much longer depletion time. However, the researchers do not take QoS into account while designing their approach.

The approach used in [29] is similar to [25], orthogonal code allocation scheme was proposed to avoid interference between co-existing WBAN networks. The interference was considered at the sensor and time-slot levels. Medium throughput and high spatial reuse were supported but not enough support for QoS. 2L-MAC in [5], supports dynamics/mobility of the WBAN networks. Also, it supports high throughput and took QoS into account in the proposed scheme. However, the scheme is non-adaptive because, at each polling, the coordinator only schedule one node for transmission regardless of the interference level. Such design is appropriate when the number of coexisting WBANs is relatively large; but when the interference level is low, this might lead to a low throughput and delay performance. This work did not specify any sensing or sleeping mechanism for the sensor nodes. Moreover, it does not make effective spatial reuse. Furthermore, the end-to-end delay is large because of the back-off mechanism.

The proposed protocol in [7] is adaptive and shows both better throughput and delay performance under all scenarios. The researchers argued that the presented framework is also flexible and give some directions on how to incorporate multi-channel and QoS support into the protocol. Nevertheless, power control is not supported to further improve the energy efficiency of the sensors. A novel DIM algorithm was proposed in [32] to enhance WBANs performance under co-channel interference. DIM combines the advantage of CSMA/CA and scheduling methods. It supports a relative high throughput and low Latency. On the contrary, no spatial reuse is mentioned in this work.

Table 2, shows a comparison between the investigated papers on terms of throughput, spatial reuse, QoS guarantee, Channel access, End-to-end delay, and whether the investigated work does provide mathematical approach, simulation approach, or both.

6.2. Power control approach

ORI [31] is a non-cooperative, distributed, and self-adaptive power-control algorithm based on game theory . ORI represents a high tradeoff between network utility and power consumption and has lower power consumption by sacrificing little utility. Also, it makes guarantee of QoS. Nevertheless, ORI does not consider dynamic channels environments and nodes mobility. Moreover, it does not focus on the design of MAC protocols to support this self-adaptive power control algorithm.
The Bayesian Game Power Control [34] considers the tradeoff between power consumption and throughput. The Bayesian Game takes sensor node into account by scheduling each sensor node's transmission in its own channel based on the type of sensors. Therefore, WBAN can adapt its power at the node level based on the information about the dynamic environment or the type of the node. The main advantage of the Bayesian game is that it works without exchanging data between WBANs. However, the severity of the interference at each sensor node is not considered, nor is the convergence time.

A non-cooperative power control game was proposed in [35], on which the cost function is well designed by considering both QoS and power consumption constraint requirements. This approach does support tradeoff between SINR squared error and power consumption. But, it does not consider the mobility of WBANs' nodes. In [36], the researchers proposed the FTPC-U algorithm using the Cucker-Smale model to solve interference problems that occur in the WBAN environment, and to guarantee QoS fairness between users. But like [35] , it does not consider the mobility of WBANs' nodes.

There is a need for an analytical tradeoff between network throughput and power consumption. Quality of Service, Delay, Reliability, and network lifespan should also be considered with interference mitigation design. Table 3 conducts a comparison between the four papers on throughput, energy consumption, mobility support, QoS support, game theory, tradeoff between throughput and energy consumption, and does the paper use the mathematical approach, simulation approach, or both.

7. Open research issues and challenges

7.1. Power Consumption

Power consumption is one of the main objectives of any WBAN application to ensure the long life of the sensor. Because of the size of its portable batteries, which cannot be replaced or recharged easily especially on implanted ones, the power capacities of sensor nodes are limited [37]. In addition, because of the interference, the power consumption increases due to competition to access the channel, retransmission of interfered data, and the idle listening channel. A good tradeoff between performance and power consumption is needed to ensure that the interference mitigation schemes work effectively, which means the good interference technique can increase the battery lifetime[4].

