SPECIAL SECTION ON BODY AREA NETWORKS FOR INTERDISCIPLINARY RESEARCH

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 11, 2016, accepted May 20, 2016, date of publication June 7, 2016, date of current version July 7, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2577681

Enabling Interference-Aware and Energy-Efficient Coexistence of Multiple Wireless Body Area Networks With Unknown Dynamics

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This work was supported in part by the National Information and Communications Technology Australia, Australian Government through the Department of Communications and in part by the Australian Research Council through the Information and Communications Technology Centre of Excellence Program.

ABSTRACT This paper presents an adaptive interference mitigation scheme for multiple coexisting wireless body area networks (WBANs) based on social interaction. The proposed scheme considers the mobility of nodes within each WBAN as well as the relative movement of WBANs with respect to each other. With respect to these mobile scenarios traffic load, signal strength, and the density of sensors in a WBAN are incorporated to optimize transmission time with synchronous and parallel transmissions to significantly reduce the radio interference and energy consumption of nodes. This approach leads to higher packet delivery ratio (PDR) and longer network lifetime even with nodes dynamically moving into and out of each others interference region. We make channel assignment more energy-efficient and further reduce power consumption using transmit power control with simple channel prediction. Simulation results show that our approach maintains optimum spatial reuse with a range of channel dynamics within, and between, coexisting BANs. This protocol based on social interaction is shown to mitigate interference and minimize power consumption, and increase the spatial reuse and PDR of each WBAN, while increasing network lifetime. In the context of the adaptive interference mitigation scheme proposed, this paper also reviews the state of the art in literature on mobility, MAC layer, and power control solutions for WBANs, as well as providing a summary of interference mitigation schemes previously applied for the coexistence of WBANs.

INDEX TERMS IEEE 802.15.6, interference mitigation, power control, spectral efficiency, wireless body area networks.

I. INTRODUCTION

Nodes in wireless body area networks (WBANs) have a heterogeneous structure in terms of the computing power and available energy to nodes, such as sensors and the hub. This should be considered in interference mitigation to avoid node depletion and minimize interference. Since WBANs have significantly limited resources, their operations should be extremely energy efficient to extend the battery-lifetime as much as possible. As well as an individual WBAN's operation being important itself, Body-to-Body Network (BBN) communications has recently attracted interest, e.g., [1]–[5]. In most configurations, BBNs consist of several WBANs that each consist of several wearable sensor nodes operating with mobile radio coordinators. However, the practical deployment of BBNs has not really progressed due to a number of challenges, specifically with regards to radio interference mitigation amongst coexisting WBANs. These challenges for BBNs are: 1) Interference in a single node depends on the independent decisions made by multiple coordinators; 2) The system architecture is decentralized as no central entity can provide continuous global control to remove interference with the nodes of different WBANs; 3) Due to the large number of nodes in many typical WBANs a solution based on a centralized agent will not be scalable; 4) Individual decisions of each WBAN coordinator have to be self-adaptive based on the decisions of the other coordinators and the surrounding environment; and, 5) Coexisting WBANs use several transmission technologies that can share the same unlicensed band (ISM band) which leads to a dramatic increase on the level of interference of coexisting WBANs and thus a decrease in their network performance. These coexisting radio technologies can include IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (Zigbee) and IEEE 802.11 (WiFi) which all use the same 2.4 GHz ISM band.

Generally a person is associated with a single WBAN, and as a simpler implementation each WBAN is coordinated by the central hub, i.e., gateway in a one-hop star topology. However, since large path losses are typical in single-link star topologies for WBAN communications, two-hop cooperative communications is included as an option in the IEEE 802.15.6 standard [6]. Data exchange between the gateway and each sensor node is accomplished via a round-robin approach. Thus, often, interference mitigation schemes will occur when two-hop star topologies are considered within individual WBANs. Unfortunately, interference mitigation schemes proposed for other networks, such as traditional wireless sensor networks (WSNs), cannot be deployed in WBANs because of the following differences: A WBAN mainly has more frequent topology changes and a higher moving speed whilst a WSN has static or low mobility scenarios; WBANs are different to mobile ad hoc networks (MANETs) in terms of their moving topology with group-based movement rather than node-based movement as in MANETs. Thus, due to the group-based movement and high mobility nature of WBANs they are not similar to WSNs or MANETs which implies interference mitigation approaches in both WSNs and MANETs cannot be used for WBANs [7]. In addition, due to the limitations of WBANs in terms of cost, size and energy consumption, the function of each sensor node needs to be very simple. Thus, advanced antenna techniques cannot be used for interference mitigation in WBANs [8]. Additionally, interference mitigation proposals for cellular networks cannot be deployed in WBANs due the following reasons: The location of a mobile station is usually uniformly distributed in cellular networks whilst nodes in WBANs are deployed more densely; also, neighbouring networks in cellular networks adjoin to each other due to the network coverage requirement, whilst there is usually a gap between WBAN networks due to people's separation, which helps to mitigate the mutual interference [8]. Thus, radio interference amongst WBANs and enabling their coexistence becomes an important problem. As coexisting WBANs are uncoordinated in nature, a certain WBAN may impose severe interference on another operating WBAN, specifically in densely populated areas. Moreover, recent technological advancements had allowed 11 million active units to be used for wearable computing in 2009 and this number is predicted to reach 485 million by 2018 [9]. Thus, addressing the problem of coexistence will become more and more important in the years to come.

The proposed interference mitigation schemes in WBANs thus far can be divided into two categories: interference reduction techniques and interference avoidance techniques. *Interference reduction* schemes focus on scenarios where devices transmit simultaneously but with different power, modulation scheme, data rate or phase. The aim here is to minimize the interference level at the receiver by optimizing the system parameters such as power, data rate and some other physical layer parameters. In *interference avoidance* techniques, the coordinators of different WBANs attempt to assign orthogonal channels to each device in the network, thus avoiding the interference with the cost of lower system throughput. In comparison, interference avoidance schemes [10]–[12] can achieve a higher signal-to-interference+noise ratio (SINR) level compared to interference reduction schemes, but their throughput is usually lower. Moreover, in terms of computational complexity, interference avoidance techniques requires less complex receivers but extra cooperation between coordinators is inevitable. In interference reduction schemes [13]–[17], the receiver has a more complex decoder because it needs to decode several messages with different levels of SINR, data rate and power; but since cooperation is not performed between coordinators lower transmission overhead can be achieved by these approaches.

In this paper, *we aim to leverage the social nature of WBANs to assist BBN communication to achieve enhanced performance, and we give significant context for this in terms of an up-to-date review of relevant literature.* More specifically, we propose to maximize performance whilst minimizing the overall power consumption with simple and low-computational models that minimize energy drainage. We build on top of the authors proposal in [18]–[21] by taking a step forward and considering the effect of channel assignment with dynamics relative to postural body movements and social interaction of the networks. Thus we make two main contributions:

1) We investigate how intra-WBAN and inter-WBAN mobility influences communication amongst multiple coexisting WBANs;
2) We provide a viable solution for interference mitigation for mobile coexisting WBANs that functions with limited resources.

The rest of this article is organized as follows: We present an extensive survey of related work in Section II to give context to the scheme to be presented. The WBAN system model is described in Section III. We propose transmit power control and incorporate mobility for the inter-WBAN interference mitigation scheme in Section IV. Simulation results are given in Section V. Finally, some conclusions are drawn in Section VI.

II. RELATED WORK

Co-channel interference mitigation in WBANs is quite challenging due to the large density, high mobility and the uncoordinated nature of WBANs. The mobility of WBANs makes interference even more challenging as these networks can move into each others range and result in a large density of WBANs needing to coexist with each other [22], [23]. Coexistence has shown to to be more severely affected at higher data rates [14]. Additionally in most applications WBANs are rational and self-interested so that they do not cooperate with each other to make power decisions and each WBAN may independently chooses its transmission power based on its belief of other WBANs' choices [15]. On the other hand, the most valuable resource of a WBAN is energy, which can be easily wasted by inter-network interference that reduces the SINR value and leads to throughput degradation. Furthermore, in order to maintain the minimum acceptable link quality, the transmit power should be limited to minimize the interference level and save battery life [14]. Therefore, interference mitigation schemes aim to decrease the average transmit power using link adaptation mechanisms whilst maintaining link quality at the cost of lower data rate or throughput [14]. This can be even more challenging in the case of WBANs as frequent battery replacement or recharging is not feasible [13]. Thus, the scarce constraint of energy in WBANs requires simple, robust, intelligent and light solutions for these networks to cope with the small processing power and small memory of their devices.

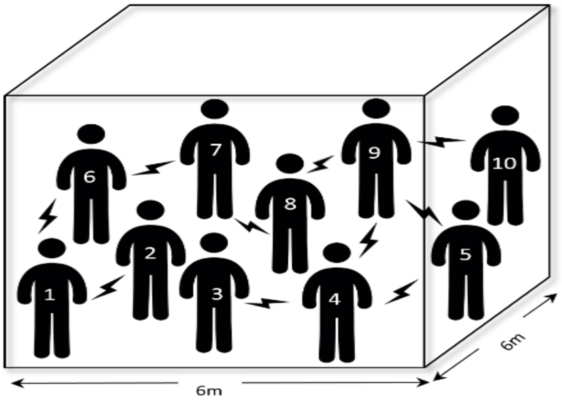

FIGURE 1. IEEE 802.15.6 Requirement: 10 coexisting WBANs in a $6m^3$ cube.

