Co-channel Interference Mitigation for Wireless Body Area Networks Coexistence Using a Non-Cooperative Game

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Abstract

In this paper, we enable the coexistence of multiple wireless body area networks (BANs) using a finite repeated non-cooperative game, in which BANs are rational players but act selfishly. A game-theoretic based transmit power control scheme employing a novel utility function is proposed to maximize each network’s packet delivery ratio (PDR) at low transmit power. The proposed utility function penalizes players with high transmission power, which reduces the interference caused to other coexisting BANs. Considering the purpose of inter-BAN interference mitigation, PDR is expressed as a compressed exponential function of inverse signal-to-interference-and-noise ratio (SINR), so it is essentially a function of transmit powers of all coexisting BANs. It is proven that a unique Nash Equilibrium (NE) exists and hence there is a subgame-perfect equilibrium, considering best-response at each stage independent of history. Realistic and extensive on- and inter-body channel models are employed. Results confirm that the effectiveness of the proposed scheme in better interference management, greater reliability and reduced transmit power, comparing with other schemes commonly applied in BAN.

Index Terms

Body area network, game theory, interference mitigation, power control.

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I. INTRODUCTION

Over the last decade, the urgent concerns for public health and physical well-being has led to a dramatic development of various types of wearable technologies. Among them, wireless body area networks (BANs) is very promising because of its affordability, flexibility and convenience. A typical BAN is comprised of several small on-body or implanted sensors that monitor physiological parameters and a gateway device, which is connected to the internet [1]. In the medical domain, this architecture ensures the user’s information is kept up-to-date at the health service centre, which is particularly beneficial for enabling comprehensive healthcare. In addition, BANs are also used in areas such as consumer fitness, entertainment, gaming and the military.

The increasing popularity of BAN has resulted in a rapid growth in active devices in the last five years [2], [3]. Considering the typical circumstance of using BANs, it is often necessary to have several BAN systems operating in close proximity to each other. However, the transmission power of BAN sensor nodes is strictly limited so as to prolong their operation time [1], which makes the system vulnerable to radio interference from other BANs. Therefore, BANs coexistence and the resultant inter-BAN interference is a major issue, which can cause severe performance degradation and packet loss as shown in [4]–[6]. In addition, inter-BAN interference is a cause of energy wastage of sensor nodes trying to compete for better signal-to-interference-plus-noise ratios (SINRs).

There have been many studies on effective interference management schemes in wireless networks [7]. Many techniques involve transmission power control that is based on a centralized [8], [9] and partially distributed [10] approach. They are effective in the context of cellular networks and general large-scale ad-hoc networks [11] as these networks have fewer resource constraints and a stabler network topology. However, these methods are difficult to apply to BANs due to their high mobility. In [12] and [13], fully distributed power control schemes were proposed, which we refer to as SINR-balancing in this paper. SINR balancing works well for distributed cellular mobile systems, but their performance is unknown for BANs. More recently, game-theoretic based resource allocation schemes have been widely proposed for various types of wireless networks, from spectrum allocation [14], [15] to transmit power control algorithms [16].

To better model the scenario of multiple BANs coexistence as shown in Fig.1, BANs are treated as rational players competing for resources in a non-cooperative game. We
employ a non-cooperative game for power control, and propose a novel price-dependent utility function. As the IEEE 802.15.6 standard clearly specifies a maximum packet error rate of 10%, we use packet delivery ratio (PDR) as our target utility. Hence, by maximizing the utility function, a higher PDR can be achieved. The instantaneous PDR is expressed as a compressed exponential function of SINR, which is essentially a function of all transmit powers of coexisting BANs. Obviously, by raising its transmit power, a BAN can achieve a better outcome if it only considers its own benefit and the other BANs keep their transmit power unchanged. However, if every BANs in the range do so, the aggregate utility gets worse due to larger interference. Therefore, a proper utility function restrains this behavior by penalizing BANs with high transmit power by degrading their utility. In [17], Kazemi also presented an interference mitigation scheme using non-cooperative power control games for BANs. However, the result of this study is based on the assumption that the channel gain within each network and between networks are constant. This is not a realistic assumption as BAN channels are dynamic and unstable [18]–[21], with channel gain varying slowly over time.

