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A Survey on Interference Mitigation for Wireless Body Area Networks

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Abstract

Wireless body area networks (WBANs) are noteworthy, dependable, and most advantageous development in many health directed applications. WBANs in health system connect tiny sensors to invasive or non-invasive medical equipment for patient examinations utilizing low power wireless technology. When WBANs are utilized in crowded areas or in conjunction with other wireless sensor networks, communication interference can arise. This can lead to unstable signal integrity, which can impair system performance. Thus, interference mitigation needs to be taken into account when designing. In this paper we survey interference mitigation methods used in WBANs, classify them, and finally point to some future research directions in this area. In particular, we start by reviewing sample papers that tackle the interference management problem through classical signal processing and shaping methods. Then we review some works on cooperative communications approaches to encounter this problem. After that we consider approaches that are not centralized through the use of game theoretic formulations. We close our discussion by surveying model free algorithm through learning based approaches.

Keywords— Interference mitigation, Wireless body area network, IEEE 802.15.6, Power control, Learning, Game theory, Optimization.

1 Introduction

These days, technology is a big aspect of our everyday life. New developments in wireless communication and microelectronics have made it possible to low-power, intelligent implants to communicate inside the human body forming what is known as wireless body area networks (WBANs). WABNs allow for the continuous monitoring of physiological condition in both immobile and mobile settings (M. J. Ali, 2017). WBANs use wireless sensor nodes on the body to remotely monitor physiological factors like blood pressure, temperature, heart rate, and blood sugar levels (Yaghoubi et al., 2022). WBANs can lower patient care expenses by monitoring vital sign data. WBANs are utilized in several applications incorporate medical behavior to sports, and military (M. Ali et al., 2016b). Several standards, including IEEE 802.15.4 and IEEE 802.15.6 are manipulated by WBAN (Rajasekaran et al., 2024). In wireless communication for a certain collection, IEEE 802.15.4 usages protocols like the media access control (MAC) layer and the physical layer (PHY). It also supports lower bit rates, reduced costs, and lower power consumption.

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The IEEE 802.15.6 standard for WBAN defines medium access control and physical sublayers for low-complexity, low-power operation of sensing nodes within or near the human body (George & Jacob, 2020). There are various challenges in WBANs MAC protocol such as security and privacy concerns which are main requirements in WBAN (Rajasekaran et al., 2024). Since more patients are using WBAN, it is important to keep patient authenticated data separate to avoid sharing patient information. Another challenge is the reliability of WBAN. This can be addressed by utilizing a variety of retransmission strategies, adaptive scheduling strategies, and transmission mechanisms. The throughput in WBANs is another concern that needs to be addressed. This can be attained by exploitation many traffic priorities styles, such as scheduling techniques. Finally, the interference is a big source of concern in any wireless transmission system. Interference is generated from different sources such as the use of industrial, scientific and medical (ISM) frequency bands as well as other wireless devices are expected to coexist with WBAN. This coexistence can produce interference which might hamper reliability of these networks.

Within the WBAN standard, there is an enormous range of applications. Moreover, a few of those applications are implanted inside the body, worn on garments, placed close to the body, and directly on the body. Applications can be broadly divided into two categories: medical and non-medical (Al-Sofi et al., 2023). WBAN technologies are standardized by the IEEE 802.15.6 group, which mandates that systems be able to manage up to ten shared networks and function within a three-meter transmitting limits (Xuan Wang & Lin Cai, 2011).

This paper presents a review of existing interference mitigation techniques used in WBANs. In Section 2, we introduce a standard WBAN architecture. Section 3 presents some common WBANs' interference scenarios. In Section 4 we discuss the existing interference management schemes. Section 5 provides some suggested future research directions for the subject under investigation. Finally, the paper conclusions are presented in Section 6.

2 Architecture of WBAN

WBAN architecture includes three tiers, which are the intra-WBAN communication tier, the inter-WBAN communication tier and the beyond-WBAN communication tier as shown in Figure 1 (Al-Sofi et al., 2023). Specifically, these layers are (Goyal et al., 2023):

1- Tier 1 or Intra-WBAN: in this part a number of body sensor nodes are intentionally placed on the skin, on clothing, or may embedded within the human body. Sensors sustain a star topology and communicate with a centralized node to collect and send physiological data. Sensors communicate with the sink, which processes and transmits information to Tier-2 via ZigBee, Bluetooth, Wi-Fi, or other short-distance technologies.

2- Tier 2 or Inter-WBAN: there is a wireless networking configuration that acts as a gateway. Potential WBAN networking technologies embrace WLAN, Bluetooth and among other wireless networking protocols. In addition, a gateway could be a laptop or cellular network. These technologies serve as tools provide a low cost communication link to transfer information to Tier 3 from the data collection sources in Tier 1.

3- Beyond-WBAN or Tier 3: The decision control unit (DCU), which achieves all important strategies is located in Tier 3. Additionally, this layer is responsible for maintaining the patient database, which allows other healthcare provider to access the patient's medical history whenever needed. Additionally, the patient can view the doctor's prescription regarding his current state of health online.