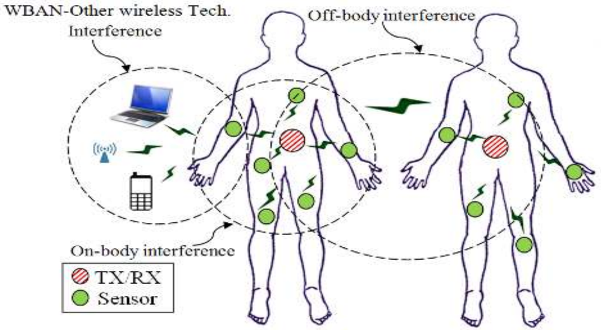

FIGURE 2. Types of Interference for WBANs as in [21].

A. OVERALL IEEE 802.15.6 STANDARD TECHNICAL REQUIREMENTS

As per the IEEE 802.15.6 standard for WBANs its requirements are as follows [24]–[28]: Bit rates in the range of 10 Kb/s to 10 Mb/s should be supported via the WBAN links; Packet Error Rate (PER) should be below 10% for a 256 octet payload for more than 95% of the best-performing links; Nodes need to adapt to being added and removed from the networks in below 3 seconds; Each WBAN should be able to support up to 256 nodes; nodes should allow reliable communication in case of mobility scenarios; data loss relative to unstable channel conditions specifically with variations in postural body movements is not acceptable; Reliability, Jitter and latency should be supported for specific WBAN applications. For instance, medical applications and non-medical of WBANs require latency to be less than 125 ms and less than 250 ms, respectively; whilst jitter should be less than 50 ms; On-body and in-body WBANs should be capable of coexisting within range; co-located WBANs should support up to 10 randomly distributed networks in a $6m^3$ cube (Fig.1); Power saving methods should be deployed to allow the efficient functioning of WBANs in a power constrained environment; QoS management features need to be deployed to be self-healing, secure and allow priority services; Devices within WBANs should allow transmission at 0.1 mW (−10 dBm) with the maximum radiated transmission power being less than 1 mW (0 dBm) [This complies with the Specific Absorption Rate (SAR) of the Federal Communications Commission's 1.6 W/Kg in 1g of body tissue].[1]

B. INTER-WBAN INTERFERENCE

Based on the proposed IEEE 802.15.6 standard, nodes in a single WBAN can avoid interference by using multiple access techniques such as time division [14]. Thus, interference is not an issue for intra-WBAN communication. However, since WBANs are considered to be social, a WBAN will encounter other WBANs in its coverage; thus, inter-WBAN interference gains importance. Based on the IEEE 802.15.6 standard, the system needs to function efficiently within a transmission range of up to 3 meters when up to 10 WBANs coexist, each of which consist of up to 256 sensors [6], [29]. Fig. 2 shows the different types of radio interference in WBANs. The interference link is most likely to be from a device on some other person (off-body) and the signal link is most likely between two devices on one person (on-body) [22], [30]. In cases where the main source of channel dynamics is subject to movement since the two objects are not synchronised, signal and interference links are uncorrelated and statistically independent when considered over a large period of time. In fact, interference occurs

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[1] http://www.fcc.gov/oet/rfsafety/sar.html

TABLE 1. Supported mobility levels in WBANs as per the IEEE 802.15.6 [6].

Static	A single BAN in a residential environment or a hospital with a single patient node and a fixed bedside hub
Semi-Dynamic	Slowly moving ambulatory patients in an elder care facility requiring infrequent and/or event-based low-rate data transfers
Dynamic	Fast moving ambulatory patients in a hospital with a large number of BANS collecting continuous data traffic from many sensor nodes

when no-coordination exists between coexisting WBANs (Inter-WBAN Interference) [14], [31]. Thus, inter-WBAN interference can be defined as when the coordinator of the WBAN of interest can hear the signal from a sensor of another WBAN in its vicinity, as shown in Fig.3.

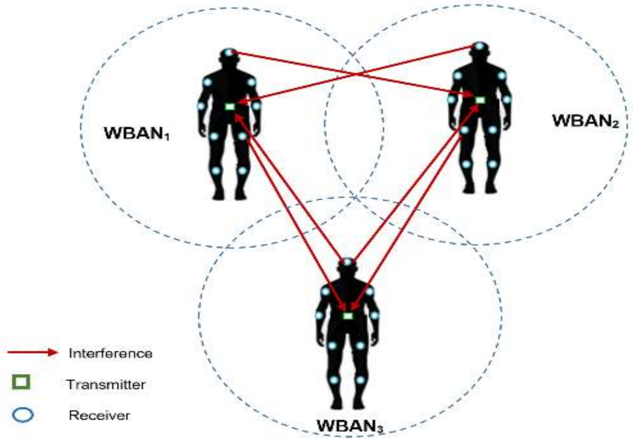

FIGURE 3. Inter-network Interference Problem amongst Coexisting WBANs.

However, the social nature of WBANs and their high mobility does not allow coexistence of multiple WBANs to be controlled via a global coordinator [32]. When coexisting WBANs use the same channel, transmissions can conflict since the active periods will overlap [10]. Additionally, the increase in the density of coexisting WBANs can lead to performance degradation. But the performance of a specific WBAN can encounter significant inter-WBAN interference even when a small number of WBANs coexist [14]. Furthermore, WBANs can practically either exchange information such as channel gain, interference and current transmission power or collect this information through their own measurements [15]. Thus, the main intention of the coordinators of different WBANs should be to distributedly eliminate the interference accumulated on a node in its network and maintain it under a certain threshold. This distributed information has the following advantages: 1) Computational efficiency as parallel processing gain is achieved. 2) Robustness and reliability as the system can tolerate uncertainty. 3) Scalability relative to the number of coordinators and dynamic changes in body posture. In addition, the unpredictable nature relative to unknown dynamics with respect to postural body movements or the movement of WBANs in relation to each other leads to nodes moving into or out of each others range [33]. In the case of wireless technologies with higher coverage areas this issue will be highlighted even more.

Three levels of mobility in WBANs are as follows (examples provided in Table.1)

- *(i) Static(S):* This state shows that there is constant interference from other WBANs for a time duration with no mobility.
- *(ii) Semidynamic (SD):* This state shows there is a constant interference from other WBANs for a certain time duration with slow mobility.
- *(iii) Dynamic (D):* This state demonstrates temporary interference from other WBANs with fast mobility.
- (iv) None (N) state indicates that there is no interference.

C. MAC IMPLEMENTATION

Coexistence amongst WBANs mainly leads to *beacon loss* and *data loss*. Since beacon transmissions do not use carrier sensing, beacons of coexisting WBANs may collide with each other. In this case a beacon is lost; so the sensors lose synchronization and must not transmit in that superframe [34]. Depending on the mode of operation, data loss can occur when a number of WBANs coexist. For instance, life critical data require retransmission and acknowledgements. However, the lack of clear channel assessment and the inflexible nature of GTS approaches leads to inefficient consequences in the period of coexistence [34]. The IEEE 802.15.6 Standard has defined new PHY and MAC layer specifications for WBANs that provides ultra-low power, low cost, low complexity and short range wireless communication in or around the human body. A typical WBAN consists of a coordinator (hub) as its central entity and up to 256 sensor nodes in a one-hop or two-hop star topology where the hub coordinates the transmissions within the WBAN. The hub/coordinator divides the entire channel into superframes for time referenced resource allocation. One period of communication between a hub and its sensor nodes is known as the superframe (referred to as T_d), followed by an idle period T_{idle}. Each superframe starts with broadcasting a *Beacon* packet from the hub to the sensors which consists of information for establishing links and synchronization. Each beacon is immediately followed by the dataframes, which mainly consist of uplink traffic from the sensors to the coordinator (Fig.4). None of the sensor nodes transmit in the idle period. In fact, the idle period can be assigned as a period at which the coordinator sends its collected data to external servers. The beacons have offsets which can be adjusted via the hub. Beacons are sent in each beacon period unless prohibited via regulations in the inactive superframes on the MICs band. The hub allows for channel access using one of the following access modes:

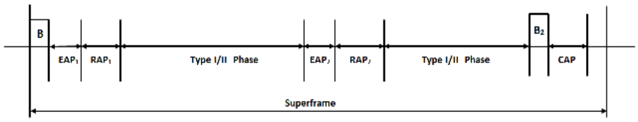

FIGURE 4. **Superframe of IEEE 802.15.6.**

1) BEACON MODE WITH BEACON PERIOD SUPERFRAME BOUNDARIES

In this mode, the hub sends beacons within each beacon period unless prohibited by restrictions in the MICS band or inactive superframes. Timed frames (T-Poll) or beacon frames are used to manage the communication of the superframe structure through the hub. In fact, the superframe structure of IEEE 802.15.6 consists of an Exclusive Access Phase 1 (EAP1), a Random Access Phase 1 (RAP1), a Type I/II phase, an Exclusive Access Phase 2 (EAP 2), a Random Access Phase 2 (RAP 2), a Type I/II phase, and a Contention Access Phase (CAP) as shown in Fig.4. Nodes attempt resource allocation either through CSMA/CA or Slotted ALOHA in CAPs, RAPs and EAPs. EAP1 and EAP2 are used for high priority traffic in reporting emergency situations; while CAP, RAP1 and RAP2 are only used for normal traffic. Type I/II phases are used for, downlink allocation intervals, uplink allocation intervals, bi-link allocation intervals and delay bi-link allocation intervals. Resource allocation in type I/II phases is obtained through polling. The application requirements can specify the duration length of these periods.

