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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 available in the 2.4 GHz unlicensed international band 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 $6m^3$ space (256 sensors in a $3m^3$). 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 sub-carrier-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 simple channel predication for *WBANs* co-existence 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 unlicensed international band (*ISM*) of *ZIGBEE* and, propose a distributed scheme based

Table I
NOTATION TABLE

Symbol	Deascription	Symbol	Deascription
OLS	orthogonal Latin set	Crđ	coordinator
P	transmission pattern	SP	superferame
M	# of ZIGBEE channels	C	channel
L	# of sensors per WBAN	Slt	time-slot
Q	max. # of WBAN interferers	FL	frame length
K	# of time-slots per SP	SR	sensor
ISM	international, scientific, medical		

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 *Crđ* 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 *Crđs* 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-*WBANs* 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 $f_{i,j} \in \{1, 2, \dots, K\}$, 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 $OLS = \{E_1, E_2, E_3, \dots, E_r\}$ 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 $(K-1)$, i.e., the number of Latin squares in the orthogonal family is $(K-1)$, 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 $a_{ij} \in \{1, 2, \dots, K\}$, 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 $E \bowtie F$.

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

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

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 Latins. 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 $\{1, 2, \dots, K\}$ to each sensor within its *WBAN*. Afterwards, each sensor determines its transmission pattern, i.e., its channel and time-slot in every

		Time-slots			
		1	2	3	4
Channels	1	W	B	G	R
	2	B	G	R	W
	3	G	R	W	B
	4	R	W	B	G

Figure 1. A $4 \cdot 4$ channel to time-slot assignment Latin square 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 *Slt* 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 1st channel in 2nd *Slt*, 2nd channel in 1st *Slt*, 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 *Slt*s 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

input : N *WBANs*, Coordinator *Crd*, M *ZIGBEE* channels, Latin rectangle R , frame length FL

- 1 **BEGIN**
- 2 $FL = K$ // default setting of the frame length
- 3 **if** $N > K$ **then**
- 4 $FL = N$ // *Crd* increases the number of time-slots in the superframe
- 5 **endif**
- 6 Each *WBAN's* *Crd* randomly picks a Latin rectangle R of size $M \cdot K$
- 7 **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_i , where $i \leq L$, may require p *Slt*s to complete its data transmission. For

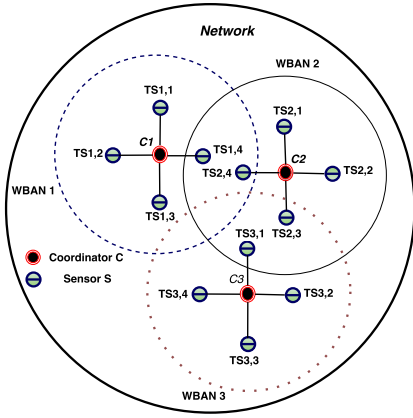


Figure 2. A network consisting of three coexisting TDMA-based WBANs example, for a sensor that samples at a rate of 10 per second, we need 10 Slt s in a frame of 1 second. If all sensors have the same requirement, $p \cdot L$ Slt s for L sensors are required in each frame. In fact, the frame size depends on two factors, 1) how big the Slt , which is based on the protocol in use, and 2) the number of required Slt s, 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 s 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 $K = \{1,2,3,4\} \iff \{G,B,R,W\}$. 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 WBAN₁ 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: WBAN₁ picks E, WBAN₂ picks F and WBAN₃ picks J, where E, F and J are considered as in (III-B). Assume 3 sensors, SR_u , SR_v and SR_w of WBAN₁, WBAN₂ and WBAN₃ 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 WBAN₁'s superframe, similarly for P_v and P_w in WBAN₂ and WBAN₃, 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 $M \cdot K$ matrix, where within each superframe, each sensor may be assigned M Slt s to transmit its data according to a unique channel to Slt assignment pattern. These patterns are generated from the orthogonal family of $M \cdot K$ Latin rectangles. However, all sensors of each WBAN share one common $M \cdot K$ 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 $M \cdot K$ 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 $f \in \{1,2,\dots,K\}$, 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 SR_i of $WBAN_i$ is surrounded by Q interfering sensors v_j of different coexisting $WBAN_j$ in the vicinity, where $j=1,2,\dots,Q$ and $i \neq j$. For simplicity, we assume, each sensor transmits one data packet in each Slt . However, sensor SR_i successfully transmits its data packet in Slt_i 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 SR_i . Let X denotes the random variable representing the number of sensors that are transmitting their data packets in the same Slt as sensor SR_i , if x packets are transmitted in the the same Slt as SR_i . Then, the probability of event X is defined by **equation (1)** below.

$$Pr(X = x) = C_x^{Q+1} \cdot \omega^x \cdot (1 - \omega)^{Q-x} \cdot (\min(M, K)/K)^x \quad \forall x \leq Q \quad (1)$$

