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To cite this version:
Mohamad Ali, Hassine Moungla, Mohamed Younis, Ahmed Mehaoua. Distributed Scheme for Interference Mitigation of Coexisting WBANs Using Latin Rectangles. The 14th Annual IEEE Consumer Communications & Networking Conference (CCNC’17), Jan 2017, Las Vegas, United States. hal-01399575

HAL Id: hal-01399575
https://hal.science/hal-01399575
Submitted on 22 Nov 2016

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Distributed Scheme for Interference Mitigation of Coexisting WBANs Using Latin Rectangles

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Abstract—The performance of wireless body area networks (WBANs) may be degraded due to co-channel interference, i.e., when sensors of different coexisting WBANs transmit at the same time-slots using the same channel. In this paper, we exploit the 16 channels of ZIGBEE, and propose a distributed scheme that opts to avoid interference through channel to time-slot hopping based on Latin rectangles, DAIL. In DAIL, each WBAN’s coordinator picks a Latin rectangle whose rows are ZIGBEE channels and columns are time-slots of its superframe. Subsequently, it assigns a unique symbol to each sensor; this latter forms a transmission pattern according to distinct positions of its symbol in the rectangle, such that collisions among different transmissions of coexisting WBANs are minimized. We further present an analytical model that derives bounds on the collision probability of each sensor’s transmission in the network. In addition, the efficiency of DAIL in interference mitigation has been validated by simulations.

I. INTRODUCTION

A WBAN is a wireless short range communication network formed of a coordinator denoted by Crd and multiple low power and miniaturized sensors that are placed inside or attached to the human body. These sensors collect health related data through continual monitoring of the physiological state of the body, while, a person is sitting, walking, running, etc. WBANs are used in various applications such as ubiquitous health care, sports and military [9]. For example, these sensors may be observing the heart (electrocardiography) and the brain electrical (electroencephalographs) activities as well as vital signs and parameters like insulin percentage in blood, blood pressure, temperature, etc.

Recently, the IEEE 802.15.6 standard [1] has proposed new specifications for WBANs that require the system to function properly within the transmission range of up to 3 meters when up to 10 WBANs are collocated. It also has to support 60 sensors in a 6m³ space (256 sensors in a 3m³). Thus, there is great possibility of interference amongst the collocated WBANs, e.g., in crowded areas such as a hospital lobby or corridor. Consequently, the interference may affect the communication links and degrade the performance of each individual WBAN. Therefore, interference mitigation is of the utmost importance to improve the reliability of the whole network. To this end, the IEEE standard proposes three mechanisms for co-channel interference mitigation in WBANs, namely, beacon shifting, channel hopping and active superframe interleaving.

In addition, the co-channel interference is challenging due to the highly mobile and resource constrained nature of WBANs. Firstly, such nature makes the allocation of a global Crd to manage multiple WBANs as well as the application of advanced antenna and power control techniques used in other networks unsuitable for WBANs. Secondly, due to the absence of coordination and synchronization among WBANs, the different superframes may overlap and the concurrent transmissions of different nearby WBANs may interfere. More specifically, when two or more sensors of different WBANs access the shared channel at the same time, their transmissions cause medium access collision. In this paper, we tackle these issues and contribute the following:

• DAIL, a distributed scheme that enables predictable time-based channel hopping using Latin rectangles in order to avoid interference among coexisting WBANs
• An analytical model that derives bounds on the collision probability for sensors transmissions

The simulation results and theoretical analysis show that our proposed approach can significantly lower the number of collisions among the individual sensors of coexisting WBANs as well as increase the power savings at both sensor- and WBAN-levels. Moreover, DAIL significantly avoids the inter-WBAN interference and do not require any mutual coordination among the individual Crds. 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 Latin squares. Section IV describes DAIL in detail. Section V analyzes the performance of DAIL. Section VI presents the simulation results. Finally, the paper is concluded in Section VI.