Therefore, this paper makes the following novel contributions:
1) We introduce a non-cooperative game theoretic transmit power control scheme for BANs to maximize the local packet delivery ratio across multiple BANs while reducing average transmit power.

2) We model the packet delivery ratio of a typical BAN system in terms of instantaneous SINR using a compressed exponential function.

3) The performance of the proposed power control scheme is evaluated using realistic on- and inter-body time-selective channel models, which is the typical operating environment for the BANs.

The rest of this paper is organized as follows. In Section II, the details of the system setup and channel models are explained. Section III defines the non-cooperative game for multiple BANs coexistence and describes our novel utility function. In Section IV, the performance of this power control method is assessed and compare with other schemes. Finally, in Section V some concluding remarks are made.

II. SYSTEM MODEL

A. BANs coexistence based on probability of overlapping

We consider multiple subjects in the proximity of each other, each wearing a typical BAN. Each BAN consists of a hub and several sensors, organised in a star topology. Time division multiple access (TDMA) is employed as the intra-BAN access scheme. Sensors transmit in a round-robin fashion after being woken up by the hub’s beacon signal.

In terms of the inter-BAN access scheme, a modified TDMA scheme is used as we assume no coordination exists between networks [22]. In this concept, the channel is temporally divided into $N_c$ orthogonal channels (time slots) and each time slot has a length of $T_d$. Each BAN chooses its transmission starting time of a superframe independently and randomly following a uniform distribution over $[0, (N_c - 1) \times T_d]$. If we assume there are total $M$ BAN networks located in close proximity to each other, then the probability $P_m$ of $m$ networks transmitting concurrently is calculated as follows:

$$P_m = \binom{M}{m} \left( \frac{2}{N_c} \right)^m \left( 1 - \frac{2}{N_c} \right)^{M-m},$$

where $m \in [1, M], N_c \geq 2$

The probability of a BAN actively transmitting with respect to any other BANs is $\frac{2}{N_c}$, because the inter-BAN TDMA scheme is unsynchronized. Fig. shows the probability of $m$ BANs
transmitting concurrently with 8 BANs \((M = 8)\) coexisting. Different colors correspond to the varying number of orthogonal channels available. In this study, the proposed power control game is simulated over many occasions with different channels, wherein each occasion the value of \(m\) is chosen randomly following the probability distribution \(\{P_m\}\). By introducing this probability distribution, it also models the mobility of BANs for multiple networks coexistence as BANs can leave and also enter the area of interest.

\subsection{B. SINR-based packet delivery ratio}

At any time, a sensor in each BAN transmits concurrently with sensor nodes in other \(m - 1\) BANs. Hence, for each BAN, the hub receives not only the signal packet from its own sensor node, but also \(m - 1\) interfering signal packets. Therefore, the SINR over a signal packet at the hub of BAN \(i\), \(\gamma_i(\tau)\), is calculated as follow:

\[
\gamma_i(\tau) = \frac{P_i(\tau)|h_i^i|^2}{\sum_{j=1, j\neq i}^m P_j(\tau)|h_i^j|^2 + \sigma^2},
\]

where \(P_i(\tau)\) is the transmission power of a sensor in the \(i\)th BAN at time \(\tau\); \(h_i^j\) represents the average channel gain across a packet time from the sensor in BAN \(j\) to the hub in BAN \(i\), in other words, the interference channel from interferer \(j\) to network \(i\). In terms of \(h_i^j\), it
is the average on-body channel gain from the sensor to its connected hub in BAN \( i \) in the same time interval.