A star topology is commonly used in WBANs. In a star topology, point-to-point links are formed between the sink node (interchangeably called the center device) and the sensor node (Rajasekaran et al., 2024). WBANs can form networks with one-hop or two-hop star topologies. One-hop topologies have direct sensor node connects to the sink, while two-hop topologies have an interrelation and sink connection.

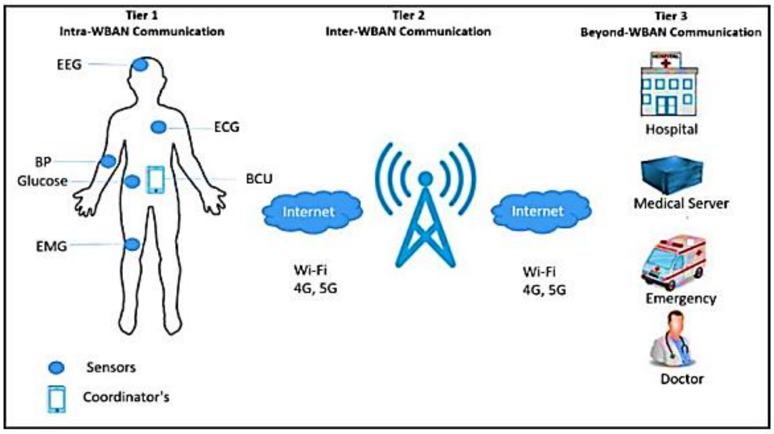

Figure 1: Architecture of WBAN (Al-Sofi et al., 2023)

3 Interference in Wireless Body Area Networks

One of the challenges with WBANs is interference caused by the short range communications. Interference on WBAN can be categorized into intra-network interference and inter-network interference. The intra-interference arises from data overlapping within the WBAN, which can be mitigated using access techniques (Shaik et al., 2018) (Yang & Sayrafian-Pour, 2011)(Movassaghi et al., 2013) . Mutual interference is caused by multiple WBANs coming in near vicinity (Shaik & Subashini, 2020) (Ashrar et al., 2018) . Moreover, Because WBAN sensors employ minimal power to preserve battery life, there is a possibility of cross-interference from the 2.4 GHz frequency device, which could have a significant impact on the coordinator.

The interference between co-existing WBANs should be carefully examined given the large density of common WBANs, since it directly affects the system performance. Figure 2 shows an example of coexisting WBANs (George & Jacob, 2020). The location of implanted/attached sensors in WBANs across the human body is a challenge for channel modeling due to the unique communication channels and linkages created by human tissue. Channel modeling is vital in designing physical layer technologies for human tissue, given its complexity. Many studies have proposed channel models for the physical layer in WBANs (M. J. Ali, 2017) . WBANs may be sensitive to interference from other coexisting wireless systems, such as other WBANs, because of their extremely low power communication. However, interference mitigation can support the simultaneous operation of more nodes whereas also preserving the quality of the link. Even so, as there is generally no coordination across different networks, interference may happen when multiple people wearing WBAN are close to one another (Yang & Sayrafian-Pour, 2011). Consequently, the performance of the communication link may deteriorate as the number of these BANs grows close to one another Different types of interference are shown in Figure 3 according to (Shaik et al., 2018)

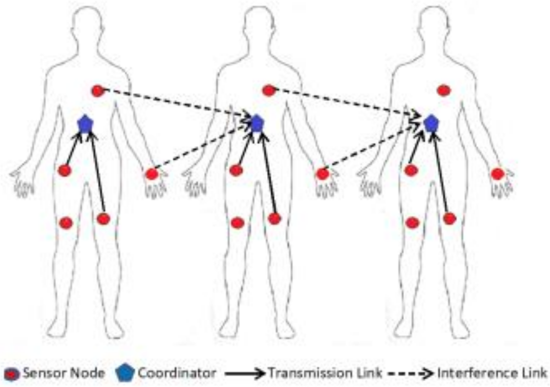

Figure 2: Coexisting WBANs (George & Jacob, 2020)

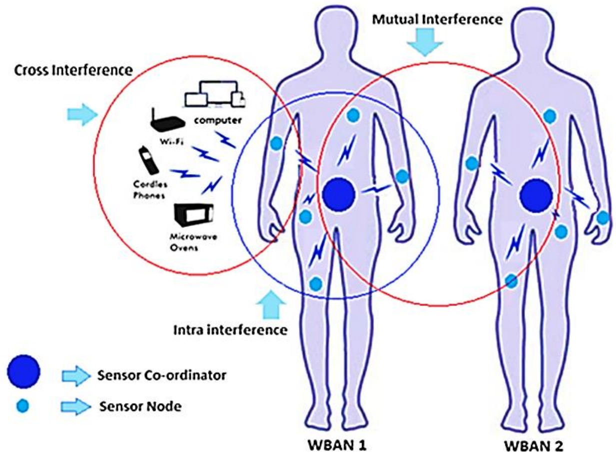

Figure 3: interferences in WBAN (Shaik et al., 2018)

4 Interference Mitigation Methods

In this part, we survey the most used methods for WBANs interference management. Generally speaking, these methods relay on signal processing techniques such as adaptive transmission and signal shaping, cooperative communications, and decentralized networks operations.

