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IoT-enabled Channel Selection Approach for WBANs

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Abstract—Recent advances in microelectronics have enabled the realization of Wireless Body Area Networks (WBANs). However, the massive growth in wireless devices and the push for interconnecting these devices to form an Internet of Things (IoT) can be challenging for WBANs; hence robust communication is necessary through careful medium access arbitration. In this paper, we propose a new protocol to enable WBAN operation within an IoT. Basically, we leverage the emerging Bluetooth Low Energy technology (BLE) and promote the integration of a BLE transceiver and a Cognitive Radio module (CR) within the WBAN coordinator. Accordingly, a BLE informs WBANs through announcements about the frequency channels that are being used in their vicinity. To mitigate interference, the superframe’s active period is extended to involve not only a Time Division Multiple Access (TDMA) frame, but also a Flexible Channel Selection (FCS) and a Flexible Backup TDMA (FBTDMA) frames. The WBAN sensors that experience interference on the default channel within the TDMA frame will eventually switch to another Interference Mitigation Channel (IMC). With the help of CR, an IMC is selected for a WBAN and each interfering sensor will be allocated a time-slot within the (FBTDMA) frame to retransmit using such IMC.

Index terms— IoT, Channel allocation, WBAN interference mitigation, Bluetooth low energy, Cognitive radio

I. INTRODUCTION

An IoT is a short-range wireless network of interconnected devices, e.g., WBANs, Wi-Fi, IEEE 802.15.4 (ZigBee), RFID, Tags, Sensors, PDAs, Smartphones, etc., that could sense, process and communicate information. Example applications of IoT are smart homes, health monitoring, wearables, environment monitoring, transportation and industrial automation. Within an IoT, various types of wireless networks are required to facilitate the exchange of application-dependant data among their heterogeneous wireless devices. However, such diversity could give rise to coexistence issues among these networks, a challenge that limits the large-scale deployment of the IoT. Therefore, new protocols are required for communication compatibility among its heterogeneous devices.

Basically, the IEEE 802.15.6 standard [1], e.g., WBANs, utilizes a narrower bandwidth than other wireless networks, e.g., IEEE 802.11. However, the IEEE 802.11 based wireless devices may use multiple channels that cover the whole international license-free 2.4 GHz Industrial, Scientific and Medical Radio, denoted by ISM, band, so there could be overlapping channel covering an IEEE 802.15.6 based network and thus create collisions between IEEE 802.15.6 and these devices. In addition, IEEE 802.11 based wireless devices may transmit at a high power level and thus relatively distant coexisting IEEE 802.15.6 devices may still suffer interference. Thus, the pervasive growth in wireless devices and the push for interconnecting them can be challenging for WBANs due to their simple and energy-constrained nature. Basically, a WBAN may suffer interference not only because of the presence of other WBANs but also from wireless devices within the general IoT simultaneously operating on the same channel. Thus, co-channel interference may arise due to the collisions amongst the concurrent transmissions made by sensors in different WBANs collocated in an IoT and hence such potential interference can be detrimental to the operation of WBANs. Therefore, robust communication is necessary among the individual devices of the collocated networks in an IoT.

In this paper, we propose a protocol to enable WBAN operation within an IoT and leverage the emerging BLE technology to facilitate interference detection and mitigation. Motivated by the reduced power consumption and low cost of BLE devices, we integrate a BLE transceiver and a CR module within each WBAN’s coordinator node, denoted by Crd, where the role of BLE is to inform the Crd about the frequency channels that are being used in its vicinity. In addition, the superframe’s active period is further extended to involve not only a TDMA frame, but also a FCS and FBTDMA frames, for interference mitigation. When experiencing high interference, the WBAN’s Crd will be notified by the BLE device to use the CR module for selecting a different channel. When engaged, the CR assigns a stable channel for interfering sensors that will be used later within the FBTDMA frame for data transmission. The simulation results show that our proposed approach can efficiently improve the spectrum utilization and significantly lower the medium access collisions among the collocated wireless devices in the general IoT.

