IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received September 6, 2019, accepted November 7, 2019, date of publication November 22, 2019, date of current version December 5, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2955395

Interference and Priority Aware Coexistence (IPC) Algorithm for Link Scheduling in IEEE 802.15.6 Based WBANs

FAWAD NAWAZ KHAN[1], RIZWAN AHMAD[1], (Member, IEEE), WAQAS AHMED[2], MUHAMMAD MAHTAB ALAM[3], (Senior Member, IEEE), AND MICHEAL DRIEBERG[4]

[1]School of Electrical Engineering and Computer Science, National University of Sciences and Technology (NUST), Islamabad 44000, Pakistan
[2]Department of Electrical Engineering, Pakistan Institute of Engineering and Applied Sciences (PIEAS), Islamabad 45650, Pakistan
[3]Thomas Johann Seebeck Department of Electronics, Tallinn University of Technology, 19086 Tallinn, Estonia
[4]Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Malaysia

Corresponding author: Fawad Nawaz Khan (fkhan.msee15seecs@seecs.edu.pk)

This work was supported in part by European Union's Horizon 2020 Research and Innovation Program under Grant 668995, in part by the European Union Regional Development Fund through the framework of the Tallinn University of Technology Development Program 2016-2022, and in part by the Estonian Research Council under Grant PUT-PRG424.

ABSTRACT This paper presents an Interference and Priority aware Coexistence (IPC) algorithm to ensure coexistence between multiple WBANs communicating within each other transmission range. By intelligently keeping an interfering WBAN silent, the IPC approach aims to maximize simultaneous (interference-free) transmissions from sensor nodes of different WBANs. Coordinators use beacons to exchange interference and priority aware metrics. This information is later used to generate an interference graph of the sensors associated with the coordinator and perform link scheduling. The IPC approach has been evaluated for two different interference scenarios namely, a High interference scenario which considers interference from the highest interfering coordinator or sensor node of all coexisting WBANs, and a Moderate interference scenario (conventionally used in the existing literature) which considers interference from the coordinator only. Considering the mobility of WBANs, the performance of IPC is evaluated in terms of spatial reuse, system throughput, delay, and packet delivery rate. IPC shows significant improvement in all performance metrics over existing schemes.

INDEX TERMS Channel utilization, coexistence, IEEE 802.15.6, interference, link scheduling, traffic priority, wireless body area network (WBAN).

I. INTRODUCTION

Wireless Body Area Network is an emerging technology devised for health care monitoring, assisted living, gesture control, gaming, military purpose, etc. [1], [2]. WBANs consist of a centralized coordinator node/hub and many in-body/on-body sensors deployed around it. The sensor node in a WBAN transmits its data to the coordinator node forming the first tier of communication. A coordinator is responsible to send all collected data to a centralized hub through any suitable technology e.g. Wifi, Bluetooth, etc forming the second tier of communication. Using the internet, a hub sends this data to its final destination i.e. service center e.g. hospitals, forming a third communication tier [3], [4]. The low power sensors nodes are connected to the coordinator using one or two hop star topology.

Initially, researchers used IEEE 802.15.4 Wireless Personal Area Networks (WPANs) standard that provides short-range, low-power and low data rate communication (up to 250kbps) to analyze the performance of WBAN networks [5]. In Nov. 2007, IEEE working group 802.15 established Task Group (TG6) which completed the baseline document in Feb. 2012 and a dedicated standard IEEE 802.15.6 for WBANs was completed [6]. IEEE 802.15.6 maps quality of service (QoS) into traffic priority starting from 1 (lowest priority) to 7 (highest priority) [7]. There are seven different priorities defined in this standard [8]. According to IEEE 802.15.6, the system should support up to 256 sensors per WBAN and a total of 10 WBANs in a 6x6x6 m^3 area [9]. This defines a high interference probability for

The associate editor coordinating the review of this manuscript and approving it for publication was Mauro Fadda.

WBANs in crowded places like sports stadiums, busy malls, hotels and restaurants, public gatherings, festivals, parks, hospitals, etc. To meet the strict interference scenarios defined in the IEEE 802.15.6 standard, some scheduling or interference mitigation schemes are required to achieve the required Quality of Service (QoS). Integration of WBANs with an internet of things (IoT) and 5G technologies will enhance its capabilities beyond health monitoring. In [10], WBAN is designed to monitor different environmental and physical parameters and WBAN is connected to the internet using an IoT-based cloud server to provide facilities like remote monitoring and mobile applications. Scheduling of prioritized data transmission for emergency alarm management over an IoT-based framework was performed in [11]. Detailed cloud-based framework and architecture for WBAN design and perspective have been presented in [12].

WBANs exhibits two types of interference scenarios, namely, heterogeneous coexistence and homogeneous coexistence [13]. Heterogeneous coexistence refers to a scenario in which the WBAN receives interference from other communication technologies such as Bluetooth, Wifi, Zigbee, etc. which uses the same 2.4 GHz frequency ISM band [14]. This interference is easy to mitigate by switching to a new channel with an acceptable SNR. This situation is depicted in Figure 1. Some research work is already carried out in this domain and optimum channel selection techniques are proposed e.g. Reinforcement learning-channel assignment algorithm (RL-CAA) interacts with the channel, learns about different channel coefficients and selects the best channel to mitigate heterogeneous interference [15].

On the other hand, homogeneous coexistence refers to a scenario in which transmission ranges of 2 or more WBANs overlap. If WBANs transmit within each others transmission range using the same channel and timeslot, severe interference and subsequently performance degradation occurs [16]. An example of a homogeneous coexistence scenario is depicted in Figure 2, where the circle represents the transmission range of a WBAN which is typically a sphere of 2 m radius as per the IEEE standard. Red dots represents biomedical sensors placed in or on a human body. The green rectangular coordinator is shown in the center and lines from a sensor to the coordinator depict their communication links.

IEEE realized this issue and following coexistence mitigation techniques are defined in the IEEE 802.15.6 standard: **i) Beacon shifting:** Relative to the start of the current beacon periods, WBAN transmits its beacons at different time offsets. This is accomplished using a Beacon Shifting Sequence field. In this way, a WBAN avoids beacon collisions and allocation conflicts between coexisting WBANs. A unique beacon shifting sequence is used by the coordinator relative to its neighbors. **ii) Channel Hopping:** By using the channel Hopping State and Next Channel Hop fields in its beacons, the coordinator can change its communication channel periodically. Channel hopping sequence is used by the coordinator that is unique to its neighboring WBANs. After a fixed number of beacon periods (superframes), the coordinator will change its channel. **iii) Active Superframe Interleaving:** A WBAN may share the same operating channel with one or more BANs by interleaving their active superframes.

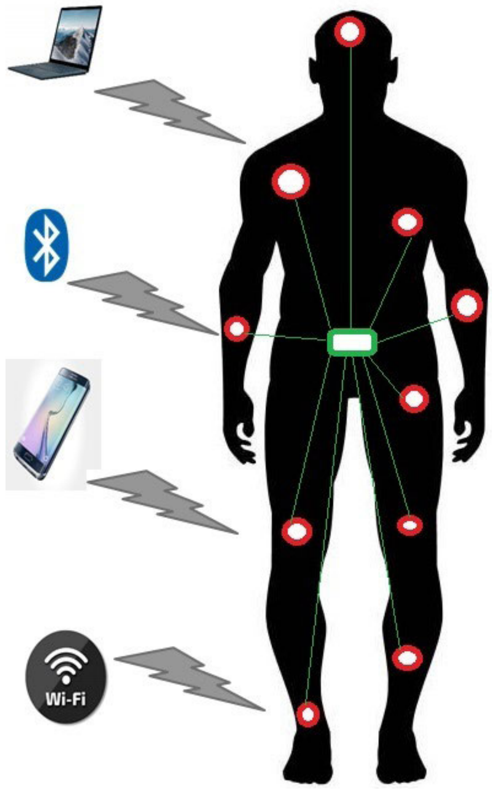

FIGURE 1. Heterogeneous coexistence.

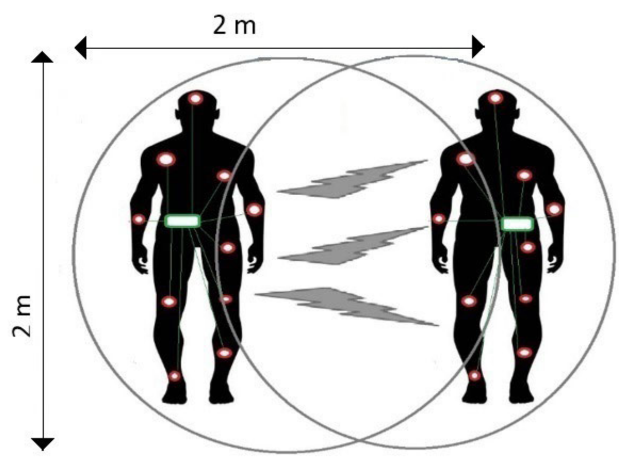

FIGURE 2. Homogeneous coexistence.

In WBANs, channel gain can be highly variable because of the mobility. The mobility includes movement of WBAN as a whole e.g. a WBAN carrier walking or running. Mobility within the WBAN network is also possible due to the postural changes. Channel prediction is difficult in WBANs as compared to conventional network technologies because of both the inter-network and intra-network mobility [17]. In short, Inter-network mobility is caused by the motion of a

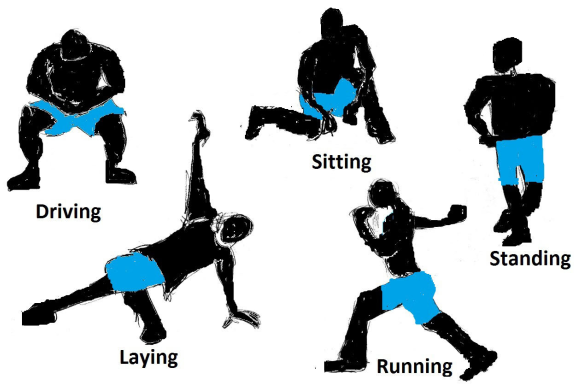

FIGURE 3. Different body postures (intra-network mobility).

WBAN carrier and Intra-network mobility is caused by postural changes of a WBAN user e.g. walking, running, driving, etc as shown in Figure 3. In [18], the authors analyzed energy efficiency against distance using direct, one hop and two-hop cooperative communication. Optimal packet sizes are calculated considering both the postural changes and energy efficiency.