2) NON-BEACON MODE WITH SUPERFRAME BOUNDARIES

This access mode is not capable of transmitting beacons and is forced to use the Timed frames (T-poll) of the superframe structure. The whole superframe is either covered by one Type I or one Type II access phase, but not both.

3) NON-BEACON MODE WITHOUT SUPERFRAME BOUNDARIES

In this access mode, only unscheduled Type II polled allocation is provided by the coordinator, meaning each node has to establish its own time schedule independently. Each period of the superframe consists of one of the following three categories: *(a) Scheduled access and variants (connection-oriented contention-free access)*–This access mode schedules slot allocations of one or multiple upcoming superframes in 1-periodic or m-periodic allocations. *(b) Unscheduled and improvised access (connectionless contention-free access)*–This access mechanism uses polling or posting for resource allocation. *(c) Random access mechanism* This access mechanism uses slotted Aloha or CSMA/CA for resource allocation.

Nodes in WBANs have stringent energy constraints and require low power techniques which can be achieved by an appropriate choice of the MAC as it has a key role in defining the energy consumption. However, the proposed MAC protocols have mainly focused on enhancing throughput, latency and bandwidth utilization whilst not considering the major requirement of energy conservation [11]. Thus, the main feature in the design of a suitable MAC protocol for WBANs is energy efficiency. Sensory devices deployed within a WBAN need to support battery life in the range of hours to months and years without further intervention. Thus, flexible and power-efficient duty cycling techniques are required to minimize idle listening, control packet overheads, packet collisions and overhearing. Additionally, the WBAN MAC should allow simultaneous operations of the in-body (MICS band) and on-body frequency bands (ISM and UWB). The other important feature of the WBAN MAC is adaptability and scalability to changes in the network in terms of bandwidth utilization, delay and throughput. The electrical properties of the human body and the diverse range of traffic patterns for in-body and on-body nodes should also be considered. QoS is another important feature of a suitable MAC protocol for WBANs, which includes delay variation and point-to-point delay [35]. The authors of [36] have designed an energy-aware MAC protocol, namely HEH-BMAC for energy harvesting, which allows for the behaviour of each WBAN to adapt to its energy level. The available energy at each time instant will be an accumulation of the energy harvested as well as the energy stored in the battery. The proposed has two modes of operation to provide priority differentiation to the sensor nodes and flexibility to the network. Also, it dynamically adapts to operational changes in terms of energy harvesting rates, packet arrival times and network size. However, further analysis is required to improve the throughput, efficiency and QoS [36].

Literature study on MAC protocols for WBANs has demonstrated that CSMA/CA protocols encounter unreliable CCA issues and heavy collision [22]. On the other hand, TDMA has proven to be more reliable and power-efficient [22]. Thus, TDMA based approaches are more preferable, however, the limitations regarding dynamic slot allocation, synchronization overhead and multi-PHY communication need to be considered. Thus, a suitable MAC protocol for WBANs needs to satisfy requirements regarding traffic heterogeneity and correlation, reliability and MAC transparency [35]. In [22], the performance of three multiple access schemes, namely CDMA, FDMA and TDMA for inter-network interference has been investigated using real-world interference measurements in terms of Bit Error Rate (BER), Statistics of SINR and probability of collision. TDMA and FDMA have shown to be more efficient for interference mitigation whilst in the case of CDMA, WBANs have a high chance of collision as no set of codes can maintain orthogonality and may transmit over the same time and frequency in entirely asynchronous systems. TDMA has $N_c - 1$ (N_c refers to the number of orthogonal frequency channels) times shorter transmission time than FDMA for the same number of bits. Since, power consumption is important in WBANs, the lower the operating time the lower the overall power consumption. Most contention-based protocols that use CSMA/CA utilize Clear Channel Assessment (CCA) to specify the status of the channel. However, the high path loss inside and outside WBANs does not guarantee this approach [11]. Scheduled based approaches like TDMA are efficient for CCA problems and traffic correlation. However, TDMA alone is not as efficient as all sensors in TDMA approaches must receive periodic control packets to synchronize their clocks and extra energy is consumed for their periodic synchronization [11].

The authors in [37] have proposed a novel channel access scheme for WBANs by dividing the contention phase into four levels depending on the priority of the packet: highest priority medical services, general health service, mixed medical and non-medical service, and non-medical services. Based on the priority level of the packets, a threshold for successful packet delivery is also defined. Later the CAP is divided into subphases by threshold and off-sets are calculated to define the length of the divided sub-phases. The proposed approach has shown to provide low complexity, high energy, low power consumption and reduced collisions compared to the IEEE 802.15.6 baseline MAC protocol. However, further analysis is required to optimize the offsets. In [38], an Adaptive Channel Estimation and Selection Scheme (ACESS) for interference mitigation amongst coexisting WBANs is proposed. The proposed approach requires each WBAN to maintain a historical table and make predictions regarding channel availability based on a two-state Markov chain with exponential control on the channel history to control the sensitivity of predictions. The proposal has been shown to improve packet reception ratio in dense deployments of WBANs. The Mixed Broadcast Protocol (MBP) proposed in [39] combines the dissemination (flooding) and knowledge (forwarding) approaches for broadcasting information within WBANs. The protocol consists of two phases, where flooding begins in the initial phase. Each of the nodes that receive the packet, check the number of hops each packet has travelled before reaching this point and compares that to a threshold. Then forwarding or flooding is selected if the number of hops travelled is less than the predefined threshold, else forwarding is selected; and else-wise flooding. However, collision amongst coexisting WBANs is not considered, as well as variations in the use of different channel models. The authors in [40], use data classification and aggregation to avoid network collision and propose a layered and dynamic channel assignment policy to manage interference by associating the available frequency channels into the two layers of local cloud and local WBAN nodes. An adaptive and energy-efficient MAC protocol based on multi-channel communication is proposed in [41]. It considers channel hopping and changing the coordinator in the WBAN network based on the residual energy of the nodes.

D. MOBILITY FOR WBANs

The IEEE 802.15.6 standard for WBANs does not provide explicit support for mobility and can perform poorly in mobility scenarios as demonstrated in [42]–[44]. The accuracy of simulations for WBANs is dramatically effected from the mobility model being used. However, the proposed mobility models for ad hoc and sensor networks cannot be deployed in WBANs to their differences in movement patterns. Nodes in WBANs have group mobility which implies nodes move within a group and have a particular relationship on the movement of others in their group. In fact, the sensor nodes used in WBANs move relative to the coordinator node of that WBAN which is used as their reference point. Since the coordinator of WBANs is mostly placed in the chest area, the relative position of the sensor nodes in its network can be predicted in correlation with it. For instance, in the case of a person walking with the coordinator placed on his chest and sensory devices placed on his/her arms, nodes on the legs and arms move forward and backward repeatedly; thus, their location can be predicted. Since the trunk is less mobile, nodes placed on it will show lower variation with respect to the coordinator. However, in the lying position the next location of the nodes is hard to be predicted accurately. But, an area in which the node is most likely to appear in can be defined. Accordingly, the movement of nodes in different postures can be predicted with details provided in [45]. Similarly, we can visualize the movement of nodes placed on the human body in different postures.

In [46], a configurable mobility model referred to as MoBAN is proposed for evaluating intra-WBAN and inter-WBAN communication. The proposed model considers variations in posture as well as mobility of sensory devices in each posture. Therefore, different postures have been specified for which specification parameters can clarify which posture belongs to which category of mobility. Then the local mobility of nodes within each posture are defined. Markov chain models are used to find the transition probability from one posture to another. However, the nodes within each sensor are fixed and the authors do not consider variations once a node joins or leaves a WBAN. The Random Contention-based Resource Allocation (RACOON) medium access control protocol proposed in [47] supports quality of service (QoS) for multi-user mobile WBANs. It considers inter-WBAN interference and inter-WBAN priorities with which impose excessive energy-wastage and inter-network collisions. A probing interference detection is used for detection of interference through which data collision is avoided by calculating distance from the interference edge. Further, the user priority and bandwidth requirement are also considered in resource allocation for them. However, the authors have not considered the mobility models of sensors in each WBAN and the movement of WBANs towards one another. They have rather used a more general and iterative approach to encounter intra and inter WBAN mobility.