The rest of the paper is organized as follows. Section II sets our work apart from other approaches in the literature. Section III summarizes the system model and provides a brief overview of the BLE and the CR. Section IV describes CSIM in detail. Section V presents the simulation results. Finally, the paper is concluded in Section VI.
II. RELATED WORK

Avoidance and mitigation of channel interference have been extensively researched in the wireless communication literature. To the best of our knowledge, the published techniques in the realm of IoT are very few and can be categorized as resource sharing and allocation, power control, scheduling techniques and medium access schemes. Example schemes that pursued the resource sharing and allocation include [2], [3], [4], [5]. Bakshi et al., [2] proposed a completely asynchronous and distributed solution for data communication across IoT, called EMIT. EMIT avoids the high overhead and coordination costs of existing solutions through employing an interference-averaging strategy that allows users to share their resources simultaneously. Furthermore, EMIT develops power-rate allocation strategies to guarantee low-delay high-reliability performance. Torabi et al., [3] proposed a rapid-response and robust scheme to mitigate the effect of interfering systems, e.g., IEEE 802.11, on WBAN performance. They proposed dynamic frequency allocation method to mitigate bi-link interferences that affect either the WBAN’s Crd or WBAN sensors and hence impose them to switch to the same frequency. Shigueta et al., [4] presented a strategy for channel assignment in an IoT. The proposed strategy uses opportunistic spectrum access via cognitive radio. The originality of this work resides in the use of traffic history to guide the channel allocation in a distributed manner. Ali et al., [5] proposed a distributed scheme that avoids interference amongst coexisting WBANs through predictable channel hopping. Based on the Latin rectangle of the individual WBAN, each sensor is allocated a backup time-slot and a channel to use if it experiences interference such that collisions among different transmissions of coexisting WBANs are minimized.

Xiao et al., [6] adopted the approach of power control and considered machine-to-machine, denoted by M2M, communication for an IoT network. The authors proposed a framework of full-duplex M2M communication in which the energy transfer, i.e., surplus energy, from the receiver to the transmitter and the data transmission from the transmitter to the receiver take place at the same time over the same frequency. Furthermore, the authors established a stochastic game-based model to characterize the interaction between autonomous M2M transmitters and receivers. Meanwhile, Chen et al., [7] introduced a new area packet scheduling technique involving IEEE 802.15.6 and IEEE 802.11 devices. The developed packet scheduler is based on transmitting a common control signal known as the blank burst from MAC layer. The control signal prevents the IEEE 802.15.6 devices to transmit for a certain period of time during which the IEEE 802.11 devices could transmit data packets.

A number of approaches pursued the medium access scheduling methodology include [8],[9],[10] to mitigate interference among the IEEE 802.11 and IEEE 802.15.4 [15], i.e., ZigBee, based devices. Wang et al., [8] proposed a new technique, namely, the Acknowledgement, denoted by ACK, with Interference Detection (ACK-ID), that reduces the ACK losses and consequently reduces ZigBee packet retransmissions due to the presence of collocated IEEE 802.11 wireless networks. Basically, in ACK-ID, a novel interference detection process is performed before the transmission of each ZigBee ACK packet in order to decide whether the channel is experiencing interference or not. Inoue et al., [9] proposed a novel distributed active channel reservation scheme for coexistence, called DACROS, to solve the problem of WBAN and IEEE 802.11 wireless networks coexistence. DACROS uses the request-to-send and clear-to-send frames to reserve the channel for a superframe time of WBAN. Along the whole beacon time, i.e., the whole superframe of the WBAN, all IEEE 802.11 wireless devices remain silent and do not transmit to avoid collisions. Zhang et al., [10] proposed cooperative carrier signaling, namely, CCS, to harmonize the coexistence of ZigBee WBANs with IEEE 802.11 wireless networks. CCS allows ZigBee WBANs to avoid IEEE 802.11 wireless network-caused collisions and employs a separate ZigBee device to emit a busy tone signal concurrently with the ZigBee data transmission.