II. RELATED WORK

The problem of interference due to WBANs coexistence has been addressed through spectrum allocation, cooperation, power control, game theory and multiple access schemes. Example schemes that pursue the spectrum allocation methodology include [10], [11], [12], [13]. In [10], a distributed spectrum allocation is proposed where inter-WBANs coordination is considered, the interfering sensors belonging to each pair of WBANs are assigned orthogonal sub-channels. Whereas, Movassaghi et al., [11] have proposed an adaptive interference mitigation scheme that operates on different parameters (e.g.,
nodes’ traffic priority, signal strength, etc.) and allocates synchronous and parallel transmission intervals for interference avoidance. The proposed scheme has considered sensor-level interference for inter-network interference mitigation rather than considering each WBAN as a whole. In the proposed DAIL scheme, we have considered the interference at both sensor- and time-slot-levels. Meanwhile, in [12], a prediction algorithm for dynamic channel allocation is proposed where, variations in channel assignment due to body gesture movements are factored in. The interference is avoided due to the allocation of transmission time based on synchronised clocks. It is worth noting that in [13] Latin squares are used in cellular networks for the sub-carrier allocations to users where, a user could be allocated multiple virtual channels. Each virtual channel hops over different sub-carriers at different orthogonal frequency division multiplexing (OFDM) symbol times. Basically, users are allocated multiple subcarrier-to-OFDM-symbol-time combinations to avoid inter-cell interference. DAIL sensors assigns single-channel-to-time-slot combination which simplifies inter-WBAN coordination and time synchronisation.

A number of approaches have adopted cooperative communication, game theory and power control to mitigate co-channel interference. Dong et al., [6] have pursued joint a cooperative communication integrated with transmit power control based on single channel prediction for WBANs coexistence problem. Similarly, in [3], a co-channel interference is mitigated using cooperative orthogonal channels and a contention window extension mechanism. Whereas, the approach of [14] employs a Bayesian game based power control to mitigate inter-WBAN interference by modelling WBANs as players and active links as types of players.

Other approaches pursued multiple access schemes for interference mitigation. Kim et al., [8] have proposed a distributed TDMA-based beacon interval shifting scheme where, the wake up period of a WBAN is made to not overlap with other WBANs by employing carrier sense before a beacon transmission. Whilst, Chen et al., [5] adopts TDMA for scheduling transmissions within a WBAN and carrier sensing mechanism to deal with inter-WBAN interference. In [4], many topology-dependent transmission scheduling algorithms have been proposed to minimize the TDMA frame length in multihop packet radio networks using Galois field theory and Latin squares. For single-channel networks, the modified Galois field design and the Latin square design for topology-transparent broadcast scheduling is proposed. The modified Galois field design obtains much smaller minimum frame length than the existing scheme while the Latin square design can even achieve possible performance gain when compared with the modified Galois field design. In one-hop rather than multi-hop communication scheme, like DAIL, using Latin squares better schedules the medium access and consequently significantly diminishes the inter-WBAN interference.

In this paper, we take a step forward and exploit the 16 channels available in the 2.4 GHz ISM of ZIGBEE and, propose a distributed scheme based on channel and time-slot hopping for interference avoidance amongst coexisting WBANs. In our proposed DAIL scheme, each WBAN autonomously picks a Latin rectangle whose rows are the ZIGBEE channels and columns are the time-slots that relates each channel to a time-slot within the Latin rectangle. Meanwhile, we depend on the special properties of Latin rectangles to minimize the probability of both time and channel matching among sensors in different WBANs.

III. SYSTEM MODEL AND PRELIMINARIES

A. System Model and Assumptions

We consider the realistic scenario when N TDMA-based WBANs coexist in a crowded environment, e.g., when a group of patients moving around in a large hall of a hospital. Each WBAN consists of a single Crd and up to L sensors, each denoted by SR and generates its data based on a predefined sampling rate and transmits data at maximum rate of 250Kb/s within the 2.4 GHz ISM band. Furthermore, we assume all Crds are equipped with unconstrained energy supply, e.g., equipped with harvesters, and are not affected by channel hopping.

Due to the WBAN’s irregular and unpredictable motion pattern, it is very hard to achieve inter-WBAN coordination or to have a central unit to mitigate the potential interference when some of them are in proximity of each other. Basically, co-channel interference may arise due to the collisions amongst the concurrent transmissions made by sensors in different WBANs in the same time-slot denoted by Slt. To address this issue, we exploit the 16 channels in the ISM band of ZIGBEE to resolve this problem through combining the frequency with time hopping. Table I summarizes the notations that we use.