The authors in [48] have proposed an enhanced group mobility model to reduce the number of control messages used in the group-based proxy mobile IPv6 (PMIPv6) domain, since (PMIPv6) has poor performance in coexistence scenarios of WBANs. Specifically, the new format of control message proposed carries many identifiers in one message to reduce the handoff delay and decrease the number of control messages and signalling cost. A new group based hand-off scheme is also proposed that consists of three phases of registration, uplink handoff and downlink handoff. Each WBANs actively scans its surrounding by sensing a beacon request to its nearby WBANs. The WBAN in its coexistence that receives the beacon, decides if it is within the same mobile access gateway or if it has moved to a new one. A learning-based prediction algorithm is proposed in [49] to predict coexistence in a multiple-WBAN environment. The proposed approach uses the SINR, packet reception ratio (PRR) and previous-state via the naive-Bayesian classifier to predict the performance of multi-WBAN scenario and measure the quality of communication. Therefore, the authors quantitatively defines the coexistence states using the duration of interference and SINR value being above or below a certain threshold. Movement of WBANs leads to substantial variations on the SIR. The authors in [50] develop a lognormal statistical model that matches distance to signal power from their time-base measurements.

In [45], a mobility model is presented for the group based movement of nodes deployed on a human body as a WBAN. Different postures are encountered such as sitting, laying, walking, etc. The movement pattern of these postures and their pattern is analysed. The transition probabilities for moving from one posture to another are calculated. The mechanism for mobility detection is accomplished through two different phases: posture selection phase and nodes movement phase. The posture is selected from sitting, standing, lying, walking and running with the probability of its change being detected from real human traces. Then, in the second phase nodes move based on the selected posture. The authors in [51] analysed the performance of the Loose association Implicit reservation Protocols for Mobile WBANs (LIMB) and found the topology to be quite dominating in their performance. In fact, the energy consumption and channel utilization of the Reduced Function Devices (RFD) has shown to be independent of the number of RFDs given a specific number of Fully Functional Devices (FFD). However, random scenarios and the effect of backbone protocols have not been investigated.

In [52], radio-location experiments for mobility detection and indoor navigation applications of WBANs have been accounted for. Behavioural analysis of time stamped radio-location with respect to human captured body mobility is proposed. In fact, RSSI measurements are used for preliminary learning and subsequent decision based on Bayesian tools and machine learning, where high deviation links account for mobile sequences. Additionally, mobility detection rates are reinforced with joint Bayesian decisions. Also, the distinction between different arm postures can be made based on absolute deviation levels. However, posture detection based on on-body links and contextual body shadowing mitigation for RSSI ranging and navigation over off-body links needs to be further investigated.

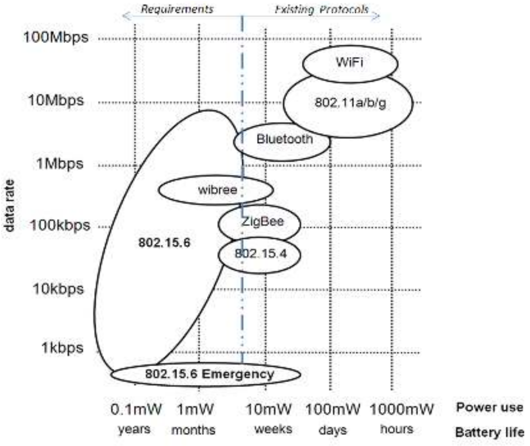

FIGURE 5. Power Requirements and Data Rates in WBANs as in [21].

E. ENERGY CONSTRAINTS AND MITIGATING INTERFERENCE

WBANs have stringent power constraints. A comparison of the data rates and power requirements of WBANs with other wireless technologies is shown in Fig. 5. As can be seen, some technologies do not meet the power requirement of less 10mw in WBANs. Thus, WBANs need more power efficiency compared to the other networks. The data rates of sensors used in WBANs can range from 1 Kbit/s to 10 Mbit/s [53]. More specifically, the data rate of in-body nodes vary from few Kbps in a pacemaker to quite a few Mbps in a capsule endoscope. Currently, most devices use Bluetooth (802.15.4) or Zigbee (802.15.1) as their monitoring station where neither of them meet the power requirements of WBANs. Two hop cooperative communication has shown to provide major benefits to WBANs in both ultra-wideband and narrow-band communications [12], [32], [54], [55]. One of these approaches considered the use of idle sensors as relays for cooperative receive diversity which achieved 15dB improvement in average bit-error probability using decode and forward relaying with cooperative diversity. In [32] cooperative communication with no cooperation between WBANs was first encountered and shown to provide up to 12dB improvement in Signal-to-interference plus noise ratio. Experimental results have shown interference to have less impact on the performance of coexisting WBANs (better SINR outage) when the hub is located on the chest. Even though using cooperative receive diversity has demonstrated significant performance in outage probability, since the proposed approach uses TDMA between coexisting WBANs there is a huge delay between the transmission of nodes of a single WBAN in the coexistence of densely deployed WBANs.

In this section we have presented the challenges of deploying multiple WBANs in each others vicinity and the interference mitigation schemes proposed thus far for WBANs. Some of the challenges of WBANs have been considered in these proposals however; their practical deployment requires further research and investigation. The future vision of WBANs is to allow for reliable, cost-effective and energy efficient communication amongst all co-located WBANs.

In [56], a power control method based on reinforcement learning is proposed to maximize the achievable throughput and mitigate internetwork interference with minimum power consumption. The learning based approach dynamically discovers the environment and learns the best model to minimize energy consumption. When compared to game theoretic and fuzzy logic approaches, the proposed approach provides 5 to 10 times higher energy lifetime. However, the complexity of the proposed approach as well as the convergence time have not been computed. A joint relay selection and transmit power control based on channel prediction is presented in [55] for a WBAN in different conditions. The proposed approach has been shown to significantly prolong battery lifetime and mitigate interference compared to direct link transmission, specifically a60% reduction in circuit power consumption and lower SINR outage probability.

On-body energy management schemes for emerging WBANs have been investigated in [57], where a WBAN-specific dynamic power control approach that adapts its body posture inference for optimal power assignment is proposed. The authors consider using a range for RSSI values to achieve a desirable balance between transmission energy consumption and packet loss. The authors have chosen the two most recent transmit power RSSI data to infer a posture position and compute the new power level since sampling more than two points can often take longer than the duration of lasting in a specific posture. The power control mechanism proposed is closed loop with a feedback that aims to infer a subjects postural position and use that knowledge to obtain the suitable transmit power.

III. SYSTEM ARCHITECTURE

We consider a set of N_c number of coexisting WBANs denoted by $\{w_k | k = 1, \ldots, N_c\}$, where w_k refers to the kth WBAN. Each WBAN consists of a homogeneous set of N_s sensors denoted by $\{s_k^i | i = 1, \ldots, N_s\}$ with equal priority communications. One coordinator node acts in each WBAN as a receiver in a one-hop star topology. We consider that the N_c coexisting WBANs use the same technology for coordinators communication with their sensor nodes (intra-WBAN communication) and create a backhaul infrastructure for inter-WBAN communication. For simplicity, we model each WBAN by two concentric circles, one of radius r known to be its sensing range, and one of radius R, known as its communication range, shown in Fig. 6(b) ($R = 2r$). Sensor nodes of each WBAN are uniformly located at random within the area of the circle.

All WBANs are considered to utilize a similar superframe structure, and inter-WBAN superframe synchronization is achieved before transmission. Thus, collisions never occur between one WBAN's control frame and another WBAN's data frame [10]. Interference may occur between coexisting WBAN's data frames in the Contention Free Periods (CFP) [58]. We assume that all sensor nodes have similar characteristics, a unique identification number (ID) and are initially provisioned with an equal amount of energy. The coordinator broadcasts a message in the R radius coverage area containing the ID of its sensor nodes, their residual energy, location in the buffer and their allocated time slot.

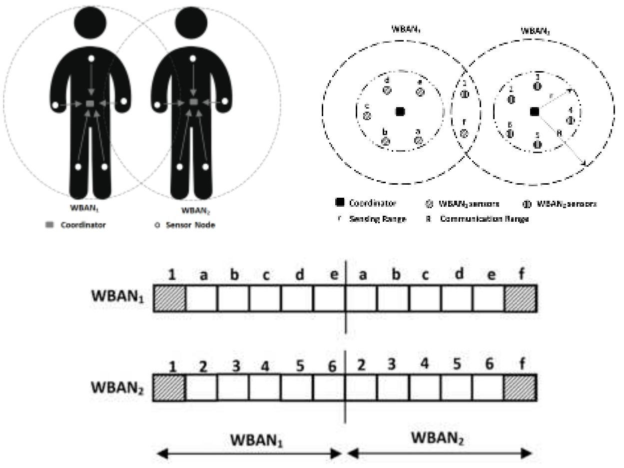

FIGURE 6. Inter-WBAN Channel Assignment for coexisting WBANs: (a) Topological distribution (b) Sensors within coexisting WBANs (c) Proposed SCA Scheme.

We assume that a TDMA based Medium Access Control (MAC) is used within each WBAN to avoid intra-WBAN network collisions. Therefore, in order to avoid inter-WBAN interference, nodes that exist in the interference set of one another need to be allocated orthogonal channels that do not coincide with one another's transmission. Hence, the placement of nodes in the buffer needs to be taken into account to avoid any channel allocation errors.