As pointed out, none of the predominant approaches can be directly applied to IoT because they do not consider the heterogeneity of the individual networks forming an IoT in their design. Motivated by the emergence of BLE technology and compared to the previous predominant approaches for interference mitigation, our approach lowers the power and communication overheads introduced on the coordinator- and sensor-levels within each WBAN.

Unlike prior work, in this paper, we propose a distributed protocol to enable WBAN operation and interaction within an existing IoT. We integrate a BLE transceiver to inform the WBAN about the frequency channels that are being used in its vicinity and a CR module within the WBAN’s Crd. Our approach relies on both BLE transceiver and the CR module for stable channel selection and allocation for interference mitigation. The CR module, when engaged determines a set of usable channels for the Crd to pick from. Each interfering sensor will then switch to the new channel to retransmit data to the Crd in its allocated backup time-slot.

III. SYSTEM MODEL AND PRELIMINARIES

A. Bluetooth Low Energy

Bluetooth Low Energy (BLE) is one of the promising technologies for IoT services because of its low energy consumption and cost. BLE is a wireless technology used for transmitting data over short distances and broadcasting advertisements at a regular interval via radio waves. The BLE advertisement is a one-way communication method. BLE devices, e.g., iBeacons, that want to be discovered can periodically broadcast self-contained packets of data. These packets are collected by devices like smartphones, where they can be used for a variety of applications to trigger prompt actions. We envision that each collocated set (cluster) of wireless devices of such IoT will have to include a BLE transceiver that periodically broadcasts the channel that is being used by the IoT devices in the vicinity. In fact, with the increased popularity of BLE, it is conceivable that every IoT device will be equipped with a BLE transceiver to announce its services.
and frequency channel. Standard BLE has a broadcast range of up to 100 meters, which makes BLE broadcasts an effective means for mitigating interference between WBANs and other IoT devices.

B. System Model and Assumptions

The IoT environment consists of different wireless networks, each uses some set of common channels in the international license-free 2.4 GHz ISM band. In addition, we assume that each network transmits using different levels of transmission power, bandwidth, data rates and modulation schemes. Meanwhile, WBANs are getting pervasive and thus form a building block for the ever-evolving future IoT. We consider N TDMA-based WBANs that coexist within the general IoT. Each WBAN consists of a single Crd and up to K sensors, each transmits its data on a channel within the international license-free 2.4 GHz ISM band [1]. Basically, we assume all Crds are equipped with richer energy supply than sensors and all sensors have access to all ZigBee channels at any time. In addition, each Crd is integrated with BLE to enable effective coordination in channel assignment and to allow the interaction with the existing IoT devices. Furthermore, each Crd has a CR module to decide the usability and the stability of a channel.

IV. CHANNEL SELECTION APPROACH FOR INTERFERENCE MITIGATION - CSIM

A co-channel interference takes place if the simultaneous transmissions of sensors and the Crd in a WBAN collide with those of other IoT coexisting devices. The potential for such a collision problem grows with the increase in the communication range and the density of sensors in the individual WBANs as well as the number of collocated IoT devices. To address this problem, our approach assigns each WBAN a default channel and in case of interference it allows the individual sensors to switch to a different channel to be picked by the Crd in consultation with the CR module to mitigate the interference. The use of BLE enables the Crd to be aware of interference conditions faster and more efficiently. To achieve that, our approach extends the size of the superframe through the addition of flexible number of backup time-slots to lower the collision probability of transmissions. At the network setup time, each Crd randomly picks a default channel from the set of ZigBee channels and informs all sensors within its WBAN through a beacon to use that channel along the TDMA frame of the superframe, as will be explained below.