4.1 Interference Mitigation of WBANs using Non Orthogonal Multiple Access (NOMA)

Recently, non orthogonal multiple access (NOMA) has drawn a lot of interest, particularly in relation to 5th and 6th generations of wireless communications (5G and 6G) (Pavithra & Chitra, 2023). Michaelides et al. in their work in (Michaelides & Pavlidou, 2020) are considered to be the first authors who adopt NOMA in WBANs. NOMA transmission enables two nodes to transmit simultaneously at different power levels. This is accomplished by using a node with a strong signal as a relay for a node with a weak signal using superposition coding. The near-far issue in WBANs is common due to node attachment to the human body, making it difficult for receivers to detect weaker signals due to adjacent-channel or co-channel interference.

The results for this strategy are evaluated with packet level simulations in OMNeT++ by using the received beams, the sent data packets, the received data packets as performance metrics. They consider the scenario of two signal transmissions occurring simultaneously, each with different power levels. Successive interference Cancellation (SIC) is assumed as an effective detection strategy at the receiver, where the detection process occurs in two stages. In order to model the uplink of WBANs, the superposition of two binary phase shift keying (BPSK) modulation is considered.

4.2 Interference Mitigation in the Internet of Medical Things (IoMT)-WBAN using NOMA

Recently, there has been a lot of interest in 5G and 6G wireless networks as well as beyond when it comes to remotely monitoring patients' vital signs. The increasing quantity of Internet of things (IoT) devices makes it possible to continually monitor patients' vital signs in both indoor and outdoor environments. These devices, which may involve smart watches and smartphones, should be able to reliably send patient vital signs to the distant healthcare center through base stations or cloud servers. In emergency scenarios for outdoor locations, the aforementioned features have lately extended the use of classic WBANs to novel, growing IoMT-based WBANs (Ghubaish et al., 2021). However, IoMT encompasses a wider range of medical devices and equipment than only the human body (Osama et al., 2023). The authors in (Askari et al., 2022) used NOMA scheduling for vital signs of patients in IoMT-WBAN with unmanned air vehicle (UAV) capability for outdoor application. IoMT devices are used by the patients to sense and collect several vital signs, while UAVs are in charge of collecting patient data packets dispersed throughout the city, including unreachable areas. Their algorithm includes two levels (see Figure 4). The first level involves scheduling the data packet transfers from each patient biosensors to the appropriate hub. The Walsh Hadamard (WH) coding technique is used to remove interference between biosensors asynchronous transmissions. With the use of this method, all of biosensor transmissions can be scheduled for the same time window without ever ramming. In second level, the city is divided into several clusters, with a single UAV allocated to each cluster. The corresponding UAV provides care for every patient in each cluster. The NOMA technique is used to schedule the hub transmissions to UAVs under the given circumstances. Several hubs are scheduled in the same time slot using NOMA. Moreover, according to (Askari et al., 2021), in order to obtain improved spectral efficiency and prevent interference, NOMA based scheduling method with the use of orthogonal WH codes is beneficial in IoMT-WBAN. In this case, the received SNR of each transmission must meet a certain threshold in order for the received signal to be acknowledged by the SIC process in NOMA.

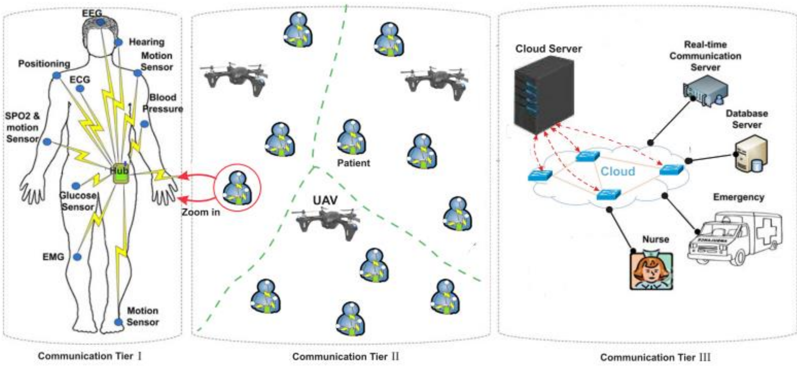

Figure 4: Architecture of IoMT in WBAN (Askari et al., 2021)

4.3 Interference Mitigation of WBANs using Adaptive Modulation, Duty Cycle, and Data Rate Adaptation

Many methods of mitigating interference have been proposed in (Yang & Sayrafian-Pour, 2011). These methods include adaptive modulation, duty cycle, and data rate adaptation. An objective measurement referred to as the interference mitigation factor (IMF) was employed to evaluate efficiency in body area network applications. The low power nodes can function in high-interference environments using specific digital modulation schemes. For example, they can employ minimum phase shift keying (MPSK), BPSK, quaternary PSK (QPSK), and eight level PSK (8PSK). The signal to interference plus noise (SINR) ratio is calculated based on channel conditions and bit error rate (BER), with 8PSK for larger bit rates and QPSK for specific thresholds. The SINR for a WBAN (i^{th} WBAN) is defined in Equation 1 below,

$$SINR_i = \frac{S_i}{N + \sum_{j \neq i} S_j} \tag{1}$$

Where S_i is the desired power at controller node of WBAN i, S_j is undesired power from interferer j, and N is additive noise power. The second mitigating approach is adaptive data rate. The data rate is allocated into M steps based on maximum and minimum values. In normal mode, the rate is set to R_{max} and adjusted by comparing the weighted sum of SINR to the target SINR. The final mitigating approach is adaptive duty cycle. Adjusting the duty cycle (η) as shown in Equation 2 involves controlling active (T_{active}) and inactive periods ($T_{inactive}$) while maintaining a constant sum, with longer inactivity reducing interference to neighboring networks.