Recent literature on WBAN coexistence either consider power adaptation at WBAN nodes or enable channel sharing between the interfering WBANs. Shared channel techniques include TDMA and CSMA/CA. The CSMA/CA technique is less energy efficient as compared to TDMA because of constant channel monitoring and re-transmissions [19]. Energy efficiency is important in WBANs because the sensor nodes are often energy-constrained [20]. Therefore, in this paper, we address the issue of coexistence by considering energy efficiency, throughput, spatial reuse and delay as performance metrics. To this end,

1) An Interference and Priority aware Coexistence (IPC) algorithm is designed to mitigate homogeneous interference between WBANs communicating within each other transmission range. This algorithm considers both the priority and packet size of interfered nodes.
2) The IPC solves the scheduling problem by defining equivalent metrics for the interference and priority constraints. These metrics are further used to carefully select an interfering WBAN to remain silent (allowing parallel transmission) while preventing its multiple silent occurrences.
3) The performance of IPC is analyzed for both the High and Moderate interference scenarios. The IPC scheme is compared with the well known existing interference mitigation schemes those are: Interference-aware, Traffic priority-based Link Scheduling (ITLS) [21] and Adaptive Internetwork Interference Mitigation (AIM) [22]. Simulation results show significant gains for all performance metrics under consideration.

This algorithm runs on the coordinator and performs distance based search for neighboring WBANs. After that, each sensor calculates received SINR and the coordinator defines them as either interfered and non-interfered sensor nodes. This information is shared with the neighbors, and a common TDMA based schedule is formed to minimize interference at every timeslot and schedule as many sensor nodes as possible in the future timeslots. Moreover, WBAN's position is assumed static during transmission time. It must be noted that this model does not add any processing burden to the sensor nodes (because they are energy-constrained) and the coordinator is responsible for exchanging information and negotiation. Energy conservation is important in WBANs and simple processing algorithms enhance node's lifetime. The rest of the article is organized as follows. In the next section, existing work on coexistence mitigation between IEEE 802.15.6 based WBANs is reviewed. In Section III, network topology, channel model, distance-based model, SINR based model, and superframe structure are discussed. In Section IV, the problem formulation is carried out. IPC algorithm is explained by an example and performance metrics namely Packet delivery rate, Spatial reuse, Average packet delay, System throughput, Energy consumption, and Energy efficiency are defined. In Section V, results are discussed for different network performance factors. Finally, Section VI concludes the paper.

II. RELATED WORK

Interference generated due to coexistence can severely degrade system performance. Many interference mitigation techniques and algorithms are proposed in the literature. These schemes can be categorized according to the shared resource allocation techniques they adopt for interference mitigation. In [23], interference mitigation schemes were grouped according to their usage. The approaches include the use of power control, MAC, cognitive radio, UWB and signal processing. This paper also provides a detailed comparison of common link scheduling algorithms with their pros and cons.

TDMA: TDMA use scheduling algorithms to assign guaranteed timeslots for channel utilization and transmission. TDMA tries to minimize interference at the neighboring nodes by selecting suitable nodes for transmission. The authors in [28] proposed an Interference-aware MAC (I-MAC) which uses SINR based scheduling while distributing fair average waiting time to all WBANs. Interference Management algorithm named as KDIM was proposed in [30] for the interference attenuation in channel switching systems. A Continuous-Time Markov Chain (CTMC) and a Flexible TDMA (FTDMA) based protocol was used to mitigate Intra-WBAN interference. A priority-based TDMA scheduling algorithm named Interference Mitigation and QoS Protocol (IMQP) was presented in [29]. Dynamic, Reliable and Energy Efficient Scheduling (DREES), presents two new TDMA based techniques to improve reliability and energy efficiency for WBANs [27]. In Link Scheduling Algorithm with Interference Prediction (LSIP), the interference prediction was carried out through the Bayesian model that estimates interference duration and the number of interfering nodes [31]. Dynamic Coexistence Management (DCM) provides distributed coexistence mitigation without exchanging

TABLE 1. Qualitative comparison of TDMA based algorithms.

Algorithm	Interference Mitigation Technique	Traffic Priority	Interference Generation Metric	Standard	Energy Consumption or Efficiency
AIM [22]	TDMA	Yes	SINR	IEEE 802.15.6	No
CBWS [24]	TDMA	No	Distance	IEEE 802.15.6	No
DCM [25]	TDMA	No	Overhearing Beacon or Beacon Drop	IEEE 802.15.4	No
DRA [26]	Orthogonal Scheduling	No	SINR	IEEE 802.15.6	No
DREES [27]	TDMA	No	SINR	IEEE 802.15.4 and 802.15.6	Yes
I-MAC [28]	TDMA	No	SINR	IEEE 802.15.4	No
IMQP [29]	Superframe Interleaving and Beacon Shifting	Yes	Distance	IEEE 802.15.6	No
IPC	TDMA	Yes	SINR	IEEE 802.15.6	Yes
ITLS [21]	TDMA	Yes	SINR	IEEE 802.15.6	No
KDIM [30]	FTDMA	No	SINR	IEEE 802.22	Yes
LSIP [31]	TDMA	Yes	SINR	IEEE 802.15.6	Yes
RIC [32]	TDMA	No	Distance	IEEE 802.15.6	No

information between the WBANs [25]. AIM uses TDMA based scheduling in which they assign an orthogonal channel to the interfered sensors [22]. Clique-Based WBAN Scheduling (CBWS) uses a coloring based approach to group sensors from single or multiple WBANs and this protocol works in a sequence of timeslots [24]. Dynamic Resource Allocation (DRA) uses the SINR based interference model and orthogonal scheduling to assign a channel to sensor nodes without considering traffic priority [26]. Random Incomplete Coloring (RIC) uses a coloring technique to assign TDMA based timeslot using a distance-based interference model, without considering the traffic priority of a transmitting node [32]. ITLS uses both the distance and SINR based model to generate an interference graph for coexisting nodes. ITLS considers traffic priority for scheduling and uses Space-Time division multiple access (STDMA) [21]. In [33], the authors consider both the contention-free and contention-based IEEE 802.15.6 MAC operation to analyze spatial throughput and outage probability for interfering WBANs using stochastic geometry. A graph coloring based cooperative scheduling scheme was proposed which creates clusters between WBANs and then schedule their transmission using smart channel assignment (SCA) [34]. Adaptive TDMA-based MAC Protocol (AT-MAC) uses TDMA based scheduling for energy harvesting WBANs. In AT-MAC, the duty cycle was adjusted dynamically based on the total amount of energy harvested [35].

The qualitative analysis of most related algorithms is presented in Table 1. After analysis of all TDMA based available algorithms, ITLS and AIM are selected for comparison with the proposed algorithm (Section V) as they both consider user priority for resource allocation and SINR based model for interference detection. Generally, ITLS provides improvements over AIM [21].

IEEE 802.15.6 based techniques: There are three types of interference mitigation techniques defined in the IEEE 802.15.6 standard. These techniques are as follows: Beacon shifting: Beacon shifting is the technique that is used to avoid beacon collision. Beacon shifting shifts or wrap around beacon periods. The coordinator is responsible to select beacon shifting sequence which is not in use from neighboring coexisting WBANs. Performance analysis of flexible beacon shifting scheme to avoid interference among WBANs is presented in [36]. Channel Hopping: Channel hopping is used to switch to a randomly chosen frequency out of allowed set of frequencies after a specific amount of time according to a predefined sequence known to both sender and receiver. An enhanced channel hopping scheme is presented in [37] to evaluate coexistence performance for WBANs. The authors in [38] proposed a fuzzy logic-based interference detection and mitigation scheme using channel hopping. Channel Hopping Interference Mitigation (CHIM) scheme is also used to select Latin triangles among coexisting WBANs in [39]. Superframe-Interleaving: WBANs can share the same channel by active superframe interleaving. To enable interleaving, WBAN sends interleaving requests to neighboring WBANs. If WBANs share channel, interleaving request is accepted otherwise it is denied. Superframe Overlapping Scheduling (SOS) uses twin token bucket based model, Traffic Specification (TSPEC), to assign QoS based timeslot by using beacon shifting and superframe interleaving techniques [40].

CSMA or CSMA/CA: CSMA or CSMA/CA-based techniques do not use predefined timeslot to use the channel, instead, the channel is constantly monitored. The data is transmitted if the channel is idle for a specific amount of time, otherwise, a random exponential back-off is added to waiting time for the transmission of data. Decentralized Interference Mitigation (DIM) uses CSMA/CA for the contention access phase (CAP) and the scheduled phase to mitigate interference in a decentralized manner [41]. In this paper, performance factors for WBANs under dynamic node mobility are evaluated using a three-dimensional Markov chain model. CSMA/CA-based access mechanism is used with user priority to access the channel. Moreover, the health-care index is used to prioritize emergency data from WBANs [42].

Reference [43] uses an RTS/CTS handshake mechanism to improve the performance of IEEE 802.15.6 based CSMA/CA in coexisting WBANs environment.

Hybrid-Techniques: These techniques mostly use the TDMA for scheduling contention-free exclusive access phase (EAP) or managed access phase (MAP) and the CSMA/CA for contention-based scheduling of random access phase (RAP) in a superframe. Hybrid Multi-Channel MAC (HM-MAC) protocol defines a superframe having both a scheduled access phase for TDMA and a random access phase for CSMA/CA to transmit data and schedule nodes [44]. In [45], a detailed analysis of hybrid protocols is presented. An EAP is dynamically adjusted to minimize resource competition in RAP in [46].

Adaptive Power: In adaptive power techniques, transmit power is adapted according to the detected interference level. In this way, the interference level to and from the neighboring WBANs is controlled [47], [48]. Cross-Layer Energy-Aware Resource allocation (CLEAR) proposes a hybrid collaborative protocol that manages link adaptation and control transmit power [47] of the sensor nodes. Adaptive power control is used to control interference between CSMA based WBANs in [48].

Adaptive Packet Size: In this approach, the packet size is made smaller or large according to the interference level. An adaptive packet size based technique is used and energy efficiency is evaluated [49]. Authors in [50] optimize packet size for Ultra-Wideband (UWB) WBANs using IEEE 802.15.6 standard and achieve an increase in optimal packet size and energy efficiency using cooperative communication. In reference [51], for energy efficiency, the optimal packet size is obtained and a detailed system was designed for WBANs using scheduled access mode.

Adaptive Modulation: Adaptive modulation is the method to modify or change the modulation scheme based on the throughput requirement by the user or channel conditions. In [52], an adaptive modulation scheme using QAM, BPSK, and QPSK is proposed which adapts modulation technique according to received SNR. In [53], a link adaptation scheme using the estimated SNR and energy capture index is proposed. In the article [54], an adaptive energy detection threshold based on queue-size and channel quality is used to obtain QoS under varying interference conditions. A CSMA/CA-based low complexity link adaptation scheme to mitigate cross-network interference was presented and appropriate modulation scheme based on SINR is selected for nodes in [55].