B. Latin Squares

In this section, we provide a brief overview of Latin squares that we used in our interference mitigation approach [4].

**Definition 1.** A Latin square is a $K \cdot K$ matrix, filled with $K$ distinct symbols, each symbol appearing once in each column and once in each row.

**Definition 2.** Two distinct $K \cdot K$ Latin squares $E = (e_{i,j})$ and $F = (f_{i,j})$, so that $e_{i,j}$ and $f_{i,j} \in \{1, 2, \ldots, K\}$, are said to be orthogonal, if the $K^2$ ordered pairs $(e_{i,j}, f_{i,j})$ are all different from each other. More generally, the set $OLS=\{E_1, E_2, E_3, \ldots, E_l\}$ of distinct Latin squares $E$ is said to be orthogonal, if every pair in OLS is orthogonal.

**Definition 3.** An orthogonal set of Latin squares of order $K$ is of size of $(K\cdot I)$, i.e., the number of Latin squares in the orthogonal family is $(K\cdot I)$, is called a complete set [2], [7].
Definition 4. An $M \cdot K$ Latin rectangle is a $M \cdot K$ matrix $G$, filled with symbols $a_{ij} \in \{1, 2, \ldots, K\}$, such that each row and each column contains only distinct symbols.

To illustrate, $E$ and $F$ are clearly orthogonal Latin squares of order 4, and when superimposed ($E \bowtie F$), where no two ordered pairs are similar as shown in the Latin square $E \bowtie F$.

$$E = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \\ 3 & 4 & 1 & 2 \\ 4 & 1 & 2 & 3 \end{bmatrix}, \quad F = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \\ 3 & 4 & 1 & 2 \end{bmatrix}, \quad J = \begin{bmatrix} 3 & 4 & 1 & 2 \\ 4 & 1 & 2 & 3 \\ 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{bmatrix}$$

$E \bowtie F = \begin{bmatrix} 1, 4 & 2, 1 & 3, 2 & 4, 3 \\ 2, 1 & 3, 2 & 4, 3 & 1, 4 \\ 3, 2 & 4, 3 & 1, 4 & 2, 1 \\ 4, 3 & 1, 4 & 2, 1 & 3, 2 \end{bmatrix}$

Throughout this paper, we denote the combination of “channel and time-slot assignment” by a symbol in a Latin rectangle.

IV. INTERFERENCE MITIGATION USING LATIN RECTANGLES

DAIL exploits the properties of Latin squares in order to reduce the probability of collision while enabling autonomous scheduling of the medium access. DAIL described in detail in the balance of this section.

A. Detailed Algorithm

To mitigate interference, DAIL opts to exploit the availability of multiple channels and allows the individual WBANs to hop among the channels in a pattern that is predictable to the sensors of the same WBAN and random to the other coexisting WBANs. To achieve that, DAIL employs Latin squares as the underlying scheme for channel and time-slot allocation to sensors. Basically, if a WBAN picks one Latin square from an orthogonal set, there will be no shared combination of channel and time-slot among the coexisting Latin squares. According to **Theorem 1**, the number of WBANs using orthogonal Latin squares is upper bounded by $K - 1$.

**Theorem 1.** If there is an orthogonal family of $r$ Latin squares of order $K$, then $r \leq K - 1$ [2].

For detailed proof of **Theorem 1**, refer to [2], [4].

The Latin size will depend on the largest among the number of time-slots sensors need, denoted by $K$, and number of channels, $M$. However, the IEEE standard [1] limits the number of channels which constitutes the rows in the Latin square to 16, no more than 16 transmissions can be scheduled.

To overcome such a limitation, DAIL employs Latin rectangles instead, i.e., does not restrict the value of $M$ and hence supports $K > M$. Thus, regardless whether there is a crowd of patients in a hospital hall or a single patient is sitting in home, each WBAN’s $Crd$ will autonomously pick a $M \cdot K$ Latin rectangle orthogonal to potentially coexisting WBANs, i.e., no two or more $Crd$s pick the same Latin rectangle. Then, the $Crd$ assigns a single symbol from the set $\{1, 2, \ldots, K\}$ to each sensor within its WBAN. Afterwards, each sensor determines its transmission pattern, i.e., its channel and time-slot in every superframe according to the position hopping of that symbol in the Latin rectangle.