$$\eta = \frac{T_{active}}{T_{active} + T_{inactive}} \tag{2}$$

The duty cycle is divided into K steps between maximum and minimum values.

4.4 Interference Mitigation of WBANs using a Cluster-based Technique

WBANs can cause co-channel interference when coexisting with other wireless networks like Wi-Fi, ZigBee, wireless sensor networks (WSNs), Bluetooth, and cellular devices that share the same 2.4 GHz ISM band (M. J. Ali, 2017).

The influence of co-channel interference on WBANs under generalized fading is examined in (Jameel et al., 2016), with a particular emphasis on the analysis of packet error probability and antenna selection strategies using cluster-based models. In order increase performance in multi-device WBAN situations, the study also explores interference mitigation strategies including using zero correlation duration (ZCD) codes and SIC with an optimal ordering mechanism. Furthermore, it examines cooperative relaying systems on WBANs over fading channels, deriving outage and symbol error probabilities, and highlighting the importance of diverse system parameters on performance.

The researchers in (Jameel et al., 2017) use a cluster-based technique to analyze the impact of inter-body interference in WBANs. The study developed a closed-form expression for outage probability for co-channel interference under Rayleigh and Rician fading for two cases, confirming their rapid application in cluster design of WBANs, using Rice and Rayleigh distributed channels.

4.5 Inter-WBAN Interference Mitigation using Orthogonal Codes

Ali et al. (M. Ali et al., 2016b) proposed the exploit the orthogonality of WH codes as a mitigation technique for co-channel interference existing among WBANs. The authors proposed a two-stage algorithm that modifies an already used algorithm in the literature. Specifically, the authors in (Tawfiq et al., 2012) proposed using WH codes in WBAN to avoid interference. However, in (Drew Fudenberg, 1991), the algorithm is developed further. Specifically, in the first stage the interacting WBANs make a list of interferers according to a distributed time correlation reference (DTRC) algorithm. The DTRC algorithm can be seen as the coordinator that specifies for each WBAN the interfering elements from other coexisted WBANs through discovering the interfering super-frames. The super-frame used is shown in Figure 5 and the interfering frames are shown in Figure 6 below. The system consists of N WBANs with up to K sensor nodes, transmitting data at 250Kb/s within the 2.4 GHz international license-free band. Within each WBAN, star topology is used between sensor nodes and the cluster head where the mobility affects individual WBANs as well as all WBAN sensor nodes. The time division multiple access (TDMA) scheme is used in every WBAN. For the WH codes that used in their interference mitigation scheme, in a time-slot TS_i of sensor r_i of a $WBAN_i$, r_i multiplies its modulated signal s_i by the spreading code ω_i. A general WH matrix $M_2{}^n$, n > 1, can be generated as given in Equation 3:

$$M_{2^n} = \begin{pmatrix} M_{2^n-1} & M_{2^n-1} \\ M_{2^n-1} & M_{2^n-1} \end{pmatrix} = M_2 \otimes M_{2^n-1} \quad (3)$$

After that, the orthogonal WH are assigned according to another algorithm that is called distributed orthogonal code cancellation (OCAIM). The OCAIM algorithm generates for each WBAN a WH sequence according to Equation 3 above. The sensors belong to the WBANs that are in the same list are assigned these WH codes and hence their transmission will be orthogonal which cancels the interference. It can be that it is the same idea of the spread spectrum communications, but using the DTRC algorithm before assigning the WH codes makes it a more intelligent algorithm.

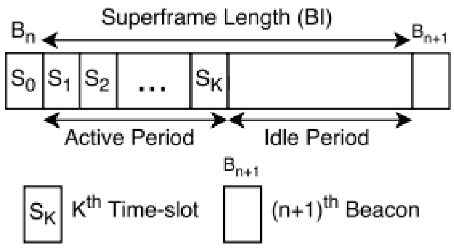

Figure 5 :Super-frame structure proposed for OCAIM scheme (M. Ali et al., 2016b)

Employing DTCRA, a WBAN can determine which of its sensors will interfere with those of other WBANs by relating the start time of other super-frames to its local time. Two basic functions are assigned to each coordinator by DTCRA: first, it identifies which super-frames that may overlap. Secondly, it identifies which time-slots inside those super-frames may intersect, as illustrated in Figure 6. The OCAA scheme directs each sensor to use a code in time-slots based on interference, extending its signal bandwidth and making it anti-interference. Each superframe adjusts the code assignment pattern, as spread spectrum approaches transmit at lower spectral power density than narrow band transmitters.

