Robust Wireless Body Area Networks Coexistence: A Game Theoretic Approach to Time-Division MAC

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The enabling of wireless body area networks (WBANs) coexistence by radio interference mitigation is very important due to a rapid growth in potential users, and a lack of a central coordinator among WBANs that are closely located. In this paper, we propose a TDMA based MAC layer Scheme, with a back-off mechanism that reduces packet collision probability; and estimate performance using a Markov chain model. Based on the MAC layer scheme, a novel non-cooperative game is proposed to jointly adjust sensor node’s transmit power and rate. In comparison with the state-of-art, simulation that includes empirical data shows that the proposed approach leads to higher throughput and longer node lifespan as WBAN wearers dynamically move into each other’s vicinity. Moreover, by adaptively tuning contention windows size an alternative game is developed, which significantly reduces the latency. Both proposed games provide robust transmission under strong inter-WBAN interferences, but are demonstrated to be applicable to different scenarios. The uniqueness and existence of Nash Equilibrium (NE), as well as close-to-optimum social efficiency, is also proven for both games.

CCS Concepts: • Computer systems organization → Embedded systems; Redundancy; Robotics; • Networks → Network reliability;

Additional Key Words and Phrases: Wireless body area networks, media access control, interference mitigation, game theory, power control, time synchronization

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1 INTRODUCTION

Wireless body area networks (WBANs) are an integral part of affordable, flexible and proactive wearable health-care to reduce costs and improve people’s quality of life. Recent advances in wireless communications and sensor hardware mean that WBANs are feasible implementations. The IEEE 802.15.6 standard approved in 2012 for wireless communication in WBANs aims to serve a variety of medical, entertainment, military and consumer electronics applications. IEEE 802.15.6 only outlined basic requirements with a choice of multiple MAC layer techniques — i.e., scheduled access, polling, and contention access — supported in a beacon-based superframe. However, with a rapid increase in active devices, which predicted to be well over a billion by 2018 [9], WBANs will suffer unavoidable inter-WBAN interference from closely-located coexisting WBANs due to no central coordinator amongst networks.

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Moreover, WBAN radios have limited battery capacity due to sensor/actuator devices small sizes, but health monitoring applications require long battery life-time, as removing, charging and replacing batteries can be very inconvenient and difficult. Because inter-WBAN interference can cause performance degradation and energy wastage of low-power sensor nodes, and sensors radio transmit power is strictly constrained, inter-WBAN interference is a major issue, where most energy wastage occurs in the wireless transceiver. Hence, a well-designed MAC layer protocol for transmission scheduling is of paramount importance to prolong network lifetime and improve the robustness of WBAN communications by reducing periods of interference. Interference mitigation schemes have been widely studied for other networks, such as traditional cellular networks and wireless sensor networks, but such schemes can not be directly implemented in WBANs. This is because WBANs have relatively high mobility, compared with other networks where gateway devices are typically stationary, leading to unique features of practical WBAN coexistence that require new approaches specifically designed for WBANs.

Existing literatures on MAC protocols for WBANs demonstrate that CSMA/CA protocols encounter unreliable CCA issues and heavy collision [30]. On the other hand, TDMA has proven to be more reliable and power efficient[35]. Therefore, here, we propose a game-theoretic formulation of a TDMA-based MAC protocol to achieve energy efficiency, reduce inter-BAN interference, improve overall throughput and reduce latency across all co-existing WBANs. The proposed method adapts to the time-varying channel and traffic by optimizing the transmission schedule. Depending on the special random back-off mechanism to minimize the probability of packets collision among sensors in different WBANs, the overall interference level can be consequently reduced. Besides, each WBANs is treated as an active player in a non-cooperative game. In each superframe, the transmission parameters, such as, transmit power, transmit probability and data rate, are determined based on a utility function, which admits a unique Nash Equilibrium. By maximizing the utility function, a higher throughput can be achieved, and the latency and power consumption is reduced.

Hence, the main contributions of this paper are:

- A novel MAC layer timing protocol to reduce inter-BAN interference by adapting back-off in TDMA.
- A Markov chain is constructed to provide performance evaluation.
- A non-cooperative game is proposed to jointly tune transmit power and data rate to improve throughput and reduce latency.
- Based on the Markov chain, an Adaptive Backoff Game is proposed for better Quality of Service (QoS) performance.
- The two games are demonstrated to reduce radio interference by improving throughput, in conjunction with reduced power and delay.