The orthogonality property of Latin rectangles avoids inter-WBAN interference by allowing each sensor $SR$, to have its unique transmission pattern that does not resemble the pattern of sensors of other WBANs, i.e., they do not share the same position of the symbol, each in its own Latin rectangle and consequently, no other sensor in the network would share the same channel in the same $Slit$ with $SR$ all the time. For instance, if sensor $RS_u$ is assigned a symbol “$B$”, then, its transmission pattern is denoted by $P_u = (C_i, Slt_j)$, $\forall i \leq M, \forall j \leq K$, where $C$ denotes a channel, will correspond to the positions of $B$ in rectangle $E$ as shown in **Figure 1**. Then, $P_u = (C_1, Slt_2, C_2, Slt_1, C_3, Slt_4, C_4, Slt_3)$, i.e., $RS_u$ may transmit through $1^{st}$ channel in $2^{nd}$ $Slit$, $2^{nd}$ channel in $1^{st}$ $Slit$, etc. Therefore, using Latin rectangles, each $Crd$ prevents the interference through orthogonal channel to time-slot assignments hopping.

Generally, DAIL makes it highly improbable for two transmissions to collide as we show in Section V. Nonetheless, collision may still occur when (i) two WBANs randomly pick the same Latin rectangle, or (ii) more than 16 WBANs coexist in the same area, which means that, the number of WBANs exceeds the number of ZIGBEE channels (16) in the Latin rectangle. DAIL handles these cases by extending the superframe size through increasing the number of columns in the Latin rectangle, i.e., increasing the number of $Slits$ in the Latin. In the next section we determine the setting of superframe size and in Section V we analyze how to set $K$ per each superframe. **Algorithm 1** provides a high level summary of DAIL.

**Algorithm 1 Proposed DAIL Scheme**

```plaintext
input : $N$ WBANs, Coordinator $Crd$, $M$ ZIGBEE channels, Latin rectangle $R$, frame length $FL$
BEGIN
    $FL = K$  // default setting of the frame length
    if $N > K$ then
        $FL = N$  // $Crd$ increases the number of time-slots in the superframe
    END
    Each WBAN’s $Crd$ randomly picks a Latin rectangle $R$ of size $M \cdot F$
END
```

B. Superframe Size

While, we consider all $M = 16$ channels of ZIGBEE available at each WBAN, we still need to determine the number of time-slots per each row of Latin rectangle, in other words, the length of each superframe. Each sensor $SR$, where $i \leq L$, may require $p Slits$ to complete its data transmission.
example, for a sensor that samples at a rate of 10 per second, we need 10 Slt in a frame of 1 second. If all sensors have the same requirement, $p \cdot L$ Slt for $L$ sensors are required in each frame. In fact, the frame size depends on two factors, 1) how big the Slt, which is based on the protocol in use, and 2) the number of required Slt, which is determined by the different sampling rates of WBAN sensors. Generally, the sum of number of samples for all sensors in a time period determines the frame size. However, DAIL requires the frame size for all WBANs to be the same so that collision could be better avoided by picking the right value for $K$. Therefore, in DAIL the superframe size is determined based on the highest sampling rate. In this case, the number of Slt to be made in the superframe, respectively, in the Latin rectangle is $K$ slots, where $K = p \cdot L$.