A. Network Operation under CSIM

CSIM depends on acknowledgements (Acks) and time-outs to detect the collision at sensor- and coordinator-levels. In the TDMA frame shown in Fig. 1, each sensor transmits its packet in its assigned time-slot to the Crd using the default channel and then sets a time-out timer. If it successfully receives an Ack from its corresponding Crd, it considers the transmission successful, and hence it sleeps until the TDMA frame of the next superframe. However, if that sensor does not receive an Ack during the time-out period, it assumes failed transmission due to interference. Basically, all sensors experienced interference within the TDMA frame wait until the FCS frame completes, and then each switches to the common interference mitigation channel. Afterwards, each sensor retransmits its packet in its allocated time-slot within the FBTDMA frame to the Crd.

| Table I | NOTATIONS AND MEANINGS |
|--------------------------------|-------------------------|
| Notation | Meaning |
| WBAN<sub>i</sub> | i<sup>th</sup> WBAN |
| S<sub>i,j</sub> | j<sup>th</sup> sensor of i<sup>th</sup> WBAN |
| defaultChannel<sub>i</sub> | default channel of i<sup>th</sup> WBAN |
| stableChannel<sub>i</sub> | stable channel of i<sup>th</sup> WBAN |
| Crd<sub>i</sub> | coordinator of i<sup>th</sup> WBAN |
| BLE<sub>i</sub> | bluetooth low power device of i<sup>th</sup> coordinator |
| CR<sub>i</sub> | cognitive radio module of i<sup>th</sup> coordinator |
| Pts<sub>i</sub> | j<sup>th</sup> packet of i<sup>th</sup> sensor |
| Ack<sub>i</sub> | i<sup>th</sup> acknowledgement transmitted to j<sup>th</sup> sensor |
| T<sub>S</sub><sub>i,j</sub> | j<sup>th</sup> time-slot of i<sup>th</sup> TDMA frame |
| I<sub>MITS</sub><sub>i,j</sub> | j<sup>th</sup> time-slot of i<sup>th</sup> FBTDMA frame |
| LCH<sub>i</sub> | i<sup>th</sup> set of channels used by nearby IoT devices |
| LIS<sub>i</sub> | i<sup>th</sup> list of interfering sensors in TDMA<sub>i</sub> |
| FCS | Flexible Channel Selection |
| FBTDMA | Flexible Backup TDMA |

B. Channel Selection

Along the TDMA frame, each Crd’s BLE collects information based on broadcast announcements made by other nearby BLE transceivers about the set of channels being used by wireless devices in the vicinity of a designated WBAN (\{LCH\}), and then reports this information to its associated CR. The CR uses the following sets of channels which are defined as follows:

- \{G\} is a set of 16 channels available in the international license-free 2.4 GHz ISM band of ZigBee standard.
- \{LCH\} is a set of channels that are being used in the vicinity of a designated WBAN.
- \{defaultChannel\} is a singleton set that involves the default channel that is being used by a designated WBAN.
- \{US\} is a set that consists of the remaining ZigBee channels that are not being used in the vicinity of a designated WBAN, where \{US\} = \{G\} - \{LCH\} ∪ \{defaultChannel\}.

In low or moderate conditions of interference, where there are some available channels, i.e., \{US\} is not empty, or the size of the set \{LCH\} is smaller than the size of the set \{G\}, the Crd will not exploit the service of the CR when notified by the BLE about a channel conflict; instead, the Crd selects one available channel from \{US\} for efficient data transmission. However, in high interference conditions, the set \{US\} will be empty. Therefore, once notified by the BLE, the Crd can not select one available channel from \{US\}, and hence the CR should scan the set \{LCH\} to eventually select the most stable channel to be used within the FBTDMA frame for interference mitigation. Basically, the designated CR looks for a usable channel from the set \{LCH\}, if the first channel is not, then it
starts sequentially sensing channels until a usable channel will be found. If it finds a usable channel and satisfies the stability condition, then it reports its index to the associated Crd to be eventually used for interference mitigation [12].