The proposed method has two principal features: (i) a novel MAC layer protocol and (ii) game theoretic power control. The MAC layer protocol focuses on rescheduling unsuccessfully transmitted packets to reduce the probability of packet collision among different co-located WBANs. Two games are proposed for power control: a rate-and-power game and a Adaptive Backoff Game (as an extension of the Link Adaptation Game). The Link Adaptation Game tuning the node’s transmit power and data rate from the Nash equilibrium of its utility function to obtain optimized throughput (in terms of Packer Delivery Ratio, PDR) and power consumption. In the Adaptive Backoff Game, the sensor node adjusts its transmit probability by dynamically changing the contention parameters (contention window size), to further improve throughput performance and minimize transmission delay. Due to the difference in delay performance and power consumption, a tradeoff of the two games can be made according to WBAN application.
The rest of this paper is organized as follows. The related literature will be reviewed in Section 2. The proposed MAC layer scheme, as well as the analytical model, will be described in detail in Section 3. The two proposed game theory methods will be depicted in Section 4 and Section 5 respectively. The performance of the proposed methods will be illustrated in Section 6.

2 RELATED WORK

In literature, many studies have been proposed to mitigate inter-WBAN radio interference, in three main categories:

- Transmit power control
- MAC layer scheduling
- Data rate and power control

2.1 Transmit Power Control

Several pioneering works on inter-WBAN interference mitigation focus on solutions at the physical layer. Many techniques involve transmission power control that is based on a centralized and partially distributed [34] approach. These techniques are proven to be effective for networks with stable topologies and fewer power constraints[21]. However, more recently, game-theoretic power control, incorporating pricing factors in utility functions, e.g., [36], [19], has been shown to improve QoS in wireless networks. Due to the general lack of a central coordinator in WBANs, transmit power control must be adopted in a distributed manner across co-located WBANs. In recent studies, WBANs have been modeled as rational players competing for resources in non-cooperative power-control games, [8] [33].

2.2 MAC layer

Recently, several MAC layer protocols that seek to solve the inter-WBAN interference problems [5] [23] [24] have been proposed. The work in [5] uses cooperative schemes to suppress the inter-WBAN interference, where a random incomplete coloring (RIC) algorithm is proposed to realize a fast and high spatial-reuse for inter-WBAN scheduling. In [23], a mixed graph coloring is used for interference mitigation among WBANs, where the proposed method pairs every two WBANs into a cluster and uses cooperative scheduling between the pairs in each cluster to reduce interference. Node-level scheduling is considered in [24] to increase spatial reuse. However, these methods only work for fixed topologies in the network. To better cope with with the required flexibility in WBAN implementations, in [4][12],[16], collision avoidance techniques, such as beacon rescheduling, channel sensing and adaptive sleeping are used to improve the overall QoS performance for interfering WBANs. Many energy efficient MAC protocols have been proposed, such as [17], [18]. In B-MAC [26], the sender needs to broadcast a long preamble to be detected by the right receiver to reduce power consumption, but this, however, incurs unnecessary transmission overhead.

2.3 Data Rate and Power Control

Comparing with transmission power control schemes, the resource allocation methods tuning some other parameters, such as transmission rate, the packet size and so on, have proven to be more effective. Research interests in this area are emerging and some centralized methods [25] have been proposed in recent studies. As for distributed algorithms, game theoretic approaches are widely used. For cellular networks, [15] game theoretic schemes with multiple discrete code rates or modulation schemes are proposed, which is also known as link adaptation [11]. The mobile terminals updating power and rate by optimizing the Utility Function to Nash Equilibrium. This idea
is further extended for wireless Ad hoc network in [13], a simple utility function only depending on Signal to Interference and Noise Ratio (SINR) and the pricing is used. However, for WBANs, there has been limited literature on this subject. [2] proposed transmission rate adaptation policy for WBANs to improve the QoS by solving a convex optimization problem, but only dynamic postures in WBANs channels are considered.

2.4 Overall IEEE 802.15.6 Requirements

As per the IEEE 802.15.6 standard for WBANs its requirements are as follows [1]:

- Bit rates in the range of 10 kbps to 10 MBps should be supported via the WBAN links.
- Packet Delivery Rate (PDR) should be larger than 90% for a 256 octet payload for more than 95% of the best-performing links;
- Up to 256 nodes should be supported by each WBAN;
- Reliability, jitter and latency should be supported for specific WBAN applications. For instance, medical applications and non-medical of WBANs require latency to be less than 125 ms and less than 250 ms, respectively; whilst jitter should be less than 50 ms;
- WBAN nodes should allow reliable communication in case of mobility scenarios for both on-body and in-body communications;
- Up to 10 randomly distributed co-located WBAN networks should be supported in a $6 \times 6m^2$ area.