Important terms, notations, and parameters used in this paper are presented in Table 2:

III. SYSTEM MODEL

In this paper, we consider a one-hop simple star topology in which 6 bio-medical sensors are connected to a centralized coordinator through a wireless link. For example, in Figure 4, 6 sensors are connected to CN_2. A transmission range of 2m is assumed for each WBAN. According to the IEEE 802.15.6 standard, one-hop star, two-hop star or bidirectional link can be used to design a network topology model for WBANs. Moreover, the coordinator of WBANs can communicate with each other to share information using a wireless link and network topology does not change in one superframe [56]. The mobility for all the nodes is realized by a random way-point mobility model. A free-space path loss channel model is used for links in a WBAN (Intra-WBAN links), which is

TABLE 2. Acronyms and symbols.

Symbols	Descriptions
α_{xy}	Priority for SN_{xy}
γ_{xy}	SINR received from SN_{xy} by CN_x
ζ_T	Power Transmitted
ζ_{xy}	Power received from SN_{xy} by CN_x
CN_x	x-th coordinator node
CV_z	Contention vector
CWI_x	Cumulative Weighted Interference for CN_x
D_A	Average packet Delay
D_P	Delay per Packet
D_T	Total Delay
E_C	Total energy consumption
E_E	Energy Efficiency
F_R	Reuse Factor
N_G	Total Number of Generated Packets
N_T	Total Number of Transmitted Packets
P_D	Packet Delivery Rate
P_N	Number of Packets per node
P_{xy}	Packet size for SN_{xy}
r	Distance between two WBANs
R	Transmission range for WBAN
R_D	Datarate
SN_{xy}	y-th sensor of CN_x
SV_z	Scheduling vector at timeslot z
T	Total transmission time
T_S	System Throughput
t_{xy}	Transmission Time required by SN_{xy}
t_z	Size of timeslot z
WI_{xy}	Weighted interference for SN_{xy}
X	Total number of WBANs
Y	Total number of sensors
Z	Total timeslots

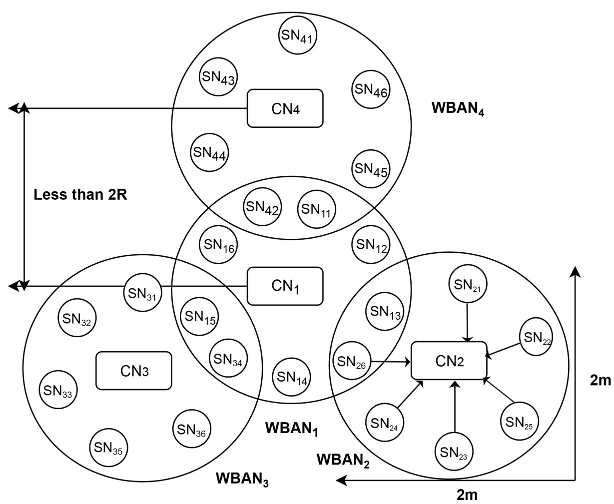

FIGURE 4. Image showing interfering WBANs for each WBAN.

given as

$$FSPL(dB) = 10log_{10}(\frac{4\pi rf}{c})^2 \quad (1)$$

The body-to-body (Inter-WBAN) channel model at 2.45 GHz is adopted from [57], in which the authors have shown through experimental results that the amplitude variation(A) in body-to-body links can be modeled by the gamma distribution. Besides, the mean and the variance of signal amplitude is expressed in terms of distance (r) between two WBANs as

$$r_{dB} = 20log_{10}r, \quad \mu_{dB} = -0.44r_{dB} - 47.2, \text{ and}$$
$$\varphi_{dB} = -0.71r_{dB} - 49. \quad (2)$$

The shape parameter (k) and scale parameter (θ) that defines gamma distribution can be calculated by equating the above parameters (in linear scale) with the standard equations of gamma distribution's mean and variance, i.e.,

$$f(A; k, \theta) = \frac{A^{k-1}e^{-a/\theta}}{\theta^k \Gamma(k)}, \quad \text{for } a > 0, \text{ and } k, \theta > 0,$$
$$E(A) = k\theta = \mu, \quad Var(A) = k\theta^2 = \varphi \quad (3)$$

The distance-based model is used to find interfering WBANs. If the distance r between the two WBANs is less than the sum of their transmission ranges (R) i.e., $r < 2R$, WBANs are listed as the interfering WBANs. The interference scenarios are depicted in Figure 4. The coordinator node of x^{th} WBAN ($WBAN_x$) is represented by CN_x, whereas the y^{th} sensor nodes of x^{th} WBAN is represented by SN_{xy}. In the example presented in Figure 4, the $WBAN_1$ receives interference from the $WBAN_2$, $WBAN_3$, and $WBAN_4$, whereas the transmission ranges of $WBAN_2$, $WBAN_3$, and $WBAN_4$ do not overlap, and they all receive interference only from $WBAN_1$.

Once the interfering WBANs are determined, the coordinator at each WBAN lists the interfered and non-interfered sensors based on the SINR threshold. The SINR is calculated based on the received signal from the k^{th} interfering sensor or coordinator. For example, if the SINR of the sensor node SN_{xy} is below the threshold (γ_{th}), the coordinator CN_x lists this sensor node as an interfered node, otherwise, it is listed as a non-interfered node. The set of interfering coordinators is denoted by CN_k while its sensors are denoted by SN_{ky}. The coordinators broadcast these lists at the start of every superframe. The SINR of sensor node SN_{xy} at CN_x can be written as

$$\gamma_{xy} = \frac{\zeta_{CN_x \to SN_{xy}}}{\sigma^2 + \sum_{k \neq x} \zeta_{CN_k \to SN_{xy}}}, \quad (4)$$

where, ζ_{xy} is the power received by CN_x from the sensor node SN_{xy}, σ^2 is the additive noise (−113 dBm), ζ_{ky} is the interference power from the interfering WBAN coordinator (CN_k) or sensor (SN_{ky}) to SN_{xy}. IEEE 802.15.6 WBAN superframe structure is used and Beacon mode with superframe boundary is considered as shown in Figure 5. Although the superframe structure also contains EAP and RAP, this work will only consider the Managed Access Phase (MAP). This is because the MAP allows TDMA transmissions. The coordinator will send a beacon at the start of a superframe and the nodes will transmit in their allowed timeslot. Similar to existing works [33], the size of a superframe is set to 100 ms. The timeslot within a superframe is defined according to the highest transmission time of any active sensor.

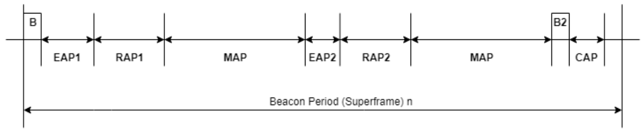

FIGURE 5. Beacon mode with superframe boundaries [9].

IV. INTERFERENCE AND PRIORITY AWARE COEXISTENCE (IPC)

As shown in Figure 4, the interference in WBANs results in severe degradation of performance and system throughput. To ensure coexistence among multiple WBANs, a scheduling scheme is therefore required that can ensure transmissions while maintaining the required system throughput and delay. Therefore, an IPC scheduling algorithm is presented in this work, which minimizes interference to improve the network performance e.g. throughput, spatial reuse, energy efficiency, and delay. In the IPC algorithm, at every timeslot, interfering nodes are first scheduled. This is beneficial as spatial reuse is improved for future timeslots, and blocking of nodes is avoided. This helps in eventually achieving higher throughput and lower delay. In the following, firstly, the scheduling problem is formulated as an optimization problem for interfering WBANs. Secondly, the IPC algorithm is presented along with an illustrative example and algorithmic procedure. Lastly, the performance metrics that are used for comparison of IPC with other schemes are defined.

The IPC algorithm decouples the interference detection and scheduling process. The algorithm for interference detection is presented in Algorithm 1. The first step in interference detection is the identification of interfering WBANs. As highlighted in Section. II, the WBANs are listed as interfering if the sum of their transmission range ($2R$) is greater than the distance (r) between them. The second step estimates the SINR of the nodes in the interfering WBANs. This helps in generating the list of interfered and non-interfered sensors at each coordinator in the third step. In the fourth step, the sink shares its list of interfered and non-interfered WBANs. Lastly, the nodes are scheduled according to IPC algorithm 2.

A. PROBLEM FORMULATION

To formalize system throughput, a variable timeslot duration within a superframe is used which is defined by t_z (as the packet size of the sensors in a WBAN is different). For any timeslot z, a scheduling vector $SV_z = [SV_x, SV_{x+1}, ...SV_{x+n}]$ is created which contains WBANs that can transmit in the timeslot z to ensure coexistence, where $SV_x = 1$, if the

Algorithm 1 Interference Detection

```
Step 1: Determine the inter-BAN interference list
for x = 1 to X do
for m = 1 to X do
    calculate r,
        if r < 2R,
    Add WBAN_m to interfering WBAN set of WBAN_x
        else
        end if
end for
end for
Step 2. Orthogonal Transmission
for x = 1 to X do
for y = 1 to Y do
    SN_xy estimates ζ_xy from CN_x and ζ_ky from all
    interfering
   WBANs (CN_k or its sensor SN_ky)
end for
end for
Step 3: Determine the intra-BAN interference list
for x = 1 to X do
for y = 1 to Y do
        if γ_xy < γ_Th
    Add SN_xy to interfered sensors
        else
    Add SN_xy to non-interfered sensors
        end if
end for
end for
Step 4: Broadcast
for x = 1 to X do
    Broadcast interference list of CN_x.
end for
Step 5: Timeslot Assignment
    Run Algorithm 2:IPC Scheduling Algorithm
```

sensor y of WBAN_x is scheduled at timeslot z, otherwise $SV_x = 0$. Hence, the system throughput per timeslot T_S can be written as

$$T_S(\text{per TS}) = \sum_{x=1}^{X}\sum_{y=1}^{Y} \frac{max(SV_z)P_{xy}}{t_z} \tag{5}$$

where, $\max(SV_z)$ shows that to achieve higher throughput, the maximum number of nodes should be scheduled at every timeslot. P_{xy} is the size of the packet transmitted by sensor y of WBAN_x and TS stands for a timeslot. There are few constraints on node selection for scheduling. These constraints are discussed below:

$$t_{xy} = \frac{P_{xy}}{R_D} \tag{6}$$

$$t_z = max(t_{xy}) \tag{7}$$

where R_D is the data rate, P_{xy} is the packet size of a sensor node and t_{xy} is the transmission time required by a sensor node. The size of a timeslot in the superframe is equal to the maximum time required by any node scheduled in that timeslot. In addition, only one sensor of the WBAN_x can transmit in a single timeslot, the maximum number of non-interfered sensors selected for transmission at any timeslot is limited by total number of WBANs i.e. X and the total number of sensor nodes selected for transmission at all timeslots in a superframe is less than or equal to the product of total number of sensor nodes and total number of WBANs.