We then obtain the mean path loss without shadowing amongst two WBANs from the Free Space Path Loss (FSPL) model based on the time varying nature of the channel and change of distance with time due to intra and inter-network dynamics to be as follows:

$$P_{dB}(d, t) = P_{0,dB} + 10n \log_{10}(d(t)/d_0) \tag{1}$$

where $P_{0,dB}$ is the path loss at reference distance d_0 (d_0 is considered to be 10cm), n is the path loss exponent considered as 2 in free space and is stated to vary in different body locations based on investigated measurements. We later consider coexisting WBANs to move towards each other using a mobility model described in Section III. Table 2 shows the list of abbreviations and notations used throughout the paper.

We implement the S-MAC (Sensor MAC) protocol proposed in [59] because S-MAC reduces energy consumption as well as providing good scalability and collision avoidance. This MAC protocol is quite beneficial for use in WBANs as it aims to eliminate energy consumption from different sources of collision, idle listening, overhearing and control overhead. This feature reduces energy consumption relative to idle listening; however, the delay is slightly increased as the radio needs to wait for the sender to wake up before sending data again. Thus S-MAC reduces energy consumption through a

TABLE 2. Notation and abbreviation summary.

Notation	Description
N_c	Number of coexisting WBANs
N_s	Number of sensors in each WBAN
T_d	Superframe Length
$R_0(t)$	Reuse factor
$D(t)$	Distance in meters between coordinators of coexisting WBANs
γ_{th}	Threshold SINR
γ_0	Reference SINR
P_r	Received power in dB
P_t	Transmit power in dB
(i, j)	Sensor j from $WBAN_i$
$SINR_{i,j}$	SINR of node j in the vicinity of $WBAN_i$
r	Radius of Sensing Range
R	Radius of Communication Range
$P_{0,dB}(d, t)$	Path loss at distance d
$P_{I,i}$	Interference Power from sensor node i
m	Number of nodes that coexist in the interference region of the WBAN of interest
α	Angle between the direction of movement of a WBAN vs the horizontal access
τ	Time at which interference between coexisting WBANs initiates
τ'	Duration for which coexisting WBANs will interfere on one another
$R\vec{P}$	Location of coordinator node of each WBAN
MN	Sensor nodes of each WBAN
$G\vec{M}$	Vector of group movement of the coordinator of each WBAN with its sensors
$R\vec{M}$	Vector of movement of sensor nodes in each WBAN towards their coordinator
Rx_{sens}	Received sensitivity

number of advantages. It allows for periodic sleep and listen which implies reducing the listen time by allowing the node to go into sleep mode. Another advantage of using S-MAC is collision and overhearing avoidance for which it uses the Request To Send (RTS)/ Clear to Send (CTS) mechanism to contend for the medium. The first node to send a RTS packet wins the channel and the receiver which is the coordinator of the WBAN of interest will respond via a CTS message. The overhearing avoidance in S-MAC allows the interfering nodes to go into sleep mode after they hear an RTS or CTS packet and therefore, reduces the energy consumption relative to overhearing packets that are not directed to that node. Additionally, the percentage of delay in the network for a sender to wake up to transmit its' packet is fairly negligible when compared to the amount of energy savings it provides. More specifically, an increase of 80 % energy efficiency is obtained for an increase of less than half a second in the delay. The proposed S-MAC protocol also allows for message passing which means long messages can be fragmented into many small fragments and transmitted in bursts using only one RTS and one CTS packet. The sender waits for a ACK message from the receiver each time a data fragment is transmitted. Failure to receive the ACK will extend the reserved transmission time for another fragment and immediately retransmit its current fragment [60].

IV. PROPOSED SCHEME

We consider to use the authors' Smart Channel Assignment (SCA) algorithm proposed in [18] as the basis of communication between coexisting WBANs in a static scenario. We then utilize the SMAC structure for the MAC layer and later embed a mobility model that best describes network dynamics within and between coexisting WBANs. Power control is further taken into account to avoid frequent updates in channel assignment which lead to energy drainage.

A. SMART CHANNEL ASSIGNMENT (SCA)

We consider a total of N_c coexisting WBANs, each consisting of N_s sensor nodes. Smart Channel Assignment (SCA) is accomplished through four stages described as follows:

- *Step I: Orthogonal Transmission:* Coordinators of coexisting WBANs assign orthogonal channels for each WBAN. Therefore, the shared channel is evenly divided evenly into N_c time-slots and further divided into N_s portions for each sensor node.
- *Step II: Interference Set Formation:* After the first round of orthogonal transmission, each coordinator creates a table consisting of the received power from each sensor of all WBANs. In the next step, each coordinator finds the minimum received power from its sensors and compares it to the received power from sensors of other WBANs. If the received power of a sensor from other WBANs is larger than the acceptable threshold, that sensor is added to the Inter-Interference list.
- *Step III: Information Exchange:* In this stage each coordinator broadcasts its interference list. Thus, each coordinator can create an interference set, which consists of all sensors that have an interference level above the acceptable interference threshold.
- *Step IV: Smart Channel Assignment:* Channel assignment is updated at this stage. We represent the number of nodes in the interference set $\mathcal{S}_i$ with s_i. Nodes that exist in the interference set are assigned with the same time slot as before whilst the remaining $N_cN_s - s_i$ time slots are equally allocated to nodes of the WBAN of interest which are not in the interference set.

An example of the proposed interference mitigation for two coexisting WBANs as in Fig.6.(b) is shown in Fig.6.(c). The intersection of coverage radius between coexisting WBANs represents their interference region. Thus, the interference region of each WBAN is formed with a tuple where the first component is the ID of the WBAN, which is interfering with the WBAN of interest, and the second component is the ID of the sensor node of that WBAN which is interfering with our WBAN of interest. Next, WBANs will broadcast their inter-network interference sets. Then, each WBAN allocates an orthogonal channel to sensors within itself that coexist in another WBANs interference set and allows the remaining sensors to simultaneously occupy the rest of the channels. This approach increases the spatial reuse as well as lowering the delay as opposed to fully orthogonal channel assignment which is done in existing schemes since interference is only looked at from the network level and not the node-level. The pseudo-code for the proposed SCA algorithm is shown in Algorithm 1.

Let $p_{m,i}$ denote the probability that m number of nodes exist in the interference region of WBAN_1, then we have:

$$p_{m,i} = \binom{N_s}{m} P_{I,i}^m (1 - P_{I,i})^{N_s - m}, \tag{2}$$

Thus, the number of nodes of each WBAN that are in the interference region is a binomial distributed random variable with parameters N_s and P_I. Therefore the mean value and variance of m can be calculated as follows:

$$m_m = \text{E}[m] = N_s P_I, \tag{3}$$

Algorithm 1 Smart Channel Assignment (SCA)

```
Step 1. Orthogonal Transmission
for $i = 1$ to $N_c$ do
    for $j = 1$ to $N_s$ do
        Sensor $(i, j)$ is transmitting
        $WBAN_\ell$ estimates the received signal power, $\gamma_{i,j}$, from sensor $(i, j)$
    end for
end for
Step 2: Determine the inter-interference set
for $i = 1$ to $N_c$ do
    $\gamma_{min,i} = \min\{\gamma_{i,j}\}$
    for $\ell = 1$ to $N_c$, $\ell \neq i$ do
        for $j_2 = 1$ to $N_s$ do
            if $\gamma_{\ell,j_2} > \gamma_{min,i} - \gamma_{Th}$ then
                Add $(\ell, j_2)$ to set $\mathcal{I}_i$
            end if
        end for
    end for
end for
Step 3: Broadcast
for $i = 1$ to $N_c$ do
    Broadcast $\mathcal{I}_i$
end for
Step 4: Determine the interference set
for $i = 1$ to $N_c$ do
    $\mathcal{S}_i = \mathcal{I}_i \cup \{(i, j) | (i, j) \in \mathcal{I}_\ell, \ell \neq i\}$
end for
Step 5: Channel assignment
for $i = 1$ to $N_c$ do
    Leave the time slots for nodes in $\mathcal{S}_i$ unchanged
    Equally assign the remaining channels to nodes that do not belong to $\mathcal{S}_i$.
end for
```

$$\sigma_m^2 = \mathrm{E}[(m - m_m)^2] = N_s P_I (1 - P_I). \tag{4}$$

The following lemma then gives the average reuse factor for WBAN$_0$.

Lemma 1: Let $R_0(t)$ denote the average reuse factor for $WBAN_0$ and $P_{I,i}(t)$ as the probability that a sensor node of WBAN$_i$ exists in the interference region of WBAN$_0$ at time t. Then $R_0(t)$ can be calculated as follows:

$$R_0(t) = N - \sum_{i=1}^{N-1} P_{I,i}(t) \tag{5}$$

Proof: Since $P_{I,i}(t)$ is the probability that a sensor node of WBAN$_i$ exists in the interference region of WBAN$_0$ at time t, then on average $N_s P_{I,i}(t)$ sensors of WBAN$_i$ exist in the interference region of WBAN$_0$, for $i = 1, 2, \ldots, N$. Due to symmetry, $N_s P_{I,i}(t)$ sensors of WBAN$_0$ exist in the interference region of WBAN$_i$. The total number of available channels is $N_c N_s$, which among them $2\sum_{i=1}^{N-1} N_s P_{I,i}(t)$ channels will be allocated orthogonally. The remaining channels will be uniformly assigned to the sensor nodes of WBAN$_0$. The number of the sensor nodes of WBAN$_0$, which are in the interference region is $\sum_{i=1}^{N-1} N_s P_{I,i}(t)$, and so the average reuse factor can be calculated as follows:

$$R_0(t) = \left(\frac{1}{N_s} (\sum_{i=1}^{N-1} N_s P_{I,i}(t)) + \frac{(NN_s - 2\sum_{i=1}^{N-1} N_s P_{I,i}(t))}{N_s - \sum_{i=1}^{N-1} N_s P_{I,i}(t)} \right. \\ \left. \times\ (N_s - \sum_{i=1}^{N-1} N_s P_{I,i}(t)) \right).$$

This completes the proof. ■

We have first considered the coexisting WBANs to be assigned interference-free channels using the SCA scheme statically. We now consider network dynamics relative to the movement of WBANs towards each other (inter-WBAN mobility) and the movement of sensors within the WBAN (intra-WBAN mobility).