C. Illustrative Example

We illustrate our approach through a scenario of 3 coexisting WBANs, where each circumference represents the interference range as shown in Figure 2. Furthermore, each WBAN is assigned $M = 4$ channels and consists of $L = 4$ sensors, in turn, each sensor is assigned a symbol from the set $K = \{1,2,3,4\} \leftrightarrow \{G,B,R,W\}$. Here, we assume that each sensor requires only one Slt to transmit its data in each superframe. Based on this scenario, any pair of sensors are interfering with each other, i.e., they transmit using the same channel in the same time, if both sensors are in the intersection of their corresponding interference ranges. However, as shown in Figure 2, $4^{th}$ sensor of WBAN$_1$ denoted by $SR_{1,4}$ and $SR_{2,4}$ are interfering, also, $SR_{3,1}$ and $SR_{2,3}$. Therefore, to address this problem, each WBAN picks a distinct Latin rectangle from an orthogonal set as follows: WBAN$_1$ picks E, WBAN$_2$ picks F and WBAN$_3$ picks J, where E, F and J are considered as in (III-B). Assume 3 sensors, $SR_u$, $SR_v$ and $SR_w$ of WBAN$_1$, WBAN$_2$ and WBAN$_3$ are, respectively, assigned symbols B, R and G in Latin rectangles E, F and J. Thus, the distinct positions of symbol B in E corresponds to the transmission pattern $P_u$ in WBAN$_1$’s superframe, similarly for $P_v$ and $P_w$ in WBAN$_2$ and WBAN$_3$, respectively. However, $B=2$ in E, $R=3$ in F and $G=1$ in J, therefore, the transmission patterns for $P_u$, $P_v$ and $P_w$ are, respectively, represented by B, R and G symbols of the matrix shown in Figure 1. As clearly seen in this figure that $SR_u$, $SR_v$ and $SR_w$ neither share the same channel nor the same Slt, i.e., no collision occurs at all.

V. MATHEMATICAL ANALYSIS

Although Latin rectangles diminishes inter-WBANs interference, there are still some possibilities for collisions as pointed out in Section IV. Therefore, it is necessary to analyze the probability of collisions among the sensors of different WBANs. In this section we opt to analyze the performance of DAIL mathematically. We consider a multichannel TDMA-based network, where superframes are constructed as an $M \times K$ matrix, where within each superframe, each sensor may be assigned $M$ Slt to transmit its data according to a unique channel to Slt assignment pattern. These patterns are generated from the orthogonal family of $M \times K$ Latin rectangles. However, all sensors of each WBAN share one common $M \times K$ Latin rectangle, where, the pattern of each sensor corresponds to a single symbol pattern in that rectangle, as shown in Figure 1.

A. Interference Bound

In this subsection we opt to determine the worst-case collision pattern for the individual sensor.

Definition 5. Let E and F be two orthogonal $M \times K$ Latin rectangles. Symbol e from E is assigned to $SR_u$, and symbol f from F is assigned to $SR_v$. Then, there exists a collision at the $j^{th}$ Slt on $i^{th}$ channel for $SR_u$ and $SR_v$, if the ordering $(e,f)$ of both rectangles appears at $i^{th}$ row, $j^{th}$ column, which means $[E_{i,j}] = e$ and $[F_{i,j}] = f$.

Theorem 2. If two sensors are assigned two distinct symbols in the same Latin rectangle, there will be no collision among their transmissions. If they are assigned symbols from two distinct orthogonal Latin rectangles, then, they will face at most one collision in every superframe.

Proof: From the definition of Latin rectangles, because every symbol occurs exactly one time in each row and exactly one time in each column, any two Slt assignment patterns constructed from the same Latin rectangle will not have any overlap in their patterns and so they will not have any collision with each other. Based on Definition 2, hence, the ordering $(e,f)$ for any pair of orthogonal Latin rectangles, where, $e$ and $f \in \{1,2,\ldots,K\}$, can only appears one time, which means that, these sensors will only have one opportunity of collision.

Theorem 3. In a crowded network of $N$ WBANs, each sensor has a channel to Slt transmission pattern corresponding to a symbol pattern chosen from one of the $K^{th}$ set of orthogonal Latin rectangles. Let us consider a sensor denoted by “s” surrounded by maximum number of $Q$ WBANs, i.e., $Q$ sensors from other WBANs, which means, $Q$ sensors may coexist in the communication range of $s$. Then, $s$ may experience at most $Q$ collisions. Additionally, sensor $s$ may face a minimal number of collisions which equal to $max(Q-K+1,0)$.