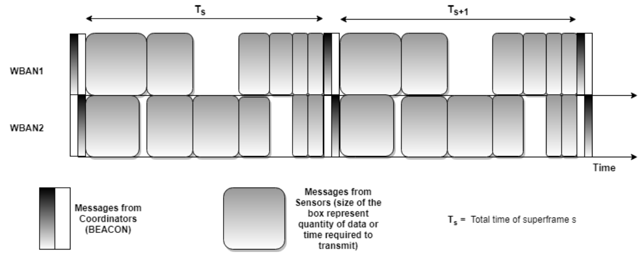

FIGURE 6. Superframe design.

$$\sum_{y=1}^{Y} SV_x \leq 1, \quad \sum_{x=1}^{X} SV_x \leq X, \quad \sum_{x=1}^{X}\sum_{y=1}^{Y}\sum_{z=1}^{Z} SV_x \leq XY \tag{8}$$

Similar to [21], a weighted interference (WI_{xy}) metric is defined to account for the priority of the interfered sensor in a WBAN. The WI_{xy} of an interfered sensor is given as

$$WI_{xy} = \gamma_{xy}\alpha_{xy}, \tag{9}$$

where y is the interfered sensor of WBAN_x and α_{xy} is the priority of sensor under consideration. Similarly, the Cumulative Weighted Interference (CWI_x) for a WBAN is defined as

$$CWI_x = \sum_{y} WI_{xy} \tag{10}$$

At each timeslot z, the CWI_x is calculated for all the WBANs and is stored in the Contention Vector (CV_z).

$$CV_z = \{CWI_1, CWI_2, \ldots, CWI_X\} \tag{11}$$

To schedule transmissions based on the interference, the WBAN with maximum CWI_x is selected at any timeslot z i.e., $\max\{CV_z\}$. To schedule transmissions, the WBAN coordinators exchange, SINR, transmission time and priority of its sensors through beacons. Based on this the coordinators create a list of interfered and non-interfered sensors. Subsequently, non-interfered nodes are allowed to transmit in parallel, whereas the interfered nodes are scheduled based on the values of the respective WI_{xy}. This is illustrated in Figure 6, where the 2 WBANs share their messages to create a common schedule which is shared between interfering WBANs.

B. IPC EXAMPLE

To illustrate IPC, we consider a scenario consisting of three WBANs with multiple sensors as shown in Figure 7. The sensors and their priorities are also provided. Both the WBAN_1

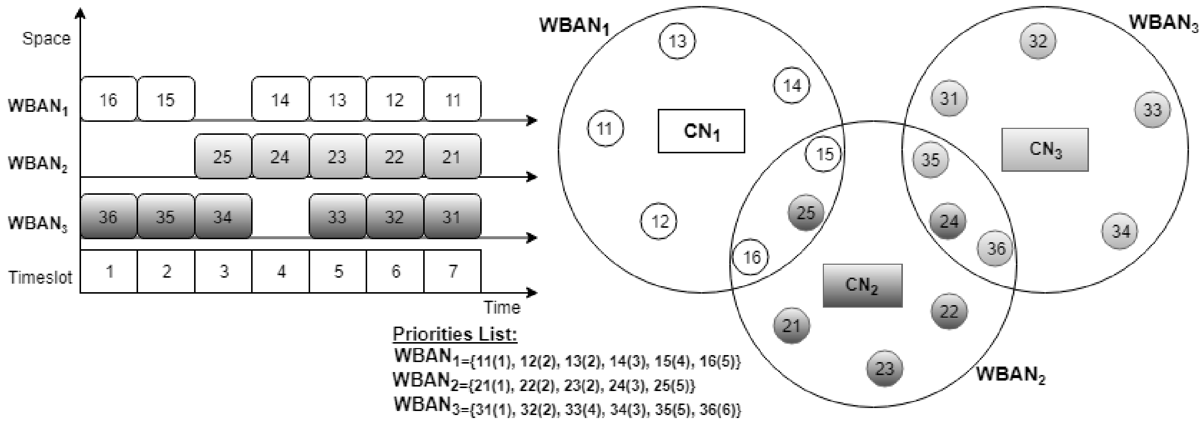

FIGURE 7. Interference scenario and priorities list for sensors.

and $WBAN_3$ are in the transmission range of $WBAN_2$, whereas $WBAN_1$ and $WBAN_3$ are not in each other's transmission range. Initially, each coordinator finds its neighbors and corresponding received SINR for all its sensors using Algorithm 1. According to the SINR received, each coordinator will group sensors into an interfered and non-interfered sensors list. The coordinators will exchange their lists and create a common interference region. Lists of interfered and non-interfered sensors for the example depicted in Figure 7 are shown in Table. 3. Once a list has been formed and exchanged, a common transmission schedule is designed among multiple WBANs. A contention vector CV_z contains values of CWI_x. A WBAN having the highest CWI_x is selected for transmission at every timeslot. The highest priority interfered node is scheduled from a selected WBAN according to the values of WI_{xy} and the WBAN interfering with this highest priority node remains silent. The neighbors (not interfering with the previous transmission) of the silent WBAN also select their interfered sensors for transmission. This enables parallel transmissions and stops unnecessary blocking of the interfering WBANs. This scheduling is depicted in Figure 7. It is important to note that for the illustration of this example the same packet size is considered for all nodes.

It is clear from Figure 7 that in the first and second timeslots, $WBAN_2$ remains silent as it interferes with both the $WBAN_1$ and $WBAN_3$. In the first timeslot, $WBAN_3$ selects the highest priority interfered sensor node SN_{36} while $WBAN_1$ also selects the interfered sensor SN_{16}, hence stopping multiple blocking of silent $WBAN_2$ (two interfered sensors scheduled in a single timeslot). Similarly, in the third timeslot, $WBAN_1$ is silent, whereas $WBAN_2$ selects the highest priority interfered sensor SN_{25} and $WBAN_3$ selects the non-interfered sensor SN_{33}. In the fourth timeslot $WBAN_3$ is silent and $WBAN_1$ selects the non-interfered sensor node SN_{14} whereas $WBAN_2$ selects the highest priority interfered sensor SN_{24}. From timeslots 5 to 7, all the nodes transmit in parallel.

TABLE 3. Coordinator list before exchanging information via beacons.

Coordinator	Interfered Sensors	Non-interfered Sensors
CN_1	15,16	11,12,13,14
CN_2	24,25	21,22,23
CN_3	35,36	31,32,33,34

In a sequential/completely orthogonal transmission scenario, 17 timeslots are needed to schedule every sensor node, whereas, IPC uses TDMA to multiplex WBAN transmissions to achieve higher spatial reuse factor and system throughput per timeslot. In the scenario depicted above, 17 nodes require only 7 timslots, therefore, the spatial reuse factor of IPC is 2.428 nodes per timeslot.

It is evident from the example above that configuring a WBAN as silent is pivotal for scheduling transmissions and subsequently network performance. The configuration is dependent upon the level of interference and node priorities. This solution improves the reuse factor to enhance system throughput and minimize the delay.

C. SCHEDULING ALGORITHM

The scheduling phase is different for AIM, ITLS, and IPC. AIM uses the simplest and straight forward solution to schedule nodes under coexistence. AIM allows parallel transmission for non-interfering nodes while orthogonal transmissions for interfered nodes. By keeping interfering WBAN silent, ITLS provides an improved solution by intelligently selecting the highest priority interfered node from a WBAN and non-interfered nodes from all other neighboring WBANs. IPC further enhance performance by selecting interfered nodes from the neighbors of silent WBAN/WBANs and non-interfered nodes from all other coexisting WBANs.

The generalized IPC algorithm is given as Algorithm 2. At line 02, Nodeindex indicates a counter which counts the total number of sensor nodes scheduled in a superframe. Nodeindex should be less than or equal to the product XY as shown in Equation 8, where X is the total number of WBANs

Algorithm 2 IPC Scheduling Algorithm

01. while t < SF
02. if Nodeindex $\leq$ X×Y
03. Calculate CWI_x
04. Find max(CV_z)
05. Return highest priority interfered sensor y of WBAN x
06. Find t_{xy} for SN_{xy}
07. Set $SV_x = 1$;
08. Remove SN_{xy} from intra-BAN interference list of $WBAN_x$;
09. Nodeindex = Nodeindex+1
10. Add interfering WBANs of SN_{xy} to silent WBANs list
11. for each $WBAN_k \in$ Inter-BAN interference list of $WBAN_x$
12. Return highest priority non-interfering sensor of $WBAN_k$
13. Set $SV_k = 1$;
14. Nodeindex = Nodeindex+1
15. end for
16. for each $WBAN_l \in$ interference list of silent WBAN
17. Return SN_{ly} such that silent WBAN is interfering for SN_{ly}
18. Set $SV_l = 1$;
19. Remove SN_{ly} from intra-BAN interference list of $WBAN_l$;
20. Nodeindex = Nodeindex+1
21. end for
22. Update t = t + max(t_{xy}, t_{ky}, t_{ly})
23. update z = z + 1
24. end if
25. end while

to be scheduled and Y is the total number of sensor nodes. At line 05, $WBAN_x$ selects the interfered sensor SN_{xy} as per the highest CV. At line 10, the silent WBAN list is the table that contains the IDs for interfering WBANs of SN_{xy}. WBANs whose IDs are in silent WBANs list in a timeslot should not schedule their transmission at that particular timeslot. At line 13, the interfering WBANs for $WBAN_x$ i.e. $WBAN_k$ schedule non-interfered sensors SN_{ky}. At line 16, the interference list of silent WBAN is the table that contains IDs for interfering WBANs of a silent WBAN. Similarly, at line 17, the interfering WBANs of a silent WBAN i.e. $WBAN_l$ schedule interfered sensors SN_{ly}. At line 22, the maximum transmission time is set as timeslot length. Lastly in line 23, next timeslot is selected for scheduling and this continues till the end of the superframe.

D. PERFORMANCE METRICS

To measure the network performance under different schemes, the following performance metrics are defined, namely, packet delivery rate, reuse factor, system throughput, average packet delay, energy consumption, and energy efficiency.