We consider the case of two coexisting WBANs, where both ($WBAN_1$ and $WBAN_2$) are approaching each other with a speed of V_{WBAN1} and V_{WBAN2} with an angle of α (α is the angle between the direction of movement of $WBAN_2$ and the horizontal axis of movement shown in Fig.7).

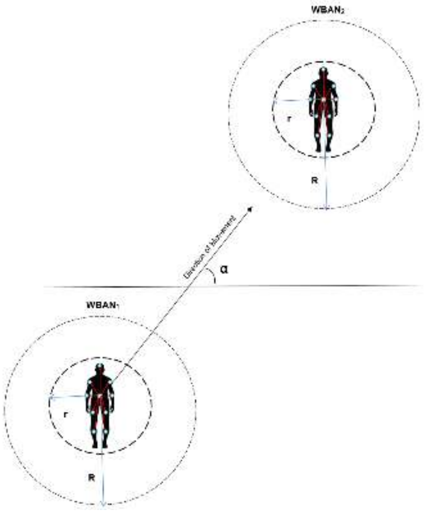

FIGURE 7. Movement of two WBANs with respect to each other.

The important aspect to discover is if the two WBANs will interfere with one another's transmission. This selection is based on three factors: α being the angle of the direction of movement between the WBANs; τ' being the duration for which the WBANs remain in each others interference region and $D(t)$ which is the distance between the coexisting WBANs. Hence, we need to find the time duration for which a sensor of coexisting WBANs will move into the interference range of the WBAN of interest. If this time duration is above the allowed threshold time (t_{TH}) allowed, changes need to be made to avoid interference which leads to throughput loss and energy drainage. The threshold time can be calculated as follows:

$$t_{TH} = \frac{T_d}{R_0(t)} \tag{6}$$

where $R_0(t)$ is the reuse factor and $T_{superframe}$ is the duration of each superframe.

Due to the social nature of WBANs, they will have interaction that lasts for a certain duration [61]. Thus, we need to find the time instant where two WBANs move into each others coexistence and further obtain the duration for which they stay in each others interference region. We consider (a, b) to be the coordinates of the center of $WBAN_1$. Since $\tan(\pi - \alpha) = -tan(\alpha)$, we have the following:

$$y(t) = -\tan(\alpha) \times x(t) + c \tag{7}$$

$$m = \frac{-1}{-\tan(\alpha)} = \cot(\alpha) \tag{8}$$

$$y(t) - a = \cot(\alpha)(x(t) - b) = \cot(\alpha)x(t) - \cot(\alpha)b + a \tag{9}$$

By substituting (7) into (9) we have the following:

$$-\tan(\alpha) \times x(t) + c = \cot(\alpha)x(t) - \cot(\alpha)b + a \tag{10}$$

Since the values of a, b and c are known in advance, we can find the value of $x(t)$ and $y(t)$. We can also calculate $D(t)$ as follows:

$$D(t) = \sqrt{(x(t) - a)^2 + (y(t) - b)^2} \tag{11}$$

If $D(t) > 2R$ we do not have intersection of regions between the coexisting WBANs. If $D(t) < 2R$, the coexisting WBAN intersect in their regions where the value of $2R - D(t)$ shows the extent of their intersection. The higher this value, the more the interference. If $D(t) = 0$ their intersection ratio will be 100%. The value of $D(t)$ also shows how far or how close we are to the r region ($D(t) < 2r$ and $D(t) > 2r$). Based on the aforementioned calculations, the WBANs will realize if they would need to make any changes to their assigned allocations.

Thus, the time at which any significant interference between two coexisting WBANs starts is a function of the speed of the co-located WBANs and can be calculated as follows:

$$\begin{aligned} D(t) - 2r &= |V_{WBAN_2} \pm (V_{WBAN_1})| \times \tau \\ \Rightarrow \tau &= \frac{D(t) - 2 \times r}{(V_{WBAN_2} + V_{WBAN_1})} \end{aligned} \tag{12}$$

The duration at which there is a likelihood for the coexisting WBANs to interfere with each other, referred to as τ' can be calculated as follows:

$$\begin{aligned} 4r &= (V_{WBAN_2} \pm V_{WBAN_1}) \times \tau' \\ \Rightarrow \tau' &= \frac{4 \times r}{(V_{WBAN_2} + V_{WBAN_1})} \end{aligned} \tag{13}$$

where the relative velocity of the coexisting WBANs is accumulated if they are moving towards each other and deducted when the coexisting WBANs are not moving towards one another.

In the case where the duration of coexistence of the new WBAN that has moved into the interference region of the WBAN of interest is less than t_{TH}, the amount of interference is negligible and no changes need to be made in the channel assignment as each sensor will be able to successfully transmit its packets. However, in the case that the duration of coexistence exceeds the threshold value, we need to consider to either update the channel assignment or proceed with node-level power control.

B. INTRA AND INTER WBAN MOBILITY MODEL

We consider the use the Reference Point Group Mobility (RPGM) model to represent the random motion of a group of WBANs as well as the random motion of each individual WBAN within the group. This model has been shown to provide high Packet Delivery Ratio (PDR), low delay and high throughput amongst other existing group based mobility models [62]. In this mobility model, the group movements of each WBAN are based upon the route travelled by a group motion vector, $\vec{GM}$ from a logical center for the entire network. The motion of the Mobile Node (MN) within their group is reliant on the motion of the group center along with their direction and speed. The random movements of each MN from their pre-defined reference point is relative to the group movement. The location of individual reference points from time instant t to $t + 1$ is updated based on the group logical center. Then, the random motion of each MN from its reference point is updated via the combination of the updated reference point $RP(t+1)$ with the random motion vector, $\vec{RM}$.

The group motion vector $\vec{GM}$ is used to calculate the new reference point of the WBAN, $RP(t + 1)$, at time $t + 1$. It is important to note that the $\vec{GM}$ can be predefined or randomly chosen. Fig. 8 provides an illustration of a WBAN consisting of a number of sensors at time instance t and $t+1$ using the RPGM model for its movement. The reference point (RP) denotes the coordinator of the WBAN of interest and the MN represents the sensor nodes within each WBAN. The movement of the sensors of each WBAN towards their coordinator is represented via the random motion vector, $\vec{RM}$. Thus, the new position of each MN is further calculated by adding the random motion vector, $\vec{RM}$, with the new reference point, $RP(t + 1)$. The length of $\vec{RM}$ is uniformly distributed within a specified radius centered at $RP(t+1)$ and its direction

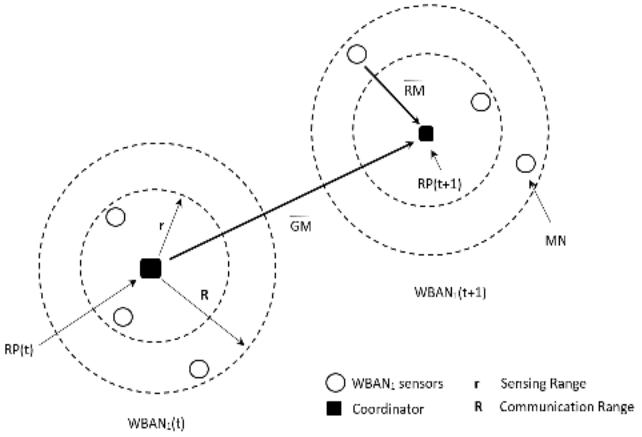

FIGURE 8. Movement of a WBAN with its sensors using the RPGM Model.

is uniformly distributed between 0 and 2π and with the length of 0 to $\frac{R}{2}$.

We consider the coordinator of the WBAN of interest at time instant t to be the origin with coordinates of (0, 0). Thus, the coordinates of the WBAN of interest at time instant $t+1$ using the movement vectors can be calculated as follows:

$$RP(t+1) = RP(t).\vec{GM} \tag{14}$$

$$MN(t+1) = MN(t).\vec{RM} \tag{15}$$

C. POWER CONTROL

In this section, we propose a power control approach on top of the proposed method for inter-network interference mitigation for WBANs. Because the WBANs are battery-supported, it is critical to reduce the energy consumption of WBAN system, prolong its lifetime and enhance the system's reliability. Therefore, the goal of the power control is to maximize the network utility while minimizing the power consumption.