Where ω 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 SR_i , i.e. y out of x sensors select symbol patterns from the same Latin rectangle as SR_i .

$$Pr(Y = y | X = x) = \left(C_y^{K+1} \cdot C_{x-y}^{Z-K} \right) / C_x^{Z-1} \quad \forall x \leq Q \ \& \ \forall y \leq x \quad (2)$$

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 SR_i 's transmission, since they (Y sensors) use the same Latin rectangle as SR_i . On the other hand, $X-Y$ sensors may collide with the transmission from sensor SR_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.

$$\begin{aligned} Pr(collTx | Y = y \ \& \ X = x) \\ = 1 - Pr(succTx | Y = y \ \& \ X = x) \\ = 1 - ((\min(M, K) - 1) / \min(M, K))^{x-y} \end{aligned} \quad (3)$$

Where $\min(M, K)$ represents the number of transmission Slt s for each sensor in each superframe. Then, the probability of a successful data packet transmission from sensor SR_i to the Crd is denoted by λ as follows:

Table II
SIMULATION SETUP & PARAMETERS

	Exp. 1	Exp. 2	Exp. 3	Exp. 4
Sensor TxPower(dBm)	-10	-10	-10	-10
# Crds/WBAN	1	1	1	1
# Sensors/WBAN	12	12	12	12
# WBANs/Network	Var	30	Var	Var
# Slots/Superframe	12	12	12	12
Latin Rectangle Size	$16 \cdot 12$	$16 \cdot Var$	$16 \cdot 12$	$16 \cdot 12$

$$\begin{aligned} \lambda &= \sum_{x=0}^Q \sum_{y=0}^x Pr(Y = y, X = x) \\ &\quad \cdot Pr(succTx | Y = y \ \& \ X = x) \\ &= \sum_{x=0}^Q \sum_{y=0}^x Pr(Y = y | X = x) \cdot Pr(X = x) \\ &\quad \cdot Pr(succTx | Y = y \ \& \ X = x) \\ &= \sum_{x=0}^Q \sum_{y=0}^x (C_x^Q C_y^{K-1} C_{x-y}^{Z-K}) / (C_x^{Z-1}) \\ &\quad \cdot \omega^x \cdot (1 - \omega)^{Q-x} \cdot (\min(M, K)/K)^x \\ &\quad \cdot ((\min(M, K) - 1) / \min(M, K))^{x-y} \end{aligned} \quad (4)$$

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 *WBAN*s. 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 *WBAN*s (Ω) 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 Ω 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 *WBAN*s 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 Ω . However, when Ω exceeds 16, McP tends to stabilize at $5 \cdot 10^{-1}$.

Meanwhile, experiment 2 studies the effect of the number of *Slt*s 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*,

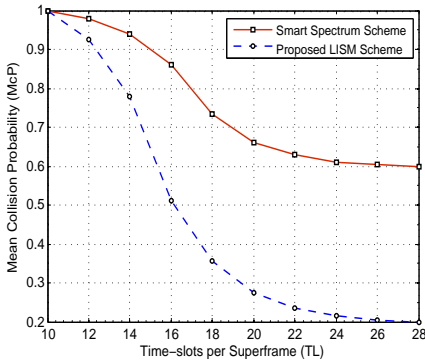


Figure 3. McP versus # of slots per superframe (TL)

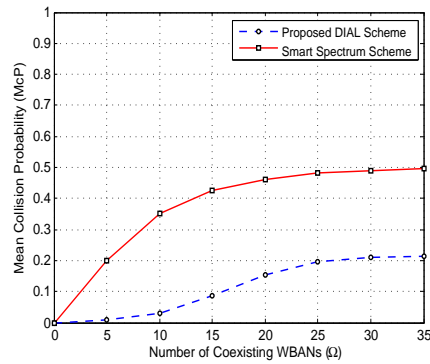


Figure 4. McP versus # of coexisting WBANs (Ω)

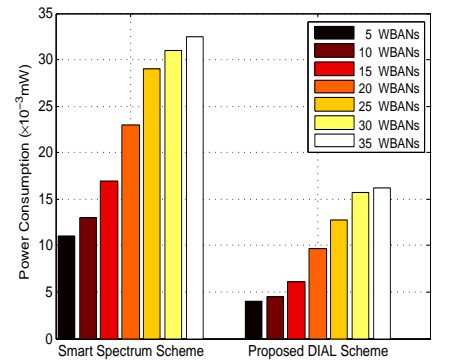


Figure 5. Mean power consumption (PC) versus (Ω)

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 Sl combinations allows distinct sensors to not pick the same channel in the same Sl , 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 $16 \cdot framesize$ 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 (Ω) for $DAIL$ and SMS are compared. **Figure 5** shows that PC for $DAIL$ is always lower than that of SMS for all values of Ω . 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 Sl 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 Sl s which results in more collisions and hence more power consumption. When Ω exceeds 30, the power consumption increases slightly to attain the maximum of $16.5 \cdot 10^{-3} mW$. 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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