The packet delivery rate P_D is defined as the ratio of the average number of packets successfully transmitted N_T and the average number of generated packets N_G

$$P_D = \frac{N_T}{N_G} \tag{12}$$

The spatial reuse factor F_R is defined as the average number of transmitting nodes per timeslot. Given Z timeslots in a total time of T, the spatial reuse factor can be represented as

$$F_R = \frac{\sum_{z=1}^{Z}\sum_{x=1}^{X} SV_x}{Z} \tag{13}$$

The total system throughput (kbps) is

$$T_S = \frac{\sum_{x=1}^{X}\sum_{y=1}^{Y} P_{xy}}{T} \tag{14}$$

To determine average packet delay D_A and total delay D_T, the delay per packet D_P and the average number of transmitted packets per node P_N are required, which are given by

$$D_P = \frac{T}{N_T}, \quad P_N = \frac{N_T}{F_R} \tag{15}$$

The total delay D_T and the average packet delay D_A is thus defined as

$$D_T = XYP_N D_P \tag{16}$$

$$D_A = \frac{D_T}{N_T} \tag{17}$$

Assuming a constant transmit power of all the nodes ζ_T, the total energy consumption E_T in the network can be calculated as

$$E_T = \sum_{z=1}^{Z}\sum_{x=1}^{X} SV_x t_{x,y} \zeta_T \tag{18}$$

Lastly, the energy efficiency E_E is defined as the total energy consumed and the total bits transmitted per second (Joules/bit/sec) and it can be written as

$$E_E = \frac{E_T}{T_S} \tag{19}$$

V. SIMULATION RESULTS

In this section, simulation results are discussed for the proposed IPC algorithm, AIM and ITLS. A 10x10 m^2 area is considered in which WBANs are randomly deployed. Each WBAN consist of one coordinator node, and six bio-medical sensors are deployed randomly around the coordinator within a 2 m radius. The sensors are assigned random priorities between 1 and 7. To simulate realistic scenarios, WBANs are static for 30 sec and mobile for 5 sec. During mobility, WBANs move with random speed varying from 0 m/s to 2 m/s. In this way, connectivity between WBANs, interference scenarios and network structure, are changed dynamically. The transmission range for each WBAN is set to 2 m. The packet size of each sensor depends on its priority

TABLE 4. Simulation parameters.

Parameters	Values
Activity Area	$10 \times 10\ m^2$
Channel Frequency	2.4 GHz
Channel Model	Free Space Path loss model without shadowing with path loss exponent of 2
Data Rate	240 kbps
Mobility Model	Random Waypoint Mobility (Move Time 5 sec, Pause Time 30 sec, Speed 0-2 m/s)
Number of WBANs	4, 6, 8, 10, 12
Packet Generation Rate	1, 2, 3, 4, 8, 16 packets/sec
Packet Size	50 bytes (priority 1) to 350 bytes (priority 7)
Priorities	1 to 7
Receiver Sensitivity	−90 dBm
Run Time	600 sec
Superframe Size	100 ms
Transmission Range	2 m
Transmit Power	−20 dBm
WBAN Topology	Star topology

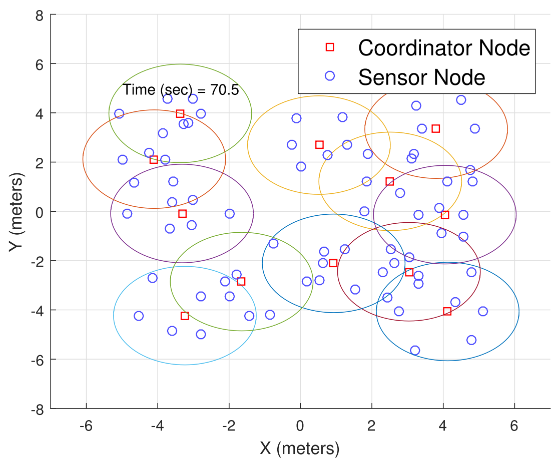

FIGURE 8. Simulation topology example.

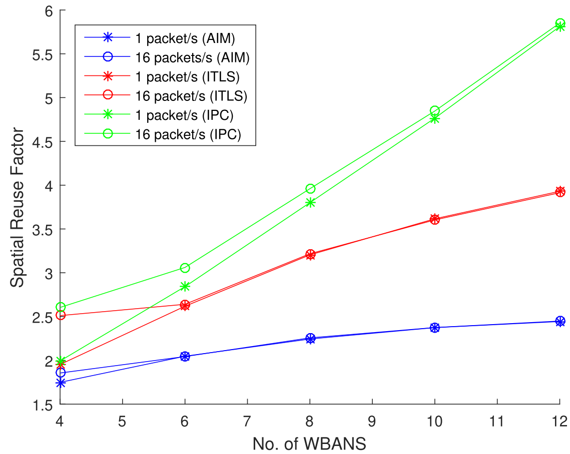

FIGURE 9. Reuse factor.

and it increases linearly from 50 bytes to 350 bytes for priority 1 to 7. The packet generation rate is also varied from 1, 2, 3, 4, 8, and 16 packets/s. Moreover, transmit power of −20 dBm, receiver sensitivity of −90 dBm and transmission rate of 240 kbps as per IEEE 802.15.6 standard is used. An example topology for 12 WBANs is shown in Figure 8. The results of the IPC algorithm are compared with those of the AIM and the ITLS algorithms [22], [21]. For more details, reading the AIM and the ITLS is recommended. These two algorithms are chosen for comparison because both consider: i) SINR at sensor node to detect the interference, ii) traffic priority of each sensor while allocating timeslots and iii) distance between WBANs to detect interfering WBANs. Simulation parameters are listed in Table 4. This work uses two simulation scenarios, 1) High Interference scenario and 2) Moderate Interference scenario.

A. SCENARIO 1: HIGH INTERFERENCE

In a high interference scenario, the interference power is received from all neighboring WBANs (either coordinators or sensors). The one generating the highest interference is taken into consideration for determining the SINR.

Figure 9 shows the reuse factor for a varying number of WBANs and different packet rates. The IPC curves show significant improvement over other algorithms when the number of WBANs is greater than 6. This is because with an increasing number of WBANS, the interference in the network increases. In the IPC approach, keeping a WBAN silent provides the opportunity to schedule the maximum number of interfering sensors of neighboring WBANs. Therefore, the IPC approach attains higher spatial reuse. The results show that when the number of WBANs is 12 and packet rate is 16 packets/s, IPC provides 50% improvement in spatial reuse when compared to ITLS and gain approaches to 140% when compared with AIM.

Figure 10 shows packet delivery rate for 4 and 12 WBANs versus the packet generation rate. The packet delivery rate decreases with an increase in the number of WBANs. This is expected as the interference and number of packets in the network increases. The packet delivery rate also decreases with an increase in the packet generation rate. A higher packet rate increases the number of packets in the network creating congestion and subsequently lower delivery rate.

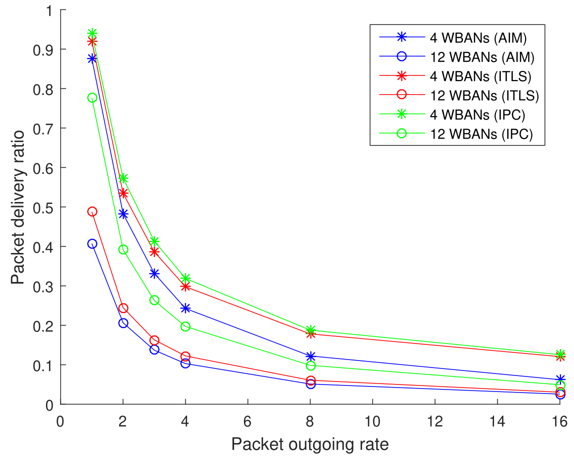

FIGURE 10. Packet delivery rate.

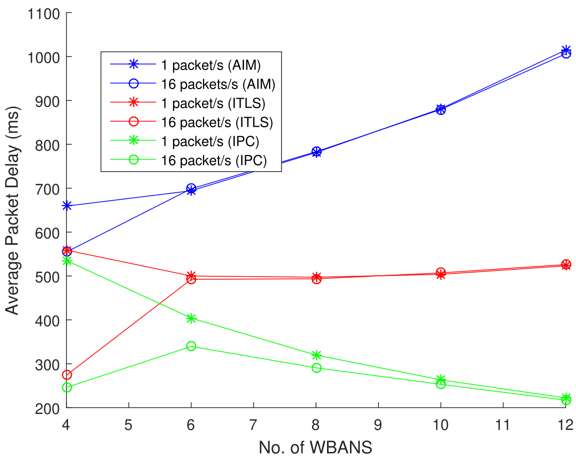

FIGURE 11. Delay per packet w.r.t. number of WBANs.

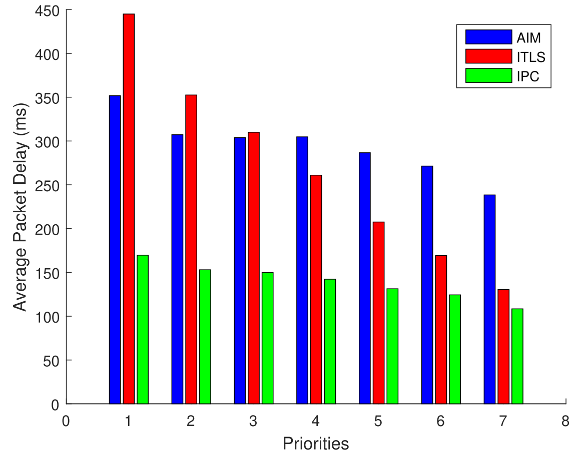

FIGURE 12. Delay per packet w.r.t. priority.

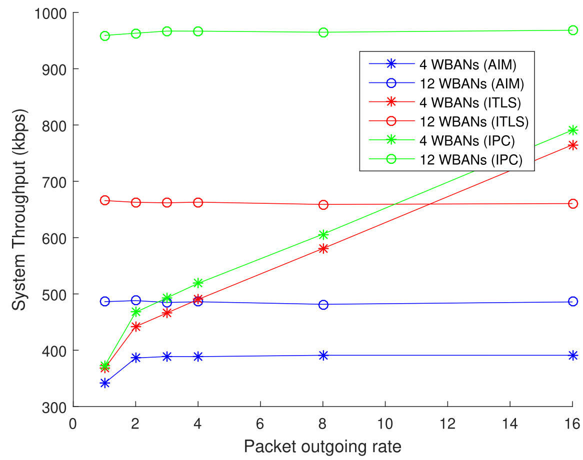

FIGURE 13. System throughput w.r.t packet outgoing rate.

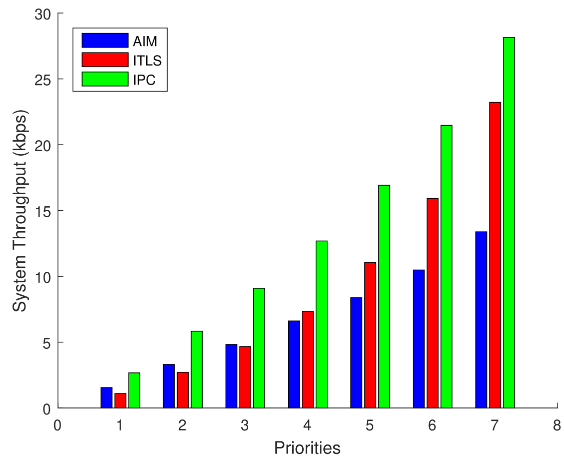

FIGURE 14. System throughput w.r.t. priority.

The analysis of IPC for 12 WBANs and 16 packets/s shows an improvement of 61.6% for ITLS and 92.5% over AIM.