C. Channel Stability

Our approach relies on CR to decide the usability and stability of a channel using the received noise power as an indicator \(Y_i\) [13]. \(Y_i\) during time-slot \(i\) is given by Eq. 1.

\[
Y_i = \frac{1}{2u} \sum_{j=1}^{2u} n_j \times n_j
\]

Where, \(u\) is the time-bandwidth product and \(n_j\) is a Gaussian noise signal with zero mean and unit variance. The probability density function, denoted by \(f\), of \(Y_i\) is given by Eq. 2.

\[
f(Y_i) = \frac{U}{\Gamma(\frac{1}{y})} k e^{-uy}
\]

Where, \(\Gamma(\cdot)\) is the gamma function, \(k = y^{n-1}\) and \(U = u^n\). Based on \(Y_i\), the CR decision criterion can be expressed as follows:

1) A channel \(C_i\) is usable, if \(Y_i < \lambda_1\)
2) \(C_i\) requires power boost (usable), if \(\lambda_1 < Y_i < \lambda_2\). In this case, we can use the theorem of Shannon (1948) [14] of the maximum transmission capacity \(P\) given in bit/s in Eq. 3
3) \(C_i\) cannot be used in time-slot \(i\) (unusable), if \(Y_i > \lambda_2\), where \(\lambda_1\) and \(\lambda_2\) are thresholds depend on the receiver sensitivity and the channel model in use.

\[
P = B\log_2(1 + SNR)
\]

Thus, the range of \(Y_i\) is divided into three regions, and is given by Eq. 4.

\[
R_j = \{Y_i: \lambda_{j-1} \leq Y_i \leq \lambda_j\}, j = 1, 2, 3
\]

Where \(\lambda_0\) is equal to 0 and \(\lambda_3\) is equal to \(\infty\). We mean by, a stable channel, if the probability of channel quality can not be decreased before the end of the transmission on that channel. The probability to being in a stable state \(j\) is given by Eq. 5.

\[
\pi_j = Pr\{Y_i \in R_j\} = Pr\{\lambda_{j-1} \leq Y_i < \lambda_j\}, j = 1, 2, 3
\]

The integration is done between \(\lambda_{j-1}\) and \(\lambda_j\). When the CR is engaged, it looks for a usable and stable channel which is done in the steps below.

**Step 1:** Crd looks for \(n\) usable channels. If the first channel is not, then the CR starts sequentially sensing channels until a usable channel is found. If the CR module finds a usable channel, then **Step 2** is executed to test the stability of the selected channel. Otherwise, the CR module informs Crd that no usable channel is available, Crd stays silent during a predetermined time-slot.

**Step 2:** If the selected usable channel satisfies the stability condition, then CR reports the index of this stable channel back to Crd.

D. Proposed Superframe Structure

In WBAN’s, sensors sleep and wake up dynamically and hence, the number of sensors being active during a period of time is unexpected. Therefore, a flexible way of scheduling different transmissions is required to avoid interference. We consider each WBAN’s superframe delimited by two beacons and composed of two successive frames: (i) active, that is dedicated for sensors, and (ii) inactive, that is designated for Crds. The superframe structure is shown in Fig. 1. During the inactive frame, Crds transmit collected data to a command center. In addition, the inactive frame directly follows the active frame and whose length depends on the underlying duty cycle being used. However, the active frame is further divided into three successive frames.

1) **Traditional TDMA Data Collection Frame - TDMA**
   The traditional TDMA frame consists of up to \(K\) time-slots that are allocated to sensors. Each WBAN’s sensor transmits its packet to its associated Crd in its allocated time-slot using the **default channel**.

2) **Channel Selection Frame - FCS**
   During the FCS which is of a fixed size, each WBAN’s Crd selects a stable interference mitigation channel and instructs all interfering sensors within its WBAN to use that channel during the **FBTDMA** frame. Based on the number of interfering sensors, each Crd determines the size of the FBTDMA frame and reports this information through a short beacon broadcast using the **default channel** to the designated sensors within its WBAN. In addition, the Crd allocates a time-slot within the FBTDMA frame for each interfering sensor to eventually retransmit its packet. Although, the beacon could be lost due to the interference, our approach enables early mitigation. Basically, the BLE alert limits the probability of collision on the **default channel** since the Crd will get a hint earlier than typical.