Observing that the graph of general PDR vs. SINR is a sigmoidal function, it is possible to express the PDR as a compressed exponential function of inverse SINR, \( 1/\gamma \) \(^{[23]}\). In (3), \( \gamma \) is calculated as (2) and \( a_c \) and \( b_c \) are constant parameters depends on particular modulation, coding scheme and packet length. Complying with the IEEE 802.15.6 standard \(^{[1]}\), BCH(31,19) coding and DPSK/BPSK modulation scheme are applied with a packet length of 256 bytes. It is found that BCH(31,19) provides about 2 dB channel coding gain as shown in Fig.3, this advantage is considered when estimating the PDR vs. SINR relation.\(^{[1]}\) With a root-mean-square error of the approximation less than 0.006, Fig.4 shows the comparison between approximated and simulated PDR vs. SINR relation for DPSK and BPSK respectively. For later simplicity of analysis, we can rearrange the equation to be expressed as (4), where \( a = -(1/a_c)^{b_c} \) and \( b = -b_c \). The values of \( a \) and \( b \) are given as in Table I for both DPSK and BPSK.

\(^{1}\)BCH(31,19) is used as an example here. There are other non-IEEE 802.15.6 compliant coding schemes which can provide higher coding gain.
TABLE I

ESTIMATED PARAMETERS IN THE COMPRESSED EXPONENTIAL FUNCTION (3) AND ITS SIMPLIFIED FORM (4)

| Modulation | $a_c$ | $b_c$ | $a$       | $b$       |
|------------|-------|-------|-----------|-----------|
| DPSK       | 0.230 | 7.409 | -337.2164 | -7.4540   |
| BPSK       | 0.293 | 6.358 | -30.0512  | -6.3470   |

$pdr = \exp \left( - \left( \frac{1}{\gamma a_c} \right)^{b_c} \right)$ \hspace{1cm} (3)

$pdr = \exp \left( a \gamma^b \right)$ \hspace{1cm} (4)

C. Channel model

To evaluate the performance of the proposed game-based power control algorithm, extensive on- and inter-body channels are modeled. We simulate the scenarios in which a random number of BANs are coexisting and moving in arbitrary directions. Since the same network topology is used in each BAN, it is a reasonable assumption that on-body channels are identical for each player. The gamma distribution can characterize the general everyday on-body channel of a BAN [20], so gamma fading with a mean 60 dB attenuation, with
shape parameter of 1.31, and scale parameter of 0.562, which considers the effect of body shadowing and BAN channel dynamics, is employed.

In terms of the inter-body interfering channel, we start with representing the movement of a player by a series of \((x(\tau), y(\tau))\) coordinates updated every 1 ms. The initial positions of players are randomly chosen within a \(6 \times 6\) m\(^2\) square area which corresponds to the requirements in the standard [1]. During their movement, a random small turning angle is introduced to model a realistic walking pattern of an individual. In addition, an average walking speed of 3 m/s with 0.2 m/s standard deviation is applied. This walking model enables us to calculate the distance \(d_{ij}\) between two players \(i\) and \(j\) at any instant throughout the simulation. The channel attenuation is then calculated based on path loss model, body shadowing and also small scale fading,

\[
d_{ij}(\tau) = \sqrt{(x_i(\tau) - x_j(\tau))^2 + (y_i(\tau) - y_j(\tau))^2},
\]

\[
h_{ij}^t = A_t(d_0/d_{ij})^{2.7/2}A_{BS}A_{SC},
\]

assuming a path loss exponent of 2.7 between BANs, typical for the environment of BAN use. The reference distance \(d_0 = 5\) m corresponds to a channel attenuation \(A_t\) of 54 dB. We consider the average case where body shadowing contributes approximately \(A_{BS} = 45\) dB attenuation and adopt a Jakes’ model with Doppler spread of 1.1 Hz as the Rayleigh distribution for the small scale fading \(A_{SC}\) between BANs.