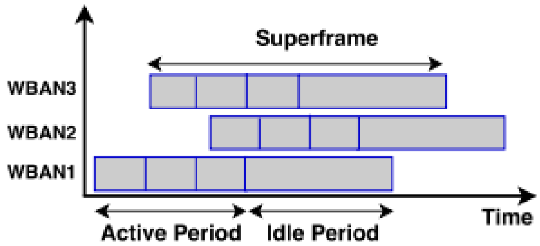

Figure 6 :Overlapping superframes scheme (M. Ali et al., 2016b)

4.6 Interference Mitigation of WBANs using Probability Approaches

The authors in (Xuan Wang & Lin Cai, 2011) developed a model to analyze the co-channel interference for densely developed WBANs using the advanced geometrical probability approach. This tool allows modeling the interference probability distribution and then they approximated it using gamma distribution. In (Balevi & Gitlin, 2018) the authors used stochastic geometry with game theory to model the interference management within a single WBAN, while a game theoretic power control algorithm is used among WBANs.

For WBANs, combined node-level interference reduction and energy harvesting are suggested. This enhances frequency reuse and network longevity by enabling lower interference nodes to broadcast on the same channel as high interference nodes (Movassaghi et al., 2014). They model the channel with gamma fading in intra-WBAN and Rayleigh fading in inter-WBAN, which is the channel between sensors and coordinators of different WBANs. The study discovered that the longer the network lifetime and the amount of energy gathered, the more coexisting WBANs that obstruct a sensor node's transmission. With this method, the limited resources in WBANs are used as efficiently as possible, resulting in a longer network lifetime and depletion time.

4.7 Interference Mitigation of WBANs using Latin Rectangles

A Latin square is a K ×K matrix filled with K distinct symbols, each symbol appearing once in each column and once in each row (Ah et al., 2017) . The work in (M. Ali et al., 2016a) (Ah et al., 2017) suggested a predictable channel hopping algorithm based on Latin rectangles, namely, CHIM. The CHIM scheme uses a Latin square matrix to allocate channels to ZigBee WBANs. It uses multiple channels to allocate a unique default channel, allowing sensors to hop between channels in a predictable pattern. CHIM expands the super-frame with additional interference mitigation backup time slots and uses Latin rectangles for channel allocation. Each super-frame consists of two frames for sensors and coordinators as shown in Figure 7.

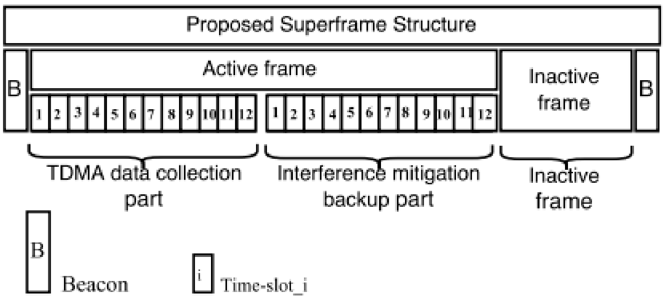

Figure 7: Proposed super frame structure (M. Ali et al., 2016a)

4.8 Interference Mitigation in Multiple WBAN using Efficient Mitigation Rules (EMR)

The authors in (Shaik & Subashini, 2020) proposed rules to mitigate interference at the central coordinator level, in WBAN. Their approach involving network data collecting, transmission, and sending to the centralized coordinator using EMR to enhance packet delivery ratio and energy efficiency. The proposed mitigating rules are:

1- The process involves checking the Inter-Coordinator to Central Coordinator path for any interruptions and ensuring the prior paths are updated with additional data.
2- The network area's default latency and cost may change if an unknown interruption occurs. If detected, idle agents activate based on the strength of the unknown frequency, transmitting data to the central coordinator.

These rules are shown pictorially in Figure 8 below.

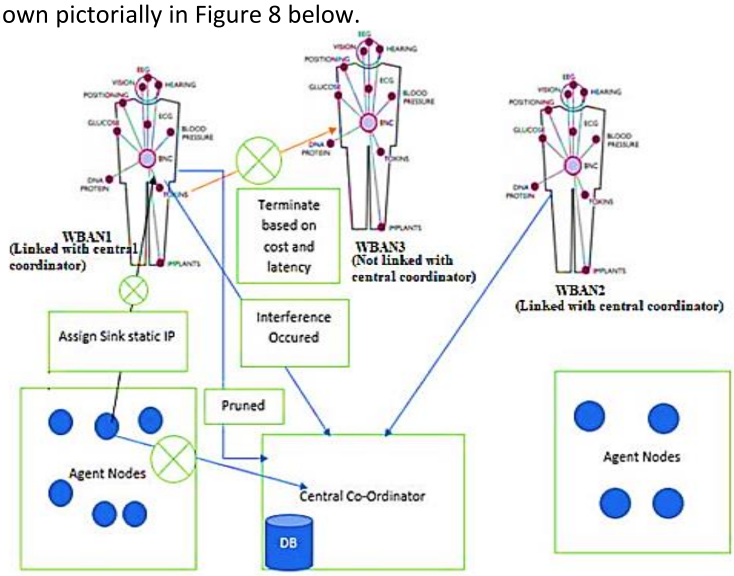

Figure 8. Architecture of proposed EMR rules (Shaik & Subashini, 2020)