3 OVERALL OF THE PROPOSED MAC SCHEME

Here, we propose a TDMA-based MAC protocol to achieve energy efficiency, reduce inter-WBAN interference and obtain low delivery latency for co-existing WBANs. Depending on the special random back-off mechanism to minimize the probability of packets collision among sensors in different WBANs, the overall level of interference and power consumption can be consequently reduced.

3.1 System Model

We consider star-topology WBANs that are closely located and coexisting. Each WBAN consists of a single hub with multiple sensors as described in Fig 1. The hub is not energy-constrained, so the energy consumption of the sensor is mainly considered. The hub facilitates the main WBAN operations such as synchronization, re-transmission and determining transmission schedules.

As interference across all co-existing WBANs is the main reason for dropped-packets and energy wastage, the following assumptions apply:

A1. All BANs are saturated, which means that they always have a packet to send (packet arrive rate is 1).
A2. Interference-dominated, where packet loss due to additive noise is negligible.
A3. All hubs are not energy constrained
A4. Time-slots across every superframe are normalized to unity

Within each WBAN the sensor devices acquire data and use TDMA to transmit to the hub to avoid idle-listening and overhearing. The intra-BAN interference is collision free when each sensor is transmitting using round-robin scheduling. However, it is infeasible to implement central coordinator among co-existing WBANs that are closely located. Thus, the transmission between different WBANs can not be synchronized. Therefore, co-channel interference may arise due to collisions amongst concurrent transmissions made by sensors in different WBANs.
### Table 1. Table of Notations

| Symbols | Description |
|---------|-------------|
| $N$     | Number of WBANs |
| $T_s$   | Length of the superframe |
| $T_b$   | Length of the beacon |
| $T_{idle}$ | Length of the inactive period |
| $T_{payload}$ | Length of the transmission period (payload) |
| $T_{ack}$ | Length of the ACK |
| $T_{slot}$ | Length of a time slot |
| $w$     | Backoff counter |
| $m$     | Maximum Backoff Stage |
| $\lambda$ | Persistence coefficient |
| $b$     | Backoff Stage |
| $W$     | Contention window size |
| $CW_{min}$ | Minimum backoff length |
| $CW_{max}$ | Maximum backoff length |
| $p_f$   | Probability of transmission failure |
| $b_{i,j}$ | Stationary distribution |
| $\tau$ | Probability of transmission in a randomly slot |
| $p_c$   | Probability of packets collision |
| $R_\tau$ | Normalization coefficient of $\tau$ |
| $\gamma$ | Signal to Noise and Interference ratio (SINR) |
| $h_{ii}$ | Intra-WBAN Channel gain |
| $h_{ij}$ | Inter-WBAN Channel gain |
| $\sigma$ | Noise gain |
| $P_i$   | Transmit power of WBAN $i$ |
| $R_i$   | Data rate of WBAN $i$ |
| $\Omega$ | Social Welfare |

#### 3.2 MAC Layer Specification

**Superframe Structure.** As described above, the sensors in each WBAN are synchronized by periodic transmission of the superframe, with constant length $T_s$. Each superframe consists of a beacon, ACK reception, several slots used for data transmission and an inactive (idle) period. The beacon is configured to contain control information for broadcasting to sensors. Due to Assumption A.3, the probability that beacon or ACK is not received at the sensor is negligible, as the hub can apply higher transmit power to avoid SINR outage. The beacon is immediately followed a data frame, which mainly consist of up-link data traffic from the sensors to the hub.

Each superframe starts with broadcasting a beacon packet from the hub to the sensors, which consists of information for establishing links and synchronization. Due to Assumption A.3, the probability that beacon or ACK is not received at the sensor is negligible, as the hub can apply higher transmit power to avoid SINR outage. The beacon is immediately followed a data frame, which mainly consist of up-link data traffic from the sensors to the hub.

**Back-off Mechanism.** In order to avoid collisions when many WBANs sharing the medium, a back-off algorithm can be used in WBAN networks. Since, if a transmission fails due to interference,
it is highly likely that a following transmission will also be blocked. Keeping the sensor in back-off states for a shorter period of time will increase packet delivery ratio and reduce collision probability.