3) **Flexible Backup TDMA frame - FBTDMA**
   The FBTDMA frame consists of a flexible number of backup time-slots that depends on the number of sensors experiencing interference in the TDMA frame. Basically, each Crd knows about these sensors through using the expected number of acknowledgement and data packets received in an allocated time-slot for each sensor. In FBTDMA frame, each interfering sensor retransmits in its allocated backup time-slot to the Crd using the selected stable channel.

V. PERFORMANCE EVALUATION

In this section, we have conducted simulation experiments to evaluate the performance of the proposed CSIM scheme. We compare the performance of CSIM with smart spectrum allocation scheme [15], denoted by SSA, which assigns orthogonal channels to sensors belonging to the interference set, denoted by IS, formed between each pair of the interfering WBANs. Furthermore, we compare the energy consumption of the WBAN’s coordinator with and without switching the BLE transceiver on [16]. We define the probability of channel’s availability, denoted by \(P_{AvChs}\), at each Crd as the frequency

![Figure 1. Proposed superframe structure](image-url)
Algorithm 1 Proposed CSIM Scheme

Require: $N$ WBANs, $K$ Sensors/WBAN, $G$ ZIGBEE Channels/WBAN

1: Stage 1: Network Setup & TDMA Data Collection
2: Sensor-level collision:
3: for $i = 1$ to $N$ do
4:   $\text{Crd}_i$ picks one defaultChannel$_i$ from $\{G\}$;
5:   for $j = 1$ to $K$ do
6:     $S_{i,j}$ transmits $\text{Pkt}_{i,j}$ in $\text{TS}_{i,j}$ to $\text{Crd}_i$ on defaultChannel$_i$;
7:     if $S_{i,j}$ receives $\text{Ack}_{i,j}$ on defaultChannel$_i$ then
8:       $\text{Crd}_i$ transmits $\text{Ack}_{i,j}$ in $\text{TS}_{i,j}$ to $S_{i,j}$ on defaultChannel$_i$;
9:     else
10:    $S_{i,j}$ waits its IMTS$_{i,j}$ within FBTDMA$_i$ frame;
11:   end if
12: end for
13: end for
14: Coordinator-level collision:
15: for $i = 1$ to $N$ do
16:   for $j = 1$ to $K$ do
17:     if $\text{Crd}_i$ receives $\text{Pkt}_{i,j}$ in $\text{TS}_{i,j}$ on defaultChannel$_i$ then
18:       $\text{Crd}_i$ will tune to stableChannel$_{i,j}$ within FBTDMA$_i$ frame;
19:     end if
20: end for
21: end for
22: Channel Selection Setup:
23: $\text{BLE}_i$ forms the set $\{LCH_i\}$;
24: $\text{Crd}_i$ forms the set $\{LIS_i\}$;
25: Stage 2: Channel Selection
26: for $i = 1$ to $N$ do
27:   $\text{Crd}_i$ forms $\text{FBTDMA}_i$ frame from $\{LIS_i\}$;
28:   $\text{Crd}_i$ selects stableChannel$_i$ from $\{US_i\}$;
29:   $\text{Crd}_i$ informs LIS$_i$ sensors by stableChannel$_i$ & FBTDMA$_i$ frame;
30: end for
31: Stage 3: Interference Mitigation
32: for $i = 1$ to $N$ do
33:   for $s = 1$ to size-of($\{LIS_i\}$) do
34:     $S_{i,s}$ retransmits $\text{Pkt}_{i,s}$ in $\text{IMTS}_{i,s}$ on stableChannel$_i$;
35:     if $\text{Ack}_{i,s}$ received by $S_{i,s}$ on stableChannel$_i$ then
36:       $S_{i,s}$ sleeps until next superframe;
37:     else
38:       $\text{Crd}_i$ receives an earlier BLE$_i$ alert of interference;
39:     end if
40:   end for
41: end for
42: 

that a channel is not being used by any of the nearby IoT devices. An IoT cluster is defined as a collection of WBANs, Wi-Fi and other wireless devices collocated in the same space. The simulation network is deployed in three dimensional space ($10 \times 10 \times 4m^3$) and the locations of the individual WBANs change to mimic uniform random mobility and consequently, the interference pattern varies. The channel interference between any two wireless devices is evaluated on probabilistic interference thresholds. The simulation parameters are provided in Table II.