Figure 11 shows that the IPC algorithm achieves lower average packet delay as compared to the other algorithms because of higher reuse factor and less blocking of nodes. When neighbors of a silent WBAN select interfered node for scheduling, idle wastage of resources is controlled. Hence, IPC achieves a higher throughput at lower delay because other nodes are less prone to silent instances (delay). Moreover, for AIM and ITLS, the delay increases for the higher number of WBANs, while for IPC, the delay is decreased for the higher number of nodes which shows that IPC performs well under interference. When the number of WBANs is 12 and the packet rate is 16 packets/s, the curves indicate a 364% improvement in delay compared to AIM and around 141% compared to ITLS. Figure 12 plots the average packet delay against the node priorities. The IPC has the lowest delay for all the priorities.

Figure 13 shows the system throughput versus packet outgoing rate. Because of the higher reuse factor and packet delivery rate, the IPC algorithm provides a 46.5% improvement over ITLS and a 100% improvement when compared to AIM. The system throughput concerning sensor priorities is presented in Figure 14 at 12 WBANs and 16 packets/s.

Figure 15 and Figure 16 show energy consumption and energy efficiency curves. The higher energy consumption is because in IPC higher number of transmissions are carried out by the sensors in the total time. It can be inferred that

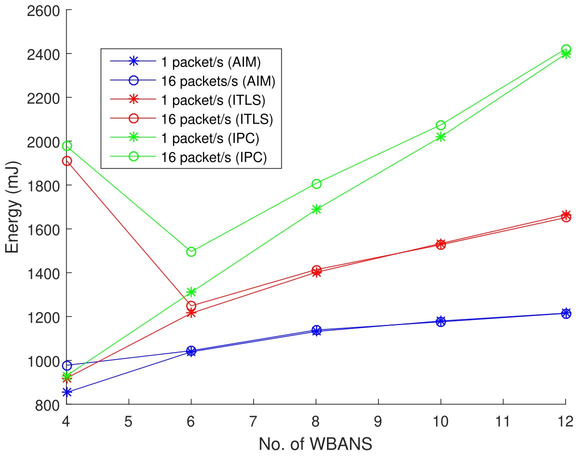

FIGURE 15. Total energy consumption w.r.t. number of WBANs.

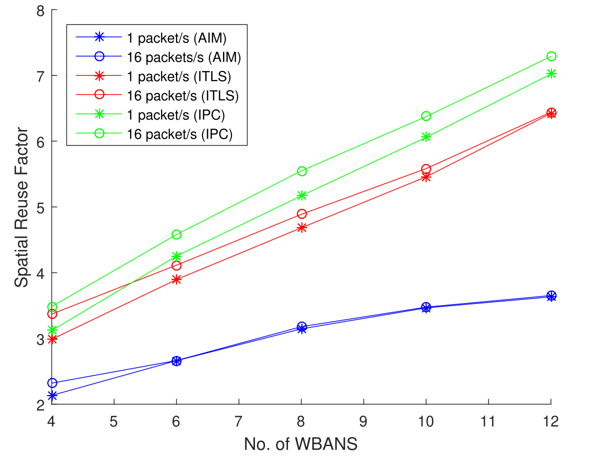

FIGURE 17. Reuse factor.

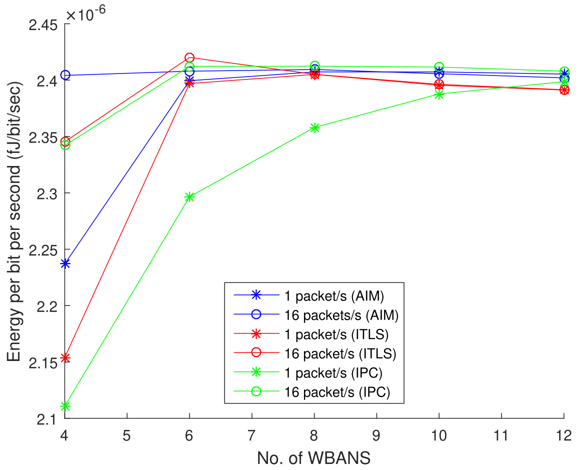

FIGURE 16. Energy efficiency w.r.t. number of WBANs.

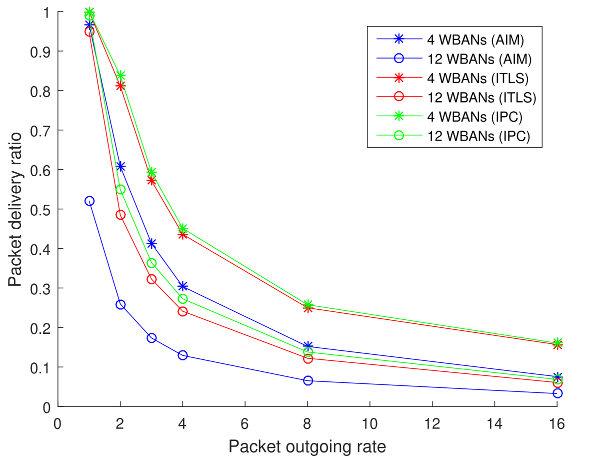

FIGURE 18. Packet delivery rate.

if the amount of data for each node is restricted to a certain value, the energy consumption of IPC will be lower compared to both the AIM and ITLS. This is because the sensor nodes consume most of the energy in the active timeslots and the IPC algorithm reduces the active time of sensors to conserve energy. The number of WBANs is varied to calculate the results of energy consumption and energy efficiency. The results are generated at both 1 packet/s and 16 packets/s. The curves at 12 WBANs and 16 packets/s show that the average energy consumption of IPC is about 46.5% higher as compared to ITLS and 100% higher compared to AIM. Energy efficiency curves in Figure 16 at 1 packets/s initially shows improvement over AIM and ITLS. However, as shown in the energy consumption curves in Figure 15, energy consumption increases if the number of WBAN increases. The energy efficiency at 16 packets/s follows a similar trend as ITLS and AIM.

B. SCENARIO 2: MODERATE INTERFERENCE

In moderate interference, the SINR calculations are carried out with only the interference received from the neighboring coordinator. This approach is similar to the one used in ITLS.

Figure 17 shows that at 12 WBANs and 16 packets/s, IPC achieves 13.3% improvement over ITLS and 102.4% for AIM.

In Figure 18, IPC shows 13.2% improvement in packet delivery rate over ITLS and 111.4% improvement as compared to AIM at 12 WBANs and 16 packets/s.

Figure 19 shows that IPC achieves 28.1% improvement in delay concerning ITLS and 330.1% improvement as compared to AIM at 12 WBANs and 16 packets/s. Analysis of delay against priority is also presented in Figure 20 at 12 WBANs and 16 packets/s.

Figure 21 shows that IPC achieves 13.2% improvement in system throughput over ITLS and 97.2% improvement as compared to AIM at 12 WBANs and 16 packets/s. Throughput versus priority is also shown in Figure 22 at 12 WBANs and 16 packets/s.

Figure 23 shows that energy consumption of IPC is 13.2% higher as compared to ITLS and 97.2% higher then AIM at 12 WBANs and 16 packets/s. Results are calculated by varying numbers of WBANs and results are generated at both 1 packet/s and 16 packets/s. Figure 24 shows that IPC algorithm schedule more node in a single timeslot and achieve

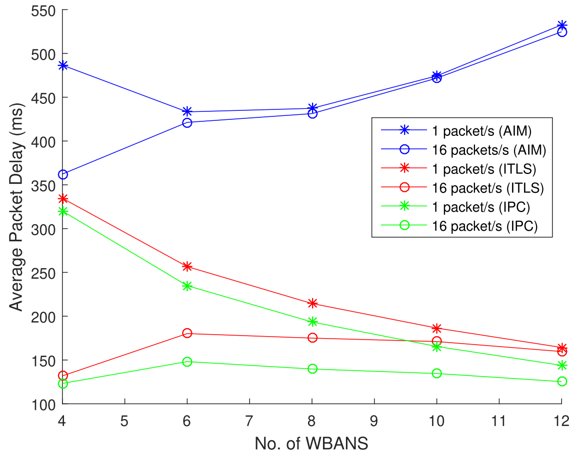

FIGURE 19. Delay per packet w.r.t. number of WBANs.

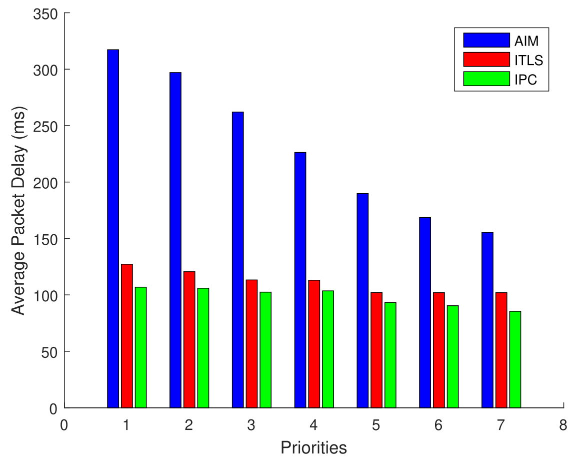

FIGURE 20. Delay per packet w.r.t. priority.

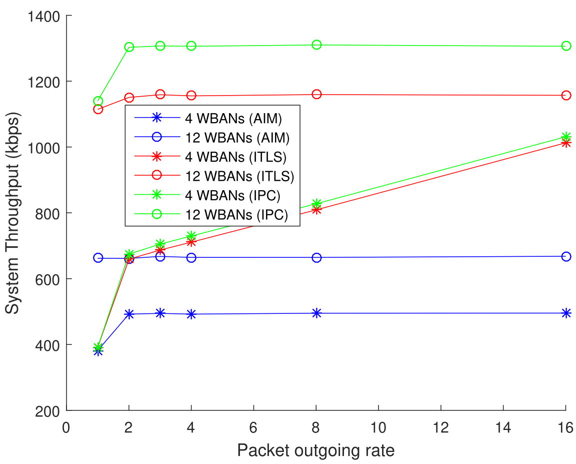

FIGURE 21. System throughput w.r.t. packet outgoing rate.

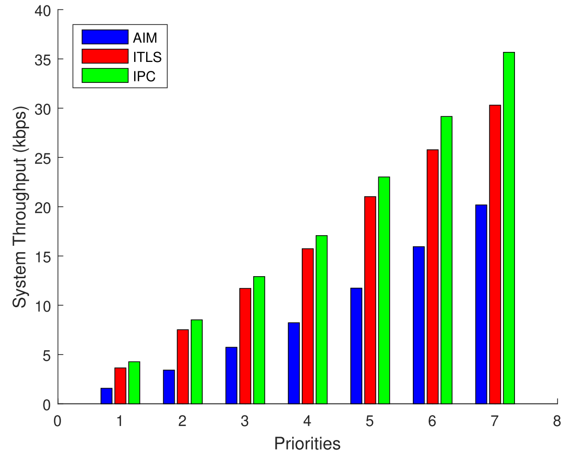

FIGURE 22. System throughput w.r.t. priority.