4.9 Interference Mitigation by Nonlinear Programming

Nonlinear programming and in particular convex programming is a mathematical optimization framework that has found applications in a many areas (Boyd & Vandenberghe, 2004). We consider the work in (Zhang et al., 2015) as a sample for the application of this elegant mathematical technique in the area of WBANs interference control. There are many references about the applications of this topic in wireless networks and we suggest the interested reader to check (Zhang et al., 2015) and the references therein as an entry to this subject in WBANs. In particular, the WBANs interference problem in (Zhang et al., 2015) is dealt with as a power control problem. In other words, each WBAN controls its transmission power level in order to achieve the desired SINR given in Equation 1 above. This is a geometric programming problem which is a special case of convex optimization problems (Boyd & Vandenberghe, 2004). Furthermore, the problem to be optimized in (Zhang et al., 2015) is the sum of the SINR of all the associated (coexisted) WBANs. As a result, this creates a semidefinite optimization problem which is a more general class of optimization problems that includes the geometric programming and at the same time is a special case of convex (nonlinear) optimization problems formulations.

4.10 Interference Mitigation for WBAN based on CSMA/CA

In (Mile et al., 2018) the authors proposed a hybrid WBAN interference mitigation model using carrier sense multiple access with collision avoidance (CSMA/CA) protocol for controlling the transmission contention window (CW) and the user's transmission priority. They simulated multiple mobility scenarios and compare it to IEEE 802.15.6. The MoBAN mobility model is used due to its ability to accommodate group mobility and postural selector.

The proposed hybrid model utilizes two techniques, a collaborative CSMA/CA's CW technique and a priority queue technique. User priorities (UP) mappings are used in the priority queue strategy to prioritize traffic. This involves giving the traffic coming from the sensor nodes different priorities, with emergency traffic receiving higher priority and all other traffic receiving lesser priority. They suggested eight different priority mapping types. The more significant the traffic, the higher the user priority value. To determine the transmission priority of each UP, the CWmin and CWmax parameters are assigned. The suggested protocol is shown in Figure 9 below.

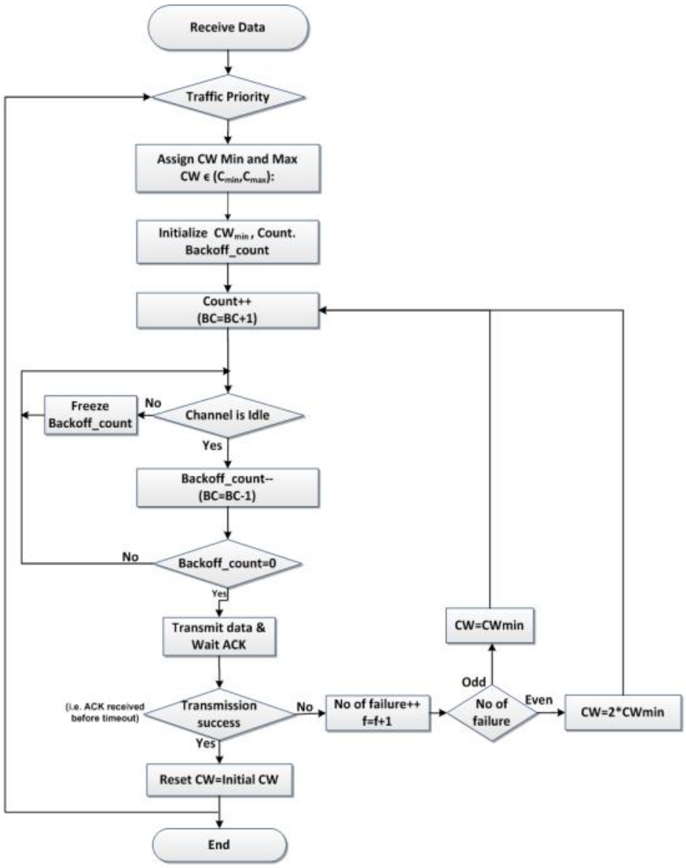

Figure 9: Proposed model in (Mile et al., 2018)

4.11 Interference Mitigation for WBAN using Cooperative Communications

Another approach that can successfully reduce interference in dense WBAN implementation is cooperative communication. Cooperative communication can greatly increase transmission reliability and energy efficiency when there is a wide transmission distance between the source and the host nodes (Xie et al., 2020) (Y. Wu et al., 2017). Dong and Smith in (Dong & Smith, 2013) in their study proposes two-hop relay-assisted cooperative communications using opportunistic relaying (OR) to improve coexistence for WBANs that is depicted in Figure 10. Using TDMA schemes for both intra-WBAN and inter-WBAN access protocols, the study uses on-body and interbody channel gain measurements. The WBAN includes a hub, two potential relays/sensors, and eight additional sensors. The study examines two approaches for relay selection: using inactive sensors as relays without extra hardware, or adding fixed relays to the WBAN system.