III. NON-COOPERATIVE POWER CONTROL GAME

A. Define the game

In this multiple BANs coexistence game, each BAN network makes an independent decision on the transmit power of the next packet based on its current SINR. Here each BAN is treated as a player in a non-cooperative repeated game \(G = \{N, P, U\}\), where:

- \(N = \{1, 2, ..., m\}\) is a finite set of players, indexed by \(i\);
- \(P\) represents the global strategy space, which is the Cartesian product of all players’ strategy spaces, i.e. \(P = P_1 \times P_2 \times \ldots \times P_m\). The pure strategy set of player \(i\), \(P_i\), is a finite set of discrete transmit powers in the range of \([P_i^{min}, P_i^{max}]\). The action of player \(i\) at any time(stage) \(\tau\) is denoted as \(p_i(\tau) \in P_i\), and \(p_{-i}\) stands for the choice of transmission power of other players except player \(i\);
- The utility function \(U_i\) is defined in terms of the current transmission power \(p_i(\tau)\) and packet delivery ratio PDR. Its objective is to maximize the PDR while minimizing the
transmit power. It is defined as follow:

\[ U(p_i, p_{dr_i}) = -p_i^{w_i} - \frac{d_i}{p_{dr_i}^{v_i}}, \]  

(7)

where \( p_{dr_i} \) is a function of SINR and thus a function of the transmit powers of all players according to (3) and (2). Hence, \( U(p_i, p_{dr_i}) \) can be rearranged and expressed as \( U(p_i, p_{-i}) \). The exponents \( v_i > 0 \) and \( w_i > 0 \) depend on the particular network configuration, and can be varied accordingly. The weighting factor \( d_i > 0 \) can be adjusted depending on the current network status. At the end of every time slot, players (BANs) update their transmit power levels to maximize the outcome from applying the utility function based on the latest transmit power and the current SINR:

\[ p_i(\tau + 1) = \arg \max(U(P_i, p_{-i})), \]  

(8)

where \( P_i = \{p_i | p_i \in [P_{i_{min}}, P_{i_{max}}]\}, \forall i \in N \)

B. Game verification

An important condition for the non-cooperative game to converge is that a unique Nash Equilibrium (NE) exists. The existence and uniqueness of the Nash Equilibrium of the defined game are proved as follow.

**Definition 1.** The action profile \( p^* = (p_1^*, p_2^*, ..., p_m^*) \in P \) is a Nash Equilibrium if, for all players, \( p_i^* \) is a best response to \( p_{-i}^* \). In the other words, there exists \( U_i(p_i^*, p_{-i}^*) \geq U_i(p_i, p_{-i}^*) \) for any choice of \( p_i \in P_i \).

**Theorem 1.** At least one Nash Equilibrium exists for the non-cooperative finite repeated game \( G = \{N, P, U\} \) proposed here.

**Proof.**

- \([P_{i_{min}}, P_{i_{max}}]\) is a nonempty, convex and compact subspace of a Euclidean space \( \mathbb{R}^m \).
- The utility function (7) is continuous in the domain \([P_{i_{min}}, P_{i_{max}}]\). This can be shown by taking the first derivative of the utility function and substituting (4) and (2):
\[
\frac{\delta U_i}{\delta p_i} = -w_i p_i^{w_i-1} + \frac{d_i v_i}{pdr_i^{v_i+1}} \frac{\delta pdr_i}{\delta p_i},
\]
\[
= -w_i p_i^{w_i-1} + \frac{d_i v_i}{pdr_i^{v_i+1}} pdr_i b^{-1} \frac{\delta \gamma_i}{\delta p_i},
\]
\[
= -w_i p_i^{w_i-1} + ab \gamma_i b^{-1} \frac{d_i v_i |h_i^t(k_i)|^2}{pdr_i^{v_i} I_{-i}},
\]
where \(I_{-i}\) is the interference and noise power experienced at the hub of player \(i\). Based on (2), we can derive the relation
\[
\frac{\delta U_i}{\delta p_i} = -w_i p_i^{w_i-1} + ab \gamma_i b^{-1} \frac{d_i v_i |h_i^t(k_i)|^2}{pdr_i^{v_i} I_{-i}}.
\]
(12)

Since \(p_i \in [P_i^{min}, P_i^{max}]\) is real and \(pdr_i\) is non-zero according to the approximation shown in (4), the first derivative function is defined. Therefore, Theorem 1 is proved.