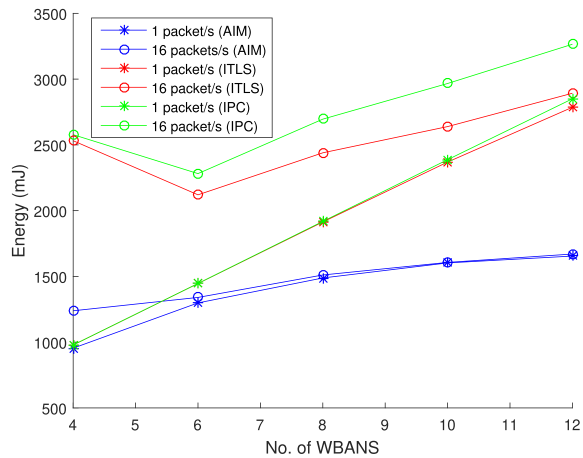

FIGURE 23. Total energy consumption w.r.t. number of WBANs.

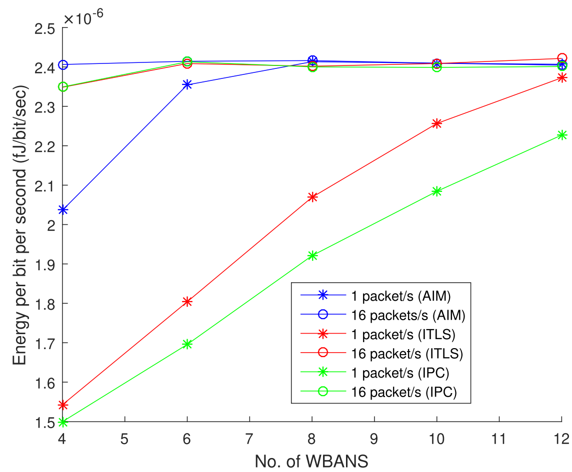

FIGURE 24. Energy efficiency w.r.t. number of WBANs.

higher reuse factor and more bits per timeslot, hence consuming less energy per bit. Analysis of this technique at 12 WBANs and 1 packet/s shows 6.75% improvement for ITLS and 8.1% improvement in energy per bit per second over AIM.

The main aim of this work was to schedule maximum possible sensor nodes in a superframe (improve reuse) while keeping interference at its minimum. Under high interference, this work achieved a 50% improvement in reuse over ITLS and 140% as compared to AIM. Similarly, this work noticed above 13% improvement in reuse over ITLS and slightly above 100% versus AIM under moderate interference.

VI. CONCLUSION

In this work, a link scheduling algorithm, IPC, to mitigate interference between coexisting WBANs is presented, which considers traffic priorities, packet lengths and SINR based interference graph formation for scheduling. The IPC enables concurrent transmissions of the coexisting WBAN nodes by reducing the number of instances where an interfering WBAN is made silent. Besides, IPC transmits the highest priority data maintaining QoS and the highest number of interfered sensors are selected to minimize idle wastage of resources at every timeslot. Two interference scenarios that cater to both the high and moderate interference scenarios are considered for simulations. Furthermore, the results are compared with the well known AIM and ITLS techniques. The simulation results show a higher reuse factor, system throughput, packet delivery rate by providing a minimum delay per packet over existing schemes. Generally, the performance gain of IPC is high compared to AIM and ITLS for both scenarios. However, it shows significant improvement in the case of high interference up to approximately 50% for system throughput. The throughput versus node priorities also exhibits similar gains in the case of high interference scenario.

REFERENCES

[1] S. Ullah, P. Khan, N. Ullah, S. Saleem, H. Higgins, and K. S. Kwak, "A review of wireless body area networks for medical applications," 2010, *arXiv:1001.0831*. [Online]. Available: http://arxiv.org/abs/1001.0831

[2] M. M. Alam, D. B. Arbia, and E. B. Hamida, "Research trends in multi-standard device-to-device communication in wearable wireless networks," in *Cognitive Radio Oriented Wireless Networks*, M. Weichold, M. Hamdi, M. Z. Shakir, M. Abdallah, G. K. Karagiannidis, and M. Ismail, Eds. Cham, Switzerland: Springer, 2015, pp. 735–746.

[3] H. Li, C. Chen, W. Yu, B. Yang, and X. Guan, "SuperSA: Superframe design based slot allocation of wireless body area networks for healthcare systems," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2012, pp. 1–6.

[4] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, and A. Jamalipour, "Wireless body area networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1658–1686, 3rd Quart., 2014.

[5] G. Fang and E. Dutkiewicz, "BodyMAC: Energy efficient TDMA-based MAC protocol for wireless body area networks," in *Proc. 9th Int. Symp. Commun. Inf. Technol.*, Sep. 2009, pp. 1455–1459.

[6] K. S. Kwak, S. Ullah, and N. Ullah, "An overview of IEEE 802.15.6 standard," in *Proc. 3rd Int. Symp. Appl. Sci. Biomed. Commun. Technol. (ISABEL)*, Nov. 2010, pp. 1–6.

[7] S. Kim and B. K. Song, "A prioritized resource allocation algorithm for multiple wireless body area networks," *Wireless Netw.*, vol. 23, no. 3, pp. 727–735, Apr. 2017, doi: 10.1007/s11276-015-1163-1.

[8] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.6: Wireless Body Area Networks*, IEEE Standard 802.15.6, ASTRIN, 2012. [Online]. Available: https://ci.nii.ac.jp/naid/20001714644/en/

[9] S. Movassaghi, B. Maleki, D. B. Smith, and M. Abolhasan, "Biologically inspired self-organization and node-level interference mitigation amongst multiple coexisting wireless body area networks," in *Proc. 13th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Jun. 2017, pp. 1221–1226.

[10] F. Wu, T. Wu, and M. Yuce, "An Internet-of-Things (IoT) network system for connected safety and health monitoring applications," *Sensors*, vol. 19, no. 1, p. 21, 2018. [Online]. Available: https://www.mdpi.com/1424-8220/19/1/21

[11] C. Yi and J. Cai, "A truthful mechanism for scheduling delay-constrained wireless transmissions in IoT-based healthcare networks," *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, pp. 912–925, Feb. 2019.

[12] A. S. Abiodun, M. H. Anisi, and M. K. Khan, "Cloud-based wireless body area networks: Managing data for better health care," *IEEE Consum. Electron. Mag.*, vol. 8, no. 3, pp. 55–59, May 2019.

[13] S. Movassaghi, A. Majidi, A. Jamalipour, D. Smith, and M. Abolhasan, "Enabling interference-aware and energy-efficient coexistence of multiple wireless body area networks with unknown dynamics," *IEEE Access*, vol. 4, pp. 2935–2951, Jun. 2016.

[14] S. Farid, Y. Zia, A. Farhad, and F. B. Hussain, "Homogeneous interference mitigation techniques for wireless body area network under coexistence: A survey," in *Proc. IEEE Asia Pacific Conf. Wireless Mobile (APWiMob)*, Sep. 2016, pp. 124–129.

[15] T. Ahmed, F. Ahmed, and Y. Le Moullec, "Optimization of channel allocation in wireless body area networks by means of reinforcement learning," in *Proc. IEEE Asia Pacific Conf. Wireless Mobile (APWiMob)*, Sep. 2016, pp. 120–123.

[16] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "Wireless body area network (WBAN): A survey on reliability, fault tolerance, and technologies coexistence," *ACM Comput. Surv.*, vol. 50, no. 1, p. 3, 2017. [Online]. Available: http://doi.acm.org/10.1145/3041956

[17] S. Misra, J. Mahapatro, M. Mahadevappa, and N. Islam, "Random room mobility model and extra-wireless body area network communication in hospital buildings," *IET Netw.*, vol. 4, no. 1, pp. 54–64, 2015.

[18] M. Waheed, R. Ahmad, W. Ahmed, M. Drieberg, and M. M. Alam, "Towards efficient wireless body area network using two-way relay cooperation," *Sensors*, vol. 18, no. 2, p. 656, 2018. [Online]. Available: https://www.mdpi.com/1424-8220/18/2/565

[19] M. M. Alam and E. Ben Hamida, "Interference mitigation and coexistence strategies in IEEE 802.15.6 based wearable body-to-body networks," in *Cognitive Radio Oriented Wireless Networks*, M. Weichold, M. Hamdi, M. Z. Shakir, M. Abdallah, G. K. Karagiannidis, and M. Ismail, Eds. Cham, Switzerland: Springer, 2015, pp. 665–677.

[20] R. Negra, I. Jemili, and A. Belghith, "Wireless body area networks: Applications and technologies," *Procedia Comput. Sci.*, vol. 83, pp. 1274–1281, Jan. 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S187705091630299X

[21] T. T. T. Le and S. Moh, "An interference-aware traffic-priority-based link scheduling algorithm for interference mitigation in multiple wireless body area networks," *Sensors*, vol. 16, no. 12, p. 2190, 2016. [Online]. Available: https://www.mdpi.com/1424-8220/16/12/2190

[22] S. Movassaghi, M. Abolhasan, D. Smith, and A. Jamalipour, "AIM: Adaptive internetwork interference mitigation amongst co-existing wireless body area networks," in *Proc. IEEE Int. Global Commun. Conf. (GC)*, Dec. 2014, pp. 2460–2465.

[23] T. T. Le and S. Moh, "Interference mitigation schemes for wireless body area sensor networks: A comparative survey," *Sensors*, vol. 15, no. 6, pp. 13805–13838, 2015. [Online]. Available: https://www.mdpi.com/1424-8220/15/6/13805

[24] Z. Xie, G. Huang, J. He, and Y. Zhang, "A clique-based WBAN scheduling for mobile wireless body area networks," *Procedia Comput. Sci.*, vol. 31, pp. 1092–1101, Jan. 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1877050914005419

[25] M. Deylami and E. Jovanov, "An implementation of a distributed scheme for managing the dynamic coexistence of wireless body area networks," in *Proc. IEEE Southeastcon*, Apr. 2013, pp. 1–6.

[26] S. Movassaghi, M. Abolhasan, and D. Smith, "Smart spectrum allocation for interference mitigation in wireless body area networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2014, pp. 5688–5693.

[27] M. Salayma, A. Al-Dubai, I. Romdhani, and Y. Nasser, "New dynamic, reliable and energy efficient scheduling for wireless body area networks (WBAN)," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2017, pp. 1–6.