Proof: Based on Theorem 2, each neighboring sensor can create at most one collision to $s$. In the worst case, all $Q$ sensors are within the range of communication of $s$. The transmissions patterns of $Q$ sensors are constructed from
Latin rectangles that are different from the Latin rectangle utilized by \( s \). Subsequently, the maximum number of possible collisions experienced by \( s \) is \( Q \). Now, to count the minimal number of collisions for \( s \), it is required to find the maximum number of sensors that construct their transmission patterns from the same Latin rectangle, which is \( K \), i.e., \( K \) sensors will have no collision according to theorem 2. Also, theorem 2 proves that there exists at most one collision for each pair of sensors constructing their transmission patterns from two different orthogonal Latin rectangles. Therefore, each of the remaining sensors \( (Q-K+1) \) will cause one collision to \( s \) because they belong to different orthogonal Latin rectangles.

As a result, the minimum number of collisions for sensor \( s \) surrounded by \( Q \) sensors is equal to \( \max((Q-K+1),0) \).

### B. Collision Probability

We consider a sensor \( S_{R_i} \) of WBAN \( i \) is surrounded by \( Q \) interfering sensors \( v_j \) of different coexisting WBAN \( j \) in the vicinity, where \( j=1,2,\ldots,Q \) and \( i \neq j \). For simplicity, we assume, each sensor transmits one data packet in each Slt. However, sensor \( S_{R_i} \) successfully transmits its data packet in Slt \( j \) and on channel \( C_i \) to the \( Crd_i \), iff, none of the \( Q \) neighbors transmits its data packet using the same Slt on the same channel as sensor \( S_{R_i} \). Let \( X \) denotes the random variable representing the number of sensors that are transmitting their data packets in the same Slt as sensor \( S_{R_i} \), if \( x \) packets are transmitted in the the same Slt as \( S_{R_i} \). Then, the probability of event \( X \) is defined by equation (1) below.

\[
Pr(X = x) = C_x^{Q+1} \cdot \omega^x \cdot (1-\omega)^{Q-x} \cdot \left(\frac{\min(M,K)}{K}\right)^x \quad \forall x \leq Q \quad (1)
\]

Where \( \omega \) is the use factor, defined as the ratio of the time that a sensor is in use to the total time that it could be in use. Now, suppose \( Y \) sensors out of \( X \) sensors schedule their transmissions according to the same Latin rectangle as sensor \( S_{R_i} \), i.e. \( y \) out of \( x \) sensors select symbol patterns from the same Latin rectangle as \( S_{R_i} \).

\[
Pr(Y = y | X = x) = \left(C_x^y \cdot C_{x-y}^{Q-K} \right) / C_x^{Q-1} \quad \forall x \leq Q \quad \forall y \leq x \quad (2)
\]

Where \( Z = K \cdot m \) is the total number of symbol patterns in the orthogonal Latin rectangle family. However, these \( Y \) sensors will not impose any collision with \( S_{R_i} \)’s transmission, since they \( (Y \) sensors) use the same Latin rectangle as \( S_{R_i} \). On the other hand, \( X-Y \) sensors may collide with the transmission from sensor \( S_{R_i} \) to the \( Crd \) on the same channel, then the conditional probability of transmission collision is denoted by \( (collTx) \) and defined by equation (3) below.

\[
Pr(collTx | Y = y \& X = x) = 1 - Pr(succTx | Y = y \& X = x) = 1 - \left(\frac{(\min(M,K)-1)}{\min(M,K)}\right)^{x-y} \quad (3)
\]

Where \( \min(M,K) \) represents the number of transmission Slts for each sensor in each superframe. Then, the probability of a successful data packet transmission from sensor \( S_{R_i} \) to the \( Crd \) is denoted by \( \lambda \) as follows:

\[
\lambda = \sum_{x=0}^{Q} \sum_{y=0}^{x} Pr(Y = y, X = x) \cdot Pr(succTx | Y = y \& X = x)
\]

\[
= \sum_{x=0}^{Q} \sum_{y=0}^{x} Pr(Y = y | X = x) \cdot Pr(X = x)
\]

\[
= \sum_{x=0}^{Q} \sum_{y=0}^{x} \left(C_x^y \cdot C_{x-y}^{Q-K} \right) / C_x^{Q-1} \cdot \omega^y \cdot (1-\omega)^{Q-x-y} \cdot \left(\frac{\min(M,K)}{K}\right)^x \quad (4)
\]

### VI. PERFORMANCE EVALUATION

We have performed simulation experiments to validate the theoretical results and evaluate the performance of the proposed DAIL scheme. In this section, we compare the performance of DAIL with the smart spectrum allocation scheme, denoted by SMS [10], which assigns orthogonal channels to interfering sensors belonging to each pair of coexisting WBANs. The simulation parameters are provided in table II.