**Theorem 2.** The Nash Equilibrium at each stage in the non-cooperative power control game \(G\) is unique, when \(d_i > 0\). With the unique Nash equilibrium at each stage, which is independent of history, there is a unique sub-game perfect equilibrium.

**Proof.**

- To show the Nash Equilibrium point \(p_i\) is unique in the range of \([P_i^{min}, P_i^{max}]\), it is sufficient to check the concavity of the utility function \(U(p_i, pdr_i)\) by taking the second derivative.

\[
\frac{\delta^2 U_i}{\delta p_i^2} = -w_i (w_i - 1) p_i^{w_i-2} + c_i \gamma_i b^{-2} \frac{d_i v_i |h_i^t(k_i)|^2}{pdr_i^{v_i} I_{-i}} \{(b - 1) - ab \gamma_i^b\};
\]
(13)

where \(c_i = abd_i v_i |h_i^t|^4 I_{-i}^{w_i-2}\). Due to the fact that \(p_i\) is always positive, the first part of (13) has a negative value as long as the constraint of exponent \(w_i > 1\) is satisfied. In addition, since \(v_i > 0\), and \(a\) and \(b\) are both negative and SINR, \(c_i\) and PDR are always positive, the second part of (13) is always negative. The addition of these two parts means the second derivative \(\frac{\delta^2 U_i}{\delta p_i^2} < 0\) in the range of \([P_i^{min}, P_i^{max}]\). Therefore, the function \(U(p_i, pdr_i)\) is concave and has a local maximum at \(p_i^*\) which occurs at the point \(\frac{\delta U_i}{\delta p_i} = 0\). In other words, the Nash Equilibrium at each stage of this game is unique. Furthermore at any given stage, it can be seen that this equilibrium is independent of the history, hence there is a sub-game perfect equilibrium.
IV. SIMULATION ANALYSIS

One individual repeated game consists of 100 repeated game-playing stages. 20 sets of channels are generated based on the description in Section II-C. Because of the random moving velocity, the walking pattern varies between different channel model sets. With each set, the same 100-stage game is played on 50 occasions, using different segments of the data. Therefore, a total of 1000 games, each with 100 stages, are conducted. Here, a maximum of 8 BAN networks locating in the vicinity is simulated, i.e. \( M = 8 \) in (1). At any time during the simulation, a various number of BANs are active with the others idle. The actual number of networks transmitting concurrently follows the probability distribution \( P_m \) described in (1). The case of \( m = 0 \) is neglected as the case of no network transmitting is irrelevant. In terms of inter-BAN TDMA scheme, we assume 4 orthogonal channels (\( N_c = 4 \)) are used. In addition, to investigate the effect of a given number of coexisting BANs on the performance of the proposed algorithm, constant numbers of BANs coexisting are also simulated, with the number coexisting from 2 to 8 each run on 1000 occasions. The exponents in the utility function \( v \) and \( w \) are set to be 4 and 1, which give the best outcomes for the game.

Based on the same configuration and channel models, we compare the proposed game with some other schemes commonly applied in BAN. The comparison is based on two criteria – (i) percentage of BANs reaching the target PDR; and (ii) transmission power at each stage. The result is averaged across all 1000 games. Complying to the IEEE 802.15.6 standard [1], the target PDR is set to be 0.9. The rest of the schemes are Sample-and-Hold [24], [25], SINR-Balancing [13] [12] and constant transmission power at \( 0/\text{dBm} \). Here in Sample-and-Hold current SINR is used for each BAN to set its’ next transmission power, unlike in [25], where it is done with respect to channel gain. Here in Sample-and-Hold the transmission power is adjusted based on the latest packet’s SINR to attempt to achieve the target SINR for the next packet.