Fig. 3 illustrates the back-off mechanism and the operation mode of the sensor. As depicted in Fig. 1, all the sensors may be in one of three different operation states: back-off state, transmission state, and inactive state.

If the ACK is not received by the sensor till the end of a superframe, the sensor executes a random backoff procedure before the next beacon is transmitted by the hub to reduce the collision probabilities among WBANs.

During the random backoff procedure, each sensor set its backoff counter $w$ as a random integer uniformly distributed over the interval of $w \in [1, W]$. The value $W$, namely Contention Window size is determined by the Backoff stage $b$ and the number of Maximum Backoff Stages $m$. The Backoff stage $b$ equals to the number of transmissions failed for the packet. At the first transmission
attempt, $W$ is set as 0. After each unsuccessful transmission, $W$ is set as the $CW_{\text{min}}$ multiplied by the persistence coefficient $\lambda$ ($W = \lambda^b CW_{\text{min}}$), until it reach the maximum value $CW_{\text{max}} = \lambda^m CW_{\text{min}}$ (in this paper $\lambda = 2$). The value $CW_{\text{min}}$ called minimum back-off length. The basic algorithms are listed in Algorithm 1.

### 3.3 Markov Model

A Markov model was initially proposed by Bianchi for IEEE 802.11 DCF [3]. The model describes the basic fundamental process of MAC layer scheme through a Markov chain. The model has been extended in several directions.

In this section, we proposed a discrete-time Markov chain, which models the operation of the proposed algorithm in the tagged WBAN and captures the key characteristics of the MAC layer timing scheme, such as, superframe structure, and re-transmission mechanism. The Markov chain model can help us investigate features of the proposed MAC layer timing scheme, such as throughput and delay.

Figure 4. shows the state transition diagram of the Markov chain of the proposed MAC scheme. In the Markov model, the state at time $t$ for tagged WBAN is represented by the stochastic process $(b(t), w(t))$. $b(t), w(t)$ represent the back-off stage and the back-off counter respectively. Here, $b(t) \in [0, m]$ represents the back-off stage of the tagged WBAN at time $t$, where $m$ is the maximum backoffs. $w(t)$ represents the value of the backoff counter at time $t$.

Initially, the values of back-off counter and re-transmission counter are set to zero. In the back-off stage, when the value of back-off counter reaches zero, the hub will re-transmit the packet. If the transmission attempt is successful, the state will move to $\{0, 0\}$, $(b(t) = 0, w(t) = 0)$, and the WBAN starts to transmit in the next frame after the in-active period. Otherwise, the sensor moves from back-off stage $j$ to $j + 1$ with its re-transmission counter incremented by 1. In addition, at the state $\{m, 0\}$, the data from the sensor will either be successfully transmitted or discarded by the sensor. The parameter $p_f$ represents the probability of transmission failure due to the inter-BAN interference, which denotes the probability of ACK reception under collision of packets. The state transition probabilities are:
Algorithm 1 The Proposed MAC Layer Protocol

1: Initializing MAC Parameters when, $W = CW_{\text{min}}$, $b = 0$, $w = 0$
2: Hub send the sensor a beacon to sensor $i$ with synchronization information
3: After receive the beacon, the sensor $i$ transmit data using the scheduled slots.
4: if Hub successfully receives the packet then
5: end if
6: Sensor keeps inactive for a period of $T_{\text{idle}}$ until the end of the superframe.
7: go to 2
8: $i \leftarrow i + 1$
9: close;
10: if The transmission fails because of the interference, the sensor will not receive the ACK then
11: $b \leftarrow b + 1$
12: if $b > \text{MaxRetransmissionLimit}$ then
13: Discard The Packet
14: go to 2
15: end if
16: close;
17: The hub calculates the backoff length
18: $W_b = \lambda^b CW_{\text{min}}$
19: $w = \text{random}(0, W_b)$
20: Sensor keeps inactive for a period of $T_{\text{idle}}$, and starts back off until the end of the superframe.
21: $w \leftarrow w - 1$
22: if $w = 0$ then
23: go to 2
24: close;
25: end if
26: end if

\[
\begin{aligned}
P_r((i, j - 1)|(i, j)) &= 1 \\
P_r((i + 1, j)|(i, 0)) &= pf \frac{1}{W_i^*} \\
P_r((0, 0)|(i, 0)) &= 1 - pf \\
P_r((0, 0)|(0, 0)) &= 1 - pf
\end{aligned}
\]  

(1)

where $W_i = 2^i CW_{\text{min}}$, $i \geq 1$.