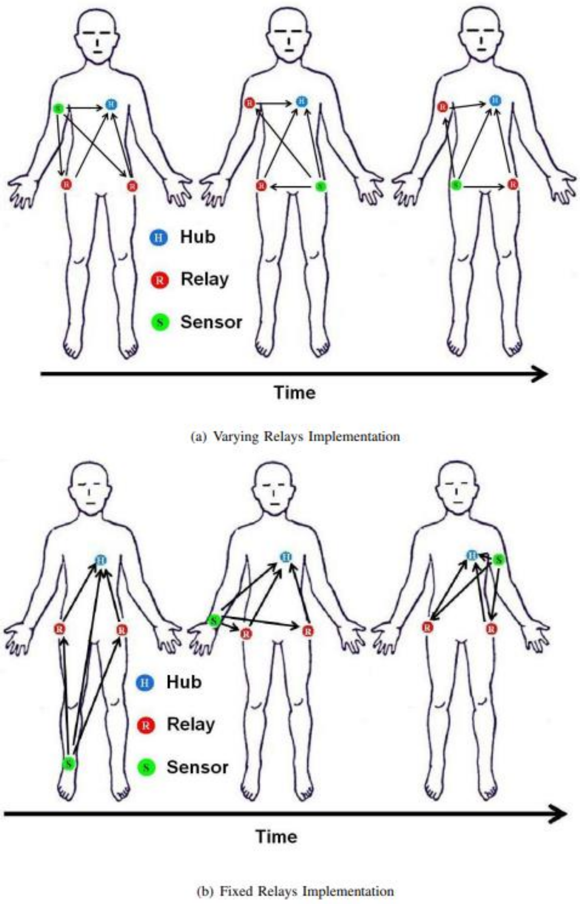

Figure 10: Two different relay selection implementations (Dong & Smith, 2013)

4.12 Interference Mitigation using Different Antennas

Wireless body area networks on two persons during indoor body movements results in inter-user interference. In (X. Wu et al., 2015) inter-user interference between WBANs during indoor body movements at 60 GHz and 2.45 GHz was investigated under using both monopole and horn antennas. As shown in Figure 11-13, for the measurement, two males were tested using monopole and horn antennas at 60 GHz and 2.45 GHz respectively. Results showed that adopting a 60 GHz carrier frequency with monopole antennas and horn antennas reduced median interference levels by 20 dB, while maintaining WBAN-to-WBAN spacing and orientation distributions. This suggests 60 GHz multi-hop WBANs offer a viable, interference-resistant option for body-centric communication.

Figure 11:Monopole antenna on the wrist (X. Wu et al., 2015)

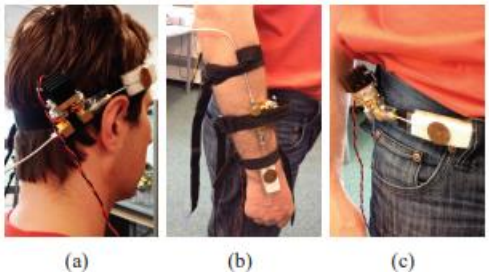

Figure 12: Monopole antenna on: (a) Head, (b) Wrist, (c) Abdomen, (X. Wu et al., 2015)

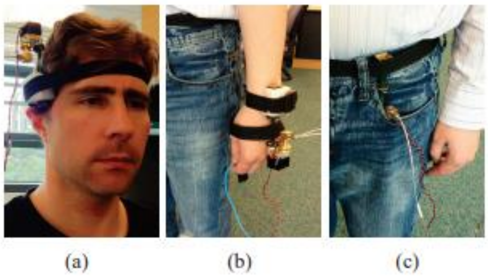

Figure 13: Horn antenna on: (a) Head, (b) Wrist, (c) Abdomen, (X. Wu et al., 2015)

4.13 Interference Mitigation using Game Theoretic Approaches

So far all the discussed methods employ a centralized controller of the WBAN(s). In particular, there is a central unit that coordinates the operations. Yet another research direction is the use of decentralized approaches to control the interference. Game theory, a Nobel winning theory in economics, is a mathematical tool for decentralized optimization where the players can be people or firms (Drew Fudenberg, 1991). Game theory also an optimal control tool that explains how to do optimization in the presence of conflict objectives (Başar & Olsder, 1998). The pioneering work of applying game theory in the field of wireless communications and interference management is first proposed by (Shah et al., 1998). This led to an explosive amount of works that is still flourishing. WBANs are of no exception and gained a lot of attention in applying games to reduce the interference. In general, game theoretic approaches for interference reduction in WBANs can be divided into two parts. The first part considers the sensors that belong to a specific WBAN as smart sensors and hence they can make decisions. More specifically, the sensors are players that compete among themselves. Such direction of work is represented by (Balevi & Gitlin, 2018) (Xu et al., 2014)(Zou et al., 2014) and the references therein. It should be mentioned that the work in (Zou et al., 2014) uses a different game model that is Bayesian game which means that plyers (WBAN nodes such as EEG sensor, ECG sensor...etc) update their beliefs and adjust their power control levels. In (J. Wang et al., 2019) a new model that combines Bayesian games and a special types of game called Stackelberg games is proposed for power control. In a nutshell, a Stackelberg game formulation assumes that there is at least one leader and one follower in the game. The leader is aware of the follower's strategies and the leader responds to this. It is also well-known that the leader gets higher payoffs (rewards) when playing a Stackelberg game than the rewards gotten if playing the classical non cooperative game (Başar & Olsder, 1998). The second line of research on applying game theoretic tool set to WBANs considers the sensors as passive agents and models the interaction among the WBANs themselves. Meaning that each WBAN acts a player that has a set of tools (strategies) to use. This direction can be seen in the work of (J. Wang et al., 2019) (Alabdel Abass et al., 2024). Specifically, the authors in (J. Wang et al., 2019) designed two games, one of them to be played among the sensors that belong to the same WBAN, while the second game is between the interacting WBANs. In (Meharouech et al., 2015) the author proposed a potential game framework to characterize the spectrum management through power control among several WBANs. The same objective is achieved in (Hammood et al., 2019) using a non-cooperative game approach. A different scenario where the interacting WBANs are assumed to have different mobility capabilities is modeled as a game in (B.N. & R, 2023) . In (Alabdel Abass et al., 2024) the authors proposed a different potential game that takes in consideration not only a direct power control approach, but instead the effect of using relaying and network coding in interfering WBANs.