We propose to reduce the transmission power of the sensor nodes that have just joined the interference region of a coexisting WBAN. Based on a simple comparison between the the received interference power of nodes at different time instances we can realize that the nodes have moved into each other interference range. If the received power from node j of $WBAN_1$ at $WBAN_2$ is above the γ_{th}, it can be predicted that they have moved into each others interference range. For instance, in the case where interference is detected between node i of $WBAN_1$ and node j of $WBAN_2$ at time t and the interference distance is d_0, then at the next time instant the transmission power of the signal of node i needs to be changed by some step which can calculated as follows:

$$P_t(t+1)_{\text{dBm}} = \max\,(\min[P_t(t) - P_r(t) + Rx_{sens} + \text{offset}, 0\text{dBm}], -30\text{dBm}) \tag{16}$$

EQ.(16) is calculated in the dB domain. In fact EQ.(16) also describes simple "Sample-and-Hold" channel prediction, where the last estimate of interfering channel gain is used as an approximate estimate of the next channel gain, following from [32], [54] Initially, we consider a constant transmit power of $0dBm$ for all sensor nodes throughout the paper ($P_t = 0dBm$) and a threshold power of -70 dB with an offset of 15dB and a received sensitivity Rx_{sens} of $-90dBm$. Then power control is only calculated in the interfering nodes. If the power of an power of interfering node at time instant $t+1$ is still above the γ_{th}, the channel assignment is updated. If not, transmissions are continued with the new calculated power. The pseudo code for the proposed prediction algorithm for capturing unknown dynamics using the SCA scheme, SMAC and power control is shown in Algorithm.2. Also, the flowchart for the step by step procedure is shown in Fig. 9.

Algorithm 2 Energy-Efficient Channel Assignment for Coexisting WBANs With Unknown Dynamics

```
Initially set $\mathcal{I}_i = \varnothing$ and $\mathcal{S}_i = \varnothing$,
for $t = 0$ to $t_{network\ lifetime}$
Step 1. Orthogonal transmission
for $i = 1$ to $N_c$
for $j = 1$ to $N_s$
Sensor $(i, j)$ is transmitting
 $WBAN_l$ estimates the received signal power, $\gamma_{i,j}$, from sensor $(i, j)$
Step 2. Determining the inter-interference set
for $i = 1$ to $N_c$
$\gamma_{min,i} = \min\{\gamma_{i,j}\}$
for $l = 1$ to $(N_c)$, $l \neq i$
for $j_2 = 1$ to $N_s$
if $\gamma_{l,j_2}(t) > \gamma_{min,i}(t) - \gamma_{Th}$
Add $(l, j_2)$ to set $\mathcal{I}_i(t)$
for $(D_{l,j_2}(t) - r) \leq 0$
if $\gamma_{l,j_2}(t) > \gamma_{min,i}(t) - \gamma_{Th}$ and $\gamma_{l,j_2}(t-1) \leq \gamma_{l,j_2}(t)$ and $t \geq t_{TH}$
if $\max(\min[P_t(t) - P_r(t) + Rx_{sens} + offset, 0dBm], -30dBm) \geq SINR_{th}$
Add $(l, j_2)$ to set $\mathcal{I}_i(t)$
else if update SCA channel assignment
else if $\gamma_{l,j_2}(t) > \gamma_{min,i}(t) - \gamma_{Th}$ and $\gamma_{l,j_2}(t-1) \geq \gamma_{l,j_2}(t)$
Remove $(l, j_2)(t)$ from set $\mathcal{I}_i(t)$
Step 3. Broadcast
for $i = 1$ to $(N_c)$
Broadcast $\mathcal{I}_i(t)$ in $R$ region
Step 4. Determining the interference set
for $i = 1$ to $(N_c)$
$\mathcal{S}_i = \mathcal{I}_i \cup \{(i, j) | (i, j) \in \mathcal{I}_l, l \neq i\}$
Step 5. Channel assignment
for $i = 1$ to $(N_c)$
Leave the time slots for nodes in $\mathcal{S}_i(t)$ unchanged
 Equally assign the remaining channels to nodes that are not belong to $\mathcal{S}_i(t)$.
$t = t + 1$ ;
```

V. SIMULATION RESULTS

In order to evaluate the performance of the proposed prediction algorithm, we have performed simulation of the proposed scheme in NS-2 simulator (version 2.34) [63] with a one hop star topology for four different cases: SCA only, SCA with S-MAC, SCA with RPGM, SCA with power control. In this section, we compare the performance of the proposed scheme in these four cases in terms of inter-WBAN communication to evaluate the delay, throughput, PDR and energy consumption. The parameters used for these simulations are provided in Table. 3.

Fig. 10 depicts the average delay of each sensor per WBAN for transmission versus the simulation time for the four considered cases. As can be seen, embedding SMAC in the SCA algorithm slightly increases the delay which is due to the channel being switched off at times where the sensors are not transmitting and then being switched back on when required to transmit. This leads to a slight delay for waiting

TABLE 3. Parameters in simulation.

Simulator	NS-2
Simulation duration (Sec)	120
Simulation area	20m X 20m
Number of Sensor Nodes per WBAN	9
Number of Coordinators per WBAN	1
Number of WBANs	from 2 to 10
MAC Layer Protocol	IEEE 802.15.4
Queue Size	50
Packet rate	4 packets/sec
Packet Size	512 Bytes
Sensing Range	100 cm
Initial Energy	50 J

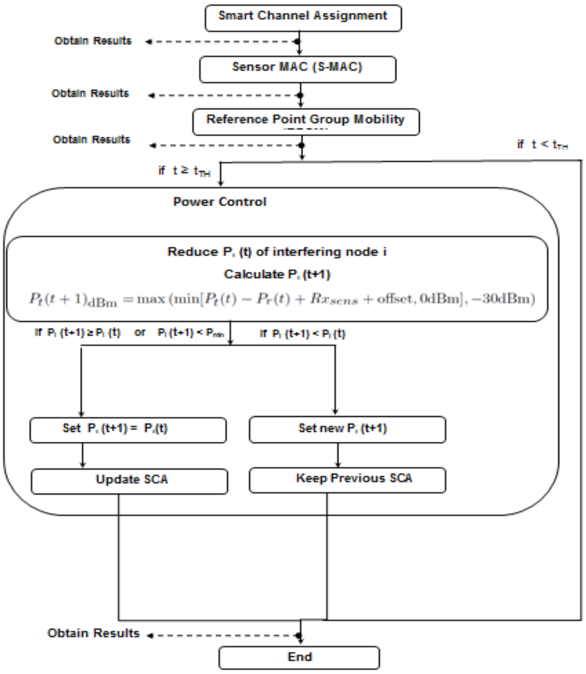

FIGURE 9. Flowchart of Proposed Approach.

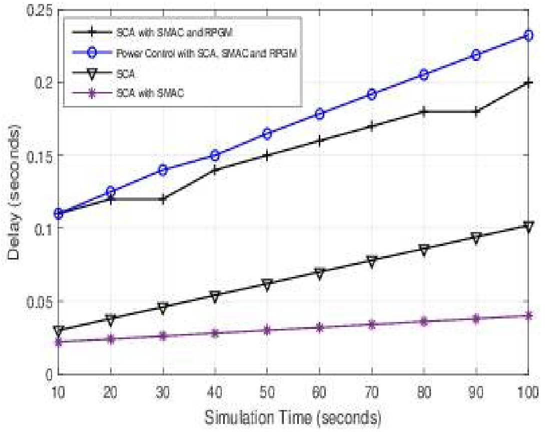

FIGURE 10. Average Delay versus Simulation Time.

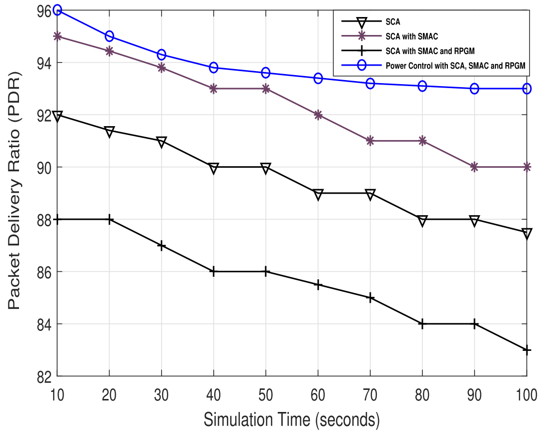

FIGURE 11. Average Packet Delivery Ratio versus Simulation Time.

to be switched back on to transmit again. In the case where coexisting WBANs move in the vicinity of one another, new sensors can move into and out of each others range, which implies the need for changes in channel assignment. In such a case, some delay is caused to compute the new channel and upgrade channel assignment to align with the SCA protocol to avoid interference and minimize energy consumption and delay. In the case that power control is also taken into account, delay is further introduced as the sensor's transmission will not be allowed if it exceeds the acceptable threshold for coexistence. Thus Fig. 10 shows the proposed approach maintains reasonable results in all four cases.

Fig.11 demonstrates that using SMAC protocol on top of the SCA algorithm improves the packet delivery ratio due to the collision avoidance features embedded in it. However, the introduction of channel dynamics imposes variations within the network which requires novel channel assignment in some cases where the transmission of a certain WBAN can be terminated upon new changes in the network that leads to lower packet delivery ratio. In the case the power control feature is also considered (as shown in Fig. 11) packet delivery ratio is enhanced as the power of the interfering sensor nodes will be reduced leading to less interference and therefore higher PDR.