[28] J. Mahapatro, S. Misra, M. Mahadevappa, and N. Islam, "Interference-aware MAC scheduling and admission control for multiple mobile WBANs used in healthcare monitoring," *Int. J. Commun. Syst.*, vol. 28, no. 7, pp. 1352–1366, 2015. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/dac.2768

[29] D.-R. Chen, P.-F. Wang, and W.-M. Chiu, "On the study of interference mitigation and QoS protocol for wireless body area networks using real-time scheduling," in *Proc. 27th Int. Telecommun. Netw. Appl. Conf. (ITNAC)*, Nov. 2017, pp. 1–6.

[30] H. Moungla, K. Haddadi, and S. Boudjit, "Distributed interference management in medical wireless sensor networks," in *Proc. 13th IEEE Annu. Consum. Commun. Netw. Conf. (CCNC)*, Jan. 2016, pp. 151–155.
[31] T. T. T. Le and S. Moh, "Link scheduling algorithm with interference prediction for multiple mobile WBANs," *Sensors*, vol. 17, no. 10, p. 2231, 2017. [Online]. Available: https://www.mdpi.com/1424-8220/17/10/2231
[32] S. H. Cheng and C. Y. Huang, "Coloring-based inter-WBAN scheduling for mobile wireless body area networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 24, no. 2, pp. 250–259, Feb. 2013.
[33] W. Sun, Y. Ge, and W.-C. Wong, "A stochastic geometry analysis of inter-user interference in IEEE 802.15.6 body sensor networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Mar. 2015, pp. 1912–1917.
[34] S. Movassaghi, M. Abolhasan, and D. Smith, "Cooperative scheduling with graph coloring for interference mitigation in wireless body area networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2014, pp. 1691–1696.
[35] X. Qi, K. Wang, D. Yue, L. Shu, Y. Liu, and H. Zhao, "Adaptive TDMA-based MAC protocol in energy harvesting wireless body area network for mobile health," in *Proc. 41st Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2015, pp. 4175–4180.
[36] S. Kim, S. Kim, J.-W. Kim, and D.-S. Eom, "Flexible beacon scheduling scheme for interference mitigation in body sensor networks," in *Proc. 9th Annu. IEEE Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw. (SECON)*, Jun. 2012, pp. 157–164.
[37] Z. Wei, Y. Sun, and Y. Ji, "A study on coexistence capability evaluations of the enhanced channel hopping mechanism in WBANs," *Sensors*, vol. 17, no. 1, p. 151, 2017. [Online]. Available: https://www.mdpi.com/1424-8220/17/1/151
[38] M. Z. Islam, M. S. Alam, and S. S. Moni, "Efficient techniques for improving coexistence problem in wireless body area network," in *Proc. 19th Int. Conf. Comput. Inf. Technol. (ICCIT)*, Dec. 2016, pp. 13–18.
[39] M. Ali, H. Moungla, M. Younis, and A. Mehaoua, "Distributed scheme for interference mitigation of wbans using predictable channel hopping," in *Proc. IEEE 18th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Sep. 2016, pp. 1–6.
[40] D. R. Chen, "A QoS bandwidth allocation method for coexistence of wireless body area networks," in *Proc. 25th Euromicro Int. Conf. Parallel, Distrib. Netw.-Based Process. (PDP)*, Mar. 2017, pp. 251–254.
[41] B. Yuan, J. Liu, W. Liu, and S. Zheng, "DIM: A novel decentralized interference mitigation scheme in WBAN," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2015, pp. 1–5.
[42] X. Yuan, C. Li, Q. Ye, K. Zhang, N. Cheng, N. Zhang, and X. Shen, "Performance analysis of IEEE 802.15.6-based coexisting mobile WBANs with prioritized traffic and dynamic interference," *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5637–5652, Aug. 2018.
[43] M. Barbi, K. Sayrafian, and M. Alasti, "Using RTS/CTS to enhance the performance of IEEE 802.15.6 CSMA/CA," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–5.
[44] T. T. T. Le and S. Moh, "Hybrid multi-channel MAC protocol for WBANs with inter-WBAN interference mitigation," *Sensors*, vol. 18, no. 5, p. 1373, 2018. [Online]. Available: https://www.mdpi.com/1424-8220/18/5/1373
[45] A. Saboor, R. Ahmad, W. Ahmed, A. K. Kiani, Y. L. Moullec, and M. M. Alam, "On research challenges in hybrid medium access control protocols for IEEE 802.15.6 WBANs," *IEEE Sensors J.*, vol. 19, no. 10, pp. 8543–8555, Oct. 2019.
[46] A. Enkoji, M. Li, J. D. Brisky, and R. Melvin, "Dynamic EAP based MAC protocol for wireless body area networks," in *Proc. Int. Conf. Comput., Netw. Commun. (ICNC)*, Feb. 2019, pp. 531–536.
[47] D.-R. Chen and W.-M. Chiu, "Collaborative link-aware protocols for energy-efficient and QoS wireless body area networks using integrated sensors," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 132–149, Feb. 2018.
[48] R. Liu and Y. Wang, "Energy efficiency of wireless body area networks coexistence," in *Proc. 11th Int. Symp. Antennas, Propag. EM Theory (ISAPE)*, Oct. 2016, pp. 391–394.
[49] K. Deepak and A. Babu, "Optimal packet size for energy efficient WBAN under M-periodic scheduled access mode," in *Proc. IEEE 20th Nat. Conf. Commun. (NCC)*, Apr. 2014, pp. 1–6.
[50] P. M. Paul and A. V. Babu, "Frame length optimization in IEEE 802.15.6 UWB cooperative body area networks," in *Proc. IEEE Recent Adv. Intell. Comput. Syst. (RAICS)*, Dec. 2015, pp. 99–104.
[51] T. Manna and I. S. Misra, "Implementation of energy efficient WBAN using IEEE 802.15.6 scheduled access MAC for e-healthcare," in *Proc. 10th Int. Conf. Commun. Syst. Netw. (COMSNETS)*, Jan. 2018, pp. 267–274.
[52] M. M. Twinkle and G. Jegan, "Design of highly compressed NB PHY transceiver of IEEE 802.15.6 based on adaptive modulation scheme," in *Proc. Online Int. Conf. Green Eng. Technol. (IC-GET)*, Nov. 2016, pp. 1–5.
[53] M. S. Mohammadi, E. Dutkiewicz, Q. Zhang, and X. Huang, "Optimal energy efficiency link adaptation in IEEE 802.15.6 IR-UWB body area networks," *IEEE Commun. Lett.*, vol. 18, no. 12, pp. 2193–2196, Dec. 2014.
[54] V. Marbukh, M. Barbi, K. Sayrafian, and M. Alasti, "A queue-size & channel quality based adaptation of the energy detection threshold in IEEE 802.15.6 CSMA/CA," in *Proc. IEEE 18th Int. Conf. e-Health Netw., Appl. Services (Healthcom)*, Sep. 2016, pp. 1–6.
[55] M. Barbi, K. Sayrafian, and M. Alasti, "Application of link adaptation in body area networks," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Oct. 2017, pp. 1–6.
[56] M. M. Alam and E. B. Hamida, "Surveying wearable human assistive technology for life and safety critical applications: Standards, challenges and opportunities," *Sensors*, vol. 14, no. 5, pp. 9153–9209, Mar. 2014. [Online]. Available: https://www.mdpi.com/1424-8220/14/5/9153
[57] Z. H. Hu, Y. Nechayev, and P. Hall, "Measurements and statistical analysis of the transmission channel between two wireless body area networks at 2.45 GHz and 5.8 GHz," in *Proc. 20th Int. Conf. Appl. Electromagn. Commun. (ICECom)*, Sep. 2010, pp. 1–4.

FAWAD NAWAZ KHAN received the B.Sc. degree in electrical engineering (communication) from the CECOS University of IT and Emerging Sciences, Peshawar, Pakistan, in 2014, and the master's degree in electrical engineering (M.S.E.E.) from the School of Electrical Engineering and Computer Science (SEECS), National University of Science and Technology (NUST), Islamabad, Pakistan, in 2019. He worked in telecom industry in the field of wireless communication. He worked in Pakistan Telecommunication Company Limited (PTCL) for landline and broadband internet departments.

RIZWAN AHMAD received the M.Sc. degree in communication engineering and media technology from the University of Stuttgart, Stuttgart, Germany, in 2004, and the Ph.D. degree in electrical engineering from Victoria University, Melbourne, Australia, in 2010. From 2010 to 2012, he was a Postdoctoral Research Fellow with Qatar University on a QNRF grant. He is currently an Assistant Professor with the School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Pakistan. He has published and served as a reviewer for the IEEE journals and conferences. His research interests include medium access control protocols, spectrum and energy efficiency, energy harvesting, and performance analysis for wireless communication and networks. He also serves on the TPC of leading conferences in the communication and networking field, including, e.g., the IEEE VTC, the IEEE ICC, and the IEEE Globecom. He was a recipient of the prestigious International Postgraduate Research Scholarship from the Australian Government.

WAQAS AHMED received the M.S. degree in systems engineering from the Pakistan Institute of Engineering and Applied Sciences, in 2005, and the Ph.D. degree in electrical engineering from Victoria University, Melbourne, Australia, in 2012. Since 2007, he has been an Assistant Professor with the Department of Electrical Engineering, Pakistan Institute of Engineering and Applied Sciences. His research interests include cognitive radios, cooperative communication, and physical layer aspects of wireless communication and networks. He has published and served as a reviewer for the IEEE journals and conferences. He also serves on the TPC of leading conferences in the communication and networking field, including, e.g., the IEEE VTC, the IEEE ICC, and the IEEE WCNC. He was a recipient of the IEEE Exemplary Reviewer Award, in 2010.

MUHAMMAD MAHTAB ALAM (SM'19) heads the Communication Systems Research Group with the Tallinn University of Technology, Estonia. He is currently a Professor of communication technologies with research interests in radio resource management for cellular wireless systems, low-power self-adaptive wireless sensor systems, the Internet-of-things, and public safety networks. He is author and coauthor of more than 75 research publications. He holds the European Research Area Chair with the Research Lab of Cognitronics. He has over 12 years of combined academic and industry experience with several leading roles as a PI in international projects funded by the European Commission, NATO, and the Estonian Research Council. He is also a contributor to two standards, the IEEE Green ICT (EECH) Working Group and ETSI SmartBAN Work Item TR 103 711, as rapporteur.

MICHEAL DRIEBERG received the B.Eng. degree from Universiti Sains Malaysia, Penang, Malaysia, in 2001, the M.Sc. degree from Universiti Teknologi PETRONAS, Seri Iskandar, Malaysia, in 2005, and the Ph.D. degree from Victoria University, Melbourne, Australia, in 2011, all in electrical and electronics engineering. He is currently a Senior Lecturer with the Department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS. His research interests include radio resource management, medium access control protocols, energy harvesting communications, and performance analysis for wireless and sensor networks. He has published and served as a reviewer for several high impact journals and flagship conferences. He has also made several contributions to the wireless broadband standards group.