All power control methods are applied and plotted in Fig.5 and 6 using BPSK and DPSK modulations respectively for the case where number of concurrently transmitting BANs follows the probability distribution \( P_m \) (1). From Fig.5(a) it is shown that using the proposed game-based power control method, approximately 93\% of the BANs are able to achieve the target PDR of 0.9 while this number is only 80\% and 77\% for Sample-and-Hold and SINR-balancing methods. Constant transmission at different power level shows similar performance to each other with about 87\% achieving target PDR. In terms of the time taken to converge
to the steady-state minimized transmit power, the proposed method and Sample-and-hold achieve this 16 time slots ahead of SINR-balancing. The short convergence time of the first two algorithms ensures that they can quickly respond to time-variations in the target channel and also interference, which is typical for BAN operation. In terms of the output transmit
power shown in Fig. 5(b) the game has an average of $-25$ dBm while sample-and-hold is about $-23$ dBm. SINR-balancing has 2 dB less in average transmission power compared with our proposed method. However, with its poor performance in percentage of BANs reaching the target and slow response time, it is not a suitable choice for enabling BANs coexistence.
Further the game has at least 15 dB less average transmit power than the constant power transmission. Similar output transmit powers can be observed in Fig.6(a) when DPSK is employed. In this case, the percentage of BANs reaching the target PDR is 92%, 85%, 76% and 74% for the proposed algorithm, constant power transmission, Sample-and-Hold and SINR-balancing respectively.

Next we show the effect of changing the number of players on the performance of the proposed power control game. Fig.7 shows the comparison when the number $m$ of coexisting BANs is fixed, $m \in [2, 8]$, with respect to the previous criteria. The same simulation parameters (exponents $v = 4$ and $w = 1$, weighting factor calculation $d_i$) are used for different values of $m$. It is observed that the average percentage of BANs reaching the target PDR of 0.9 decreases with increasing $m$, from 97% to 83%. In Fig.7(a), the intercept point of the red broken line and each solid line indicates the approximate time slot for game convergence, which shows that the more players that join the game the longer it takes for the game to converge. In Fig.7(b), we can see that transmit power rises from $-27$ dBm to $-21$ dBm as $m$ increases from 2 to 8. Note that the performance of the proposed algorithm for different values of $m$ always outperforms any of the previously described schemes described previously in the case of the average percentage of BANs reaching the target. Although SINR balancing uses slightly smaller transmit power it sacrifices a lot in terms of reliability.

V. CONCLUSION

Co-channel interference a major issue for BANs, which can cause severe performance degradation. For better interference management when multiple BANs are in close proximity to each other, a non-cooperative power control game has been proposed. In this game, a novel utility function, which constrains output transmit power is applied for each player. The unique Nash Equilibrium, and sub-game perfect equilibrium leads to a converging outcome after a certain number of stages, in terms of all BANs reaching target packet delivery ratio at the lowest possible transmit power. Based on extensive simulation over different instantiations of a realistic channel model, our proposed scheme can achieve a significantly higher number of BANs reaching target PDR more rapidly than other power control methods that are typically employed in distributed wireless networks. In addition, the lower circuit power consumption as result of lower transmit power using the proposed game, can significantly prolong the lifetime of a typical small battery as part of a sensor radio. Finally, increasing the number of coexisting BANs degrades the performance of the proposed power control game by a small
Fig. 7. Different number of BANs coexisting scenarios

amount, but outperforms other commonly used methods. For future work, we will investigate the existence of Pareto optimality for this non-cooperative game.
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