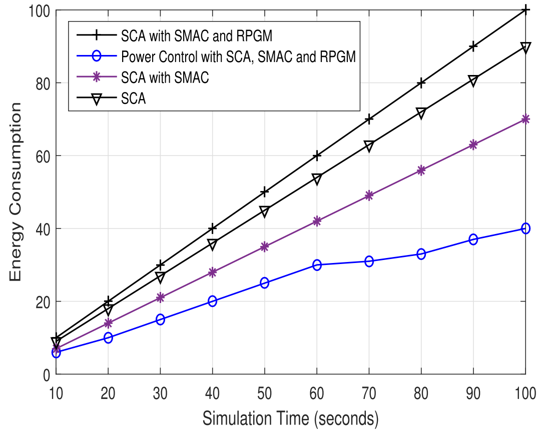

FIGURE 12. Average Consumed Energy versus Simulation Time.

Fig. 12 shows the average consumed energy at the sensor node versus the simulation scenario time for the four different cases. As can be clearly seen in this figure, the SCA with

S-MAC scheme provides higher energy savings as it goes into sleep/idle mode at instances that it is not transmitting. However, in the case that mobility is induced into the network which implies changes in the interference region more assignment might be required which leads to more energy. The most important message conveyed from Fig.12 is that variations in energy consumption is very low and can be neglected in return for massive gains in throughput and reuse. Fig.13 depicts the average convergence time for different stages of the protocol. As can be seen, there is only a slight increase of up to 80 milliseconds for embedding the power control feature as well as encountering mobility and SMAC on the SCA scheme which reassures its computational complexity.

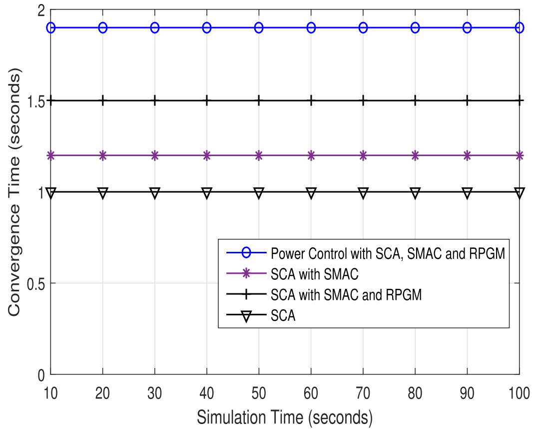

FIGURE 13. Average Convergence Time versus Simulation Time.

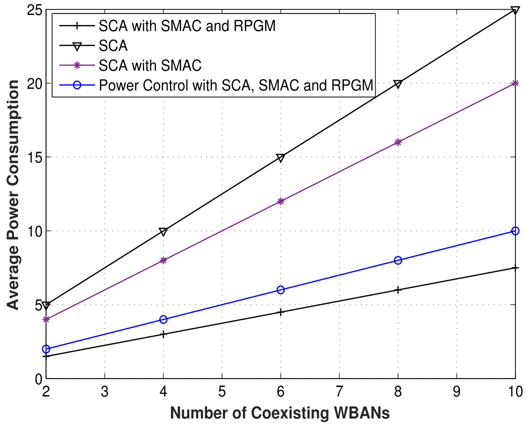

FIGURE 14. Average Power Consumption versus the Number of Coexisting WBANs.

Next, we evaluate the performance of the proposed scheme with different density of coexisting WBANs from 2 to 10. As expected and also demonstrated in Fig.14, the increase in the density of coexisting WBANs increases the power consumption, with the highest rate of energy consumption in the SCA scheme on its own. Whilst, the incorporation of SMAC with SCA has shown to decrease energy consumption as it introduces idle periods that avoid excess energy usage. The best attribute is the performance of the proposed protocol when mobility is introduced which shows less energy consumption that implies the introduction of network dynamics has been well predicted in advance and taken care of ahead of time.There is only marginal degradation from this when transmit power control is introduced.

Fig.15 depicts the average packet delivery ratio(PDR) versus the density of coexisting WBANs. As expected, the PDR increases, as the number of coexisting WBANs increases. But, as can be seen, the introduction of network dynamics has not deteriorated the performance of the proposed protocol. In fact, the introduction of SMAC has increased the packet delivery ratio. However, introducing network dynamics by deploying the RPGM model has led to a slight decrease in the packet delivery ratio compared to the SCA and SCA with SMAC scheme. This has been well overcome by incorporating power control in the proposed approach as the power control scheme reduces the power of sensory devices, therefore creating less radio interference in the new mobility scenario, leading to higher packet delivery ratio, compared to incorporating the mobility model on the top of the SMAC and the SCA scheme on their own.This case with power control maintains a packet delivery ratio above 93%, well above the 90% guideline in the IEEE 802.15.6 requirements

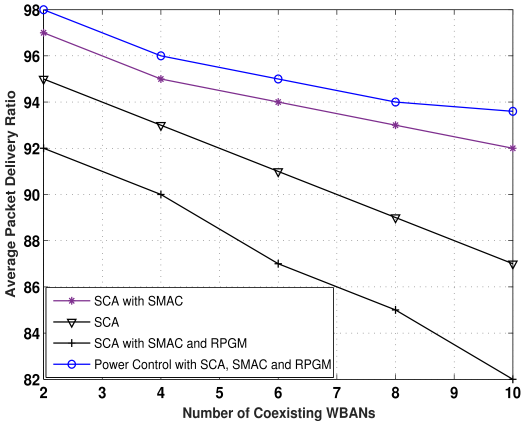

FIGURE 15. Average Packet Delivery Ratio versus the Number of Coexisting WBANs.

The amount of delay versus density of coexisting WBANs is shown in Fig.16. It can be noted that, as expected, as the number of coexisting BANs increase the average delay increases. Also, incorporating SMAC with the SCA scheme slightly increases the delay since it introduces idle periods and then needs to initiate again. There is a slight delay between the time the network goes into idle period and becomes active again which introduces this slight amount of delay. As shown the main drawback of incorporating power control is an increased delay of over 500ms for 10 coexisting WBANs.

Fig.17 shows the convergence time versus the number of coexisting WBANs. As can be seen, deploying SMAC with

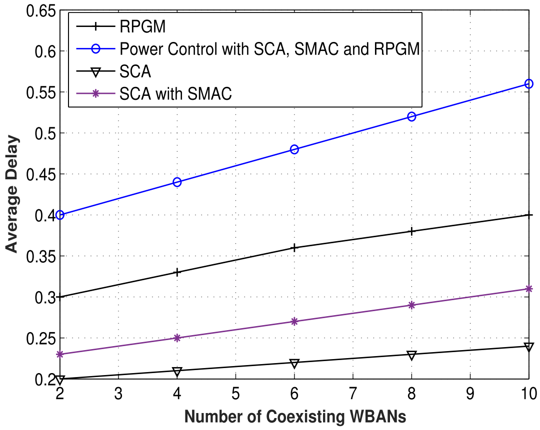

FIGURE 16. **Average Delay versus the Number of Coexisting WBANs.**

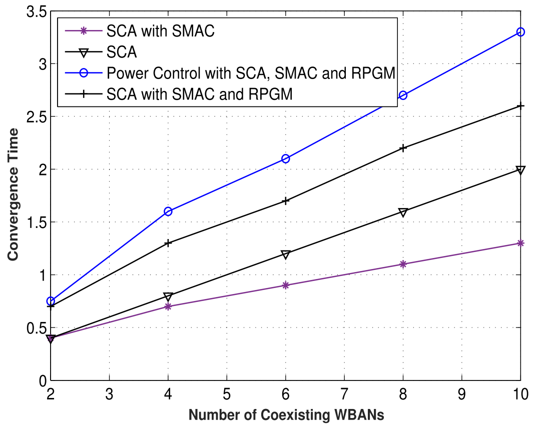

FIGURE 17. **Average Convergence Time versus the Number of Coexisting WBANs.**

the SCA scheme has slightly reduced the convergence time, whilst introducing mobility via the RPGM mobility model has not drastically impacted the convergence time and only slightly increased, in the range of 0.2 to 0.6 seconds. Then introducing power control on top of the RPGM mobility model also provides a relatively small impact on convergence time.

VI. CONCLUSION

In this paper, we have presented a social interaction based channel assignment for inter-WBANs interference mitigation. In this context we have provided significant background and context from literature with respect to MAC, mobility, transmit power control and radio interference mitigation for WBANs. Unlike previous work, our WBANs channel assignment proposal is designed based on social interaction detection and prediction, which considers the unique social interaction features of cyber-physical WBAN systems. Firstly, we built the interference model based on social interaction information. Secondly, we modeled the social interaction and presented a methodology for interference mitigation based on network interaction distances. NS2 simulations were used to verify the correctness of our proposed model. Thirdly, we applied node-level power control at the interfering nodes to control the WBANs' transmission power effectively, using simple "Sample-and-Hold" channel prediction in order to mitigate the interference as well as reduce circuit power consumption. The effectiveness of the proposed algorithm is further demonstrated through comprehensive results showing overall benefits of the system in terms of throughput, delay, packet delivery ratio and throughput.

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