A. Probability of channel’s availability

1) Probability of channel’s availability vs. number of WBANs

In experiment 1, the probability of channel’s availability, denoted by $Pr_{AvChs}$, versus the cluster size, denoted by $\Omega$, for CSIM and SSA are compared, and results are shown in Fig. 2. As seen in the figure, CSIM always provides a higher $Pr_{AvChs}$ than SSA because of the channel selection is done at the WBAN- rather than sensor-level. For CSIM, the $Pr_{AvChs}$ significantly decreases from 0.79 to 0.27, when $5 \leq \Omega < 40$ because of the larger number of ZigBee channels that are being used by IoT devices than the number of channels available at each $\text{Crd}$. When $\Omega \geq 40$, $Pr_{AvChs}$ decreases very slightly and eventually stabilizes at 0.215 because all ZigBee channels are used by the IoT devices which makes it very hard for $\text{Crd}$s to select stable channels. However, for SSA, it is also observed from this figure that $Pr_{AvChs}$ decreases significantly from 0.51 to 0.08 when $5 \leq \Omega < 35$ because of the larger number of ZigBee channels that are being assigned to the sensors in the interfering set ($IS$) for any pair of WBANs. When $\Omega \geq 35$, $Pr_{AvChs}$ decreases very slightly and eventually stabilizes at 0.07 because of the maximal number of ZigBee channels being assigned to sensors coexisting within the interference range of a designated WBAN, i.e., the number of these sensors exceeds the 16 channels of ZigBee.

2) Probability of channel’s availability vs. signal-to-noise ratio threshold

Experiment 2 studies the effect of signal-to-noise ratio threshold denoted by $SNR_{Thr}$ on $Pr_{AvChs}$. The results in Fig. 3 shows that CSIM always achieves higher $Pr_{AvChs}$ than SSA for all $SNR_{Thr}$ values. In CSIM, the $Pr_{AvChs}$ significantly increases as $SNR_{Thr}$ increases from $-50$ to $-35$; similarly increasing $SNR_{Thr}$ in CSIM diminishes the interference range of each WBAN, i.e., lowers the number of interfering IoT devices. Therefore, limiting the frequency of channel assignments prevents distinct WBANs to pick the same channel, which decreases the probability of collisions among them. When $SNR_{Thr} \geq -35$, the $Pr_{AvChs}$ increases

| Simulation Parameters | Exp. 1 | Exp. 2 | Exp. 3 |
|-----------------------|--------|--------|--------|
| # Sensors/WBAN        | 10     | 10     | Var    |
| # WBAN/network        | Var    | 10     | 10     |
| Sensor txPower (dBm)  | -10    | -10    | -10    |
| SNR threshold (dBm)   | -25    | Var    | -25    |
| # Time-slots/TDMA frame | K      | K      | K      |
very slightly and eventually stabilizes at 0.92 because of the minimal number of interfering IoT devices and hence, a high \( P_{\text{AvChs}} \) is expected due to the larger number of ZigBee channels than the number of those interfering devices. However, SSA always achieves lower \( P_{\text{AvChs}} \) than CSIM for all \( SNR_{\text{Thr}} \) values. The \( P_{\text{AvChs}} \) significantly decreases from 0.6 to 0.2 as \( SNR_{\text{Thr}} \) increases from \(-50\) to \(-25\). Basically, increasing \( SNR_{\text{Thr}} \) in SSA is similar to increasing the interference range of each WBAN, and hence putting more sensors in the WBAN interference set. Therefore, more channels are needed to be assigned to those sensors and that \( P_{\text{AvChs}} \) is reduced. When \( SNR_{\text{Thr}} \geq -25 \), the \( P_{\text{AvChs}} \) eventually stabilizes at 0.21 because of the maximal number of sensors in the interference set is attained by each WBAN.