7.2. The effect on the Human Body

Since biometric sensors are planted in or placed on the human body, raise in the temperature causes damage to the tissues in the human body so the WBAN should be designed to take the node temperature control on account. The thermal alert routing algorithm can help avoid thermal radiation [38]. Furthermore, RF radiation can negatively affect the human body. RF radiation has been investigated in interaction with biological systems in terms of both thermal and non-thermal biological effects [39].

7.3. Mobility issue

Interference problems are increased by increasing the number of nodes. Also, when the WBAN network becomes mobile due to patient's movement, the interference problem arises [40]. Several research was conducted to reduce interference in the fixed state of WBAN. It is necessary to design a technique or protocol to mitigate the interference at the mobile and dynamic environment in order to better respond to the quality of service[3], [4].

7.4. Interoperability issue

WBANs have the ability to suppress interference by working independently without negotiating or sharing information with other WBAN networks. On this non-negotiated methods, WBAN needs to improve its performance, converge quickly, and recognize the network system on its own. On the negotiation methods, exchanging information between WBAN networks may cause long delays or slow affinity, but WBANs perform better if they are familiar with the entire network system [4].

7.5. Quality of Services (QoS)

QoS is important and crucial in WBANs. It is necessary to have high QoS under emergency conditions and continuous monitoring. WBANs contain QoS requirements for each type of sensor or application[41], [42]. Specifically, the QoS constraint depends on the bit error rate (BER) or the transmitted signal priority. Interference can result in degradation of the quality of service in the system. In a hospital intervention or a long queue in a public place, high quality QoS networks must be of higher priority to access the channel because they may carry vital data about a chronic disease such as heart disease. In order to achieve good throughput, minimum delay, non-redundancy and reliability, there is a need for good MAC and routing protocols [43].

7.6. Reliability

Reliability is considered in terms of packet delay and the possibility of packet loss. The end-to-end delay of data received depends on the WBAN application; for example, the delay of the ECG signal and the video signal should be less than 250 ms and 20 ms, respectively [38]. Moreover, in the case of WBAN interference, it leads to low end-to-end delay when the WBAN returns quickly to a stable state after interference. Moreover, the packet loss probability determines the extent to which the packet drop rate affects WBAN reliability in terms of bit error rate (BER) or packet error rate (PER) [27].

7.7. Security and privacy requirement

WBAN data is transported wirelessly. Therefore, security and privacy issues are very important and have to be considered. Data privacy must be guaranteed and this means the data can only be accessed by authorized persons for further analysis. Sangawana A. and Bhattacharya P. P. [44] discussed the requirements for data storage and data access security in WBAN. They considered the requirements that manages security such as confidentiality, integrity, and reliability. To access the data, the security requirements are to access control, accountability, revocability, and non-repudiation. Based on the two-tier architecture, the authors of [45] developed a lightweight trust management and an attack resistant called ReTrust. Security analysis and experimental results showed that ReTrust is feasible to improve the network performance and security of real medical sensor networks (MSN) applications. The experimental results of the Collection Tree Protocol, using their proposed TelosB network system, showed that ReTrust can not only detect malicious / malformed behaviors efficiently, but can also significantly improve network performance in practice.

8. Conclusions

Interference is dangerous in WBAN networks because it affects WBANs' performance and reliability. In medical applications, it puts the patient's health at risk. Therefore, the adoption of interference mitigation plans is mandatory in WBAN design. In this survey, the coexistence of WBAN networks with respect to interference problems has been reviewed, the current mitigation plans for WBAN have been classified, and the WBAN mutual interference mitigation schemes were introduced and compared qualitatively. This survey has recommended a mitigation scheme that take the merits of the two discussed approaches, MAC approach and power control approach. Although many interference mitigation schemes are reported, there is no dominant scheme that outperforms other systems. There is a need for an analytical tradeoff between network throughput and power consumption. Quality of Service, Delay, Reliability, and network lifespan should also be considered with interference mitigation design. Because the performance and QoS of WBANs are severely affected by interference, various interference mitigation algorithms will be developed in the future. Finally, some open research issues have been introduced to be a useful source of inspiration for future research directions.

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