#### A. Collision Probability

In experiment 1, the mean collision probability denoted by \( McP \) versus the number of coexisting WBANs \( (\Omega) \) for DAIL and that for SMS are compared in figure 4. As can be clearly seen in the figure, DAIL provides a much lower \( McP \) because of the combined channel and Slt hopping. It is observed from this figure that \( McP \) of DAIL is very low when \( \Omega \leq 12 \) due to the large number of channel and Slt combinations. When \( 12 < \Omega \leq 25 \), \( McP \) significantly increases due to the growth in the number of sensors which makes it possible for two or more sensors to be assigned the same channel in the same time-slot. However, when \( \Omega \) exceeds 25, \( McP \) increases very slightly and eventually stabilizes at \( 21 \cdot 10^{-2} \) because of the maximal number of collisions is attained by each WBAN. In SMS, \( McP \) significantly increases when \( 0 < \Omega \leq 18 \), i.e., the number of channels and the number of WBANs are similar. Then, \( McP \) slightly increases until it stabilizes at \( 5 \cdot 10^{-1} \) when \( 18 < \Omega \leq 35 \) since the interference attains its maximum and all channels are already assigned. \( McP \) significantly grows for as long as the number of channels is smaller than \( \Omega \). However, when \( \Omega \) exceeds 16, \( McP \) tends to stabilize at \( 5 \cdot 10^{-1} \).

Meanwhile, experiment 2 studies the effect of the number of Slts per a superframe denoted by \( TL \) on \( McP \). As can be clearly seen in figure 3, DAIL always achieves lower collision probability than SMS for all \( TL \) values. In DAIL,
McP significantly decreases as TL increases from 10 to 28, where increasing TL is similar to enlarging the size of the Latin rectangle. Therefore, a larger number of channel and Slit combinations allows distinct sensors to not pick the same channel in the same Slit, which decreases the chances of collisions among them. However, SMS depends only on the 16 channels to mitigate interference, and the channel assigned to a sensor stays the same for all the time. Thus, a high McP is expected due to the larger number of interfering sensors than the available channels. Moreover, a sensor has 16 possibilities in SMS, while it has \(16 \cdot \text{framesize}\) different possibilities in DAIL to mitigate the interference, which explains the large difference in McP amongst two schemes.

### B. WBAN Power Consumption

In experiment 3, the power consumption of each WBAN denoted by \(PC\) versus the number of coexisting WBANs (\(\Omega\)) for DAIL and SMS are compared. Figure 5 shows that \(PC\) for DAIL is always lower than that of SMS for all values of \(\Omega\). Such distinct performance for DAIL is mainly due to the reduced collisions that lead to fewer retransmissions and consequently lower power consumption. For DAIL, the figure shows that \(PC\) slightly increases when \(\Omega \leq 10\), i.e., there is a larger number of channel and Slit combinations than the interfering sensor pairs which lowers the number of collisions among sensors and hence the power consumption is decreased. \(PC\) significantly increases when \(10 < \Omega \leq 30\) due to the large number of sensors competing for the same channel in the same Slits which results in more collisions and hence more power consumption. When \(\Omega\) exceeds 30, the power consumption increases slightly to attain the maximum of \(16.5 \cdot 10^{-3}\mu\text{W}\). However, in SMS, \(PC\) is high due to the collisions resulting from the large number of sensors that compete for the available channels (16 channels).

### VII. CONCLUSIONS

In this paper, we have presented DAIL, a distributed TDMA-based interference avoidance scheme for coexisting WBANs based on the properties of Latin squares. DAIL combines the channel and time-slot hopping to lower the probability of collisions among transmission of sensors in different coexisting WBANs. Accordingly, each distinct WBAN’s Crd autonomously picks an orthogonal Latin rectangle and assigns its individual sensors unique transmission patterns. Compared with most existing algorithms, DAIL has low complexity and does not require any inter-WBAN coordination. We have analyzed the expected collision probability. Simulation results show that DAIL outperforms other competing schemes.

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