3) Probability of channel's availability vs. number of sensors

Experiment 3 studies the effect of the number (\( \# \)) of sensors per a WBAN, denoted by \( \delta \), on \( P_{\text{AvChs}} \). As can be seen in Fig. 4, CSIM always achieves higher \( P_{\text{AvChs}} \) than SSA for all values of \( \delta \). It is also observed from this figure that \( P_{\text{AvChs}} \) decreases very slightly and from 0.905 to 0.8 when \( 2 \leq \delta \leq 10 \) and eventually stabilizes at 0.8 when \( \delta \geq 10 \). In both cases, the \( P_{\text{AvChs}} \) is high due to two reasons, 1) the number of WBANs is fixed to 10 which is smaller than the number of ZigBee channels, which makes it possible for two or more distinct WBANs to not pick simultaneously the same channel and, 2) CSIM selects a stable channel based on the number of interfering WBANs rather than the number of interfering sensors. However, the \( P_{\text{AvChs}} \) decreases significantly from 0.9 to 0.1 when \( 2 \leq \delta \leq 14 \) because adding more sensors into WBANs increases the probability of interference and consequently requires more channels to be assigned to those sensors; consequently \( P_{\text{AvChs}} \) is reduced. Furthermore, SSA assigns channels to interfering sensors rather than to interfering WBANs, which justifies the decrease of \( P_{\text{AvChs}} \) when \( \delta \) grows. When \( \delta \geq 14 \), the \( P_{\text{AvChs}} \) eventually stabilizes at 0.1 because of the maximal number of sensors in the interference set is attained by each WBAN.

4) Average reuse factor vs. interference threshold

Fig. 5 shows the average reuse factor, denoted by \( \text{avgRF} \), versus the interference threshold, denoted by \( \rho \), for all WBANs. As seen in this figure, CSIM achieves a higher \( \text{avgRF} \) for all \( \rho \) values. However, increasing the interference threshold puts more interfering sensors in the interference range of any specific WBAN than the corresponding WBANs of these sensors, i.e., SSA requires more channels to be assigned to sensors than to WBANs in CSIM.

5) Energy consumption vs. interference threshold

The average energy consumption of the WBAN coordinator, denoted by \( \text{avgEC} \), versus the interference threshold (\( \rho \)) for CSIM with (CSIM-W) and without switching the BLE transceiver on (CSIM-WO) are compared, and results are shown in Fig. 6. As seen in the figure, CSIM-W always provides a lower \( \text{avgEC} \) than CSIM-WO because of the earlier BLE alerts of interference to the coordinator, i.e., the coordi-
nator scans the channels only upon receiving of these alerts. For CSIM-W, the avgEC increases slightly as the interference threshold grows, which increases the number of interfering sensors, hence the frequency of BLE alerts of interference increases, and consequently, the energy consumption increases due to the additional scanning. When $\rho$ exceeds -20, the avgEC increases very slightly and eventually stabilizes at $0.46 \times 10^{-3}$ mW; this reflects the case where all channels are used by nearby IoT devices forcing the Crd to engage the CR for finding a stable channel. For CSIM-WO, the avgEC increases significantly with all values of $\rho$ because of the continuous scanning of all ZigBee channels all the time, i.e., the coordinator periodically scans all the channels to find out which channels are not noisy. It is worth saying that the BLE alerts reduces the frequency of channel scanning and hence saves the coordinator’s energy.

VI. CONCLUSIONS

In this paper, we have presented CSIM, a distributed protocol to enable WBAN operation and interaction within an existing IoT. CSIM leverages the emerging BLE technology to enable channel selection and allocation for interference mitigation. In addition, the superframe’s active period is further extended to involve not only a TDMA frame, but also a FCS and FBTDMA frames, for interference mitigation. We integrate a BLE transceiver and a CR within the WBAN’s coordinator, where the role of the BLE transceiver is to inform the WBAN about the frequency channels that are being used in its vicinity. When experiencing high interference, the BLE device notifies the WBAN’s Crd to call the CR which determines a different channel for interfering sensors that will be used later within the FBTDMA frame for interference mitigation. The simulation results show that CSIM outperforms sample competing schemes.

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