4.14 Interference Mitigation using Machine Learning (ML) Approaches

The previous approaches to the interference handling problem are based on some assumed models that are based on solid theoretical and practical backgrounds. However, with the current advances in electronic component fabrications, there is a tend to use model free models or in particular ML models where the interacting entities can learn from data. In this section, we consider as examples to this direction, the works in (L. Wang et al., 2020) (Roy et al., 2022)(Chen et al., 2019)(Ahmad et al., 2020)(Periyamuthaiah & Vembu, 2024). It also should be mentioned that work in this area still active and there is a room for more contributions. Specifically, the authors in (L. Wang et al., 2020) have formulated the problem of interference mitigation of coexisting WBANs jointly with time slot allocation through a Markov decision process (MDP) that is solved using deep reinforcement learning. In (Roy et al., 2022) a different use of interference is proposed by energy harvesting. Meaning that the WBAN collects the energy from the ambient and interference can be used as a collected energy. The problem is also formulated as a MDP that is solved through the Q-learning algorithm (Q-learning is a learning algorithm proposed in (Watkins & Dayan, 1992). Furthermore, the authors in (Chen et al., 2019) used reinforcement learning (in particular Q-learning algorithm) to construct a WBAN sensors strategy that aims to control the transmission power and the sensors' transmission priority with taking in consideration the battery level and the transmission delay of sensors. Ahmad et al. in (Ahmad et al., 2020) proposed a modified Q-learning algorithm to manage interference. In particular, their algorithm is designed such that the users learn the optimal CSMA/CA strategy. Finally, an algorithm that takes fairness among users using deep learning is proposed in (Periyamuthaiah & Vembu, 2024). In particular, the authors considered using the Hungarian optimization approach, the transmission power level among other factors with deep probabilistic neural network.

5 Future Directions

In this section we briefly consider several possible research directions. Starting with the counterintuitive fact that interference may not be so bad all the time. Also designing WBAN so that reducing the interference may not be the best metric to be considered. There are security challenges associated with any wireless transmission and WBAN is of no exception. Some of these challenges are addressed in (ElDiwany et al., 2019)(Moosavi & Bui, 2016) where the transmitted signal can be eavesdropped. Friendly and controlled interference can play a positive rule in overcoming this type of security violations (Yener & Ulukus, 2015).

The decentralized modeling of WBANs through game theoretical models still not mature. For example, many ideas can be inspired from the coexistence between the WiFi and the new standards such as (long term evolution) LTE systems as well as non-classical game theoretic models that tackle this problem. For example, the authors in (Alabdel Abass et al., 2019) used evolutionary game theory to model the coexistence issue. Cooperative and dynamic game models have not been fully explored in the WBANs field. Other coexisting techniques that can be tailored to the WBAN interference mitigation problem are briefly mentioned in (Alabdel Abass et al., 2019) and the references therein.

Another metric that is also associated with interference management is the age of information metric (AoI) or information freshness. The AoI represents the age of an update packet since the last update has occurred under the assumption that the transmission time is considered negligible (Yates et al., 2021). However, this metric has been investigated that much with WBANs and only one work (to the authors' best of knowledge) has considered it where machine learning is used to jointly control the transmission power and reduce the AoI (Xin et al., 2023). As a result, WBAN research area is still fruitful and smart interference mitigation is needed.

6 Conclusions

WBANs frequently experience interference, which degrades performance. In terms of medical applications, this puts the patient's health at risk. However, the majority of WBAN wireless technologies operate in the 2.4 GHz ISM band, which causes interference with neighboring wireless technologies that utilize the same frequency. Consequently, while designing WBAN, it is crucial to incorporate efficient interference management techniques. In this study, we defined interference, categorized interference, and discussed mitigation strategies based on the type of interference taken into account by the WBAN system. We provide an explanation of each operation of techniques as well as how it affects the process of lowering or managing interference. We used a variety of strategies, including mathematical models and experimental models. We also pointed out some future research directions.

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