3.3.1 Steady-State Solution. To complete the construction of the Markov chain in Fig. 1, a form solution for the Markov chain is required.

Let the stationary distribution of the Markov chain be, $b_{i,j} = \lim_{t \to \infty} Pr(s(t) = i, b(t) = j)$, where $i \in (0, m)$, $j \in (0, W_i)$. Then, we can calculate the stationary distribution for all the values of $b_{i,j}$. By using the equation (1), $b_{i,j}$ can be expressed as functions of the value $b_{0,0}$ and of the transmission failure probability $pf$. $b_{0,0}$ is finally determined by imposing the normalization condition:

\[
b_{0,0} + \sum_{k=1}^{m} \sum_{j=0}^{W_k} b_{k,j} = 1
\]  

(2)

that simplifies to:

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We can now express the probability $\tau$ that a WBAN sensor attempts to carry out a superframe transmission in a randomly chosen slot time. The transmission occurs when the backoff time counter is equal to zero. Thus, we can write the probability $\tau$:

$$\tau = \sum_{k=0}^{m} b_{k,0}$$  \hspace{1cm} (4)

$$\tau = \frac{2(1 - p_f)(1 - 2p_f)}{2CW_{min} p_f (1 - (2p_f)^m)(1 - p_f) + (2 + p_f)(1 - p_f^m)(1 - 2p_f)}$$  \hspace{1cm} (5)

With probability $\tau$, the probability of transmission failure $p_f$ is the intersection of the probability of collision and the packet error rate (PER):

$$p_f = p_c \cap \text{PER} = (1 - \text{PDR})(1 - (1 - \eta\tau)^{N-1}),$$  \hspace{1cm} (6)

where PDR is the packet deliver ratio and $\eta\tau$ is a coefficient that normalizes $\tau$ by the average number of time slots staying in an arbitrary state of the Markov chain.

By using (5) and (6), the values of $p_f, \tau$ and $b_{0,0}$ can be solved and used in performance metrics.
3.4 Performance Validation

By comparing the analytical modeling with simulation results, we can evaluate the accuracy of the Markov Model described in the previous section. We simulated $N$ single-link star topology WBANs co-existing in the saturated regime (all WBANs always have a packet to transmit). A performance analysis is also conducted based on the steady-state solutions. We assumed when intra-WBAN interference occurs that the packets collision will result in transmission failure $p_f = p_c$ as PER = 1(PDR = 0).

In our experiment, the data rate is set as $32 \text{ kbit s}^{-1}$. The retransmissions limits $m = 4$, and the minimum back-off length $CW_{min} = 64$. The duration of one superframe is $T_s = 64ms$. Each superframe consist of 256 time slots. Each time slot last for $T_{\text{slot}} = 250\mu s$. The beacon, payload and the ACK are set to be 30,110,10 bytes respectively.

![Fig. 5. The Comparison of Probability of Collision](image1)

![Fig. 6. The Comparison of Goodput](image2)
Fig. 5 and Fig. 6 show that, in terms of Probability of Collision and Goodput ($S$), the analytical model matches the simulation results accurately. Goodput is defined as the ratio between time elapsed successfully delivering a packet and the total time. Analytically, the goodput is calculated as:

$$\text{Goodput}(S) = \frac{(1 - p_f)\tau T_{\text{payload}}}{\tau T_s + (1 - \tau)T_{\text{slot}}}$$  (7)

where

$$T_s = T_{\text{beacon}} + T_{\text{payload}} + T_{\text{ack}} + T_{\text{idle}}$$  (8)

$T_{\text{beacon}}, T_{\text{payload}}, T_{\text{ack}}, T_{\text{idle}}$ represent the duration of beacon, payload, ACK and idle respectively. However, weak matching occurs when less WBANs are co-existing, as randomness of the back-off counter in the simulation is relatively large. Fig. 6 shows that when more WBANs are co-located, the system’s Goodput decreases as the collision probability increases.

## 4 Link Adaptation Game Algorithm

The majority of existing game theoretic algorithms in WBANs only focus on transmit power control. However, when considering saturated traffic conditions, in particular interfering networks, selfishly changing the transmit power may increases packet losses, and thus, reduce the overall throughput. Thus, we observed that greater system efficiency can be achieved by varying performance-impacting characteristic such as modulation or data rate.

One of the objectives in this paper is to exploit the above MAC layer scheme to find a method that can further increases the system’s energy efficiency and reduce inference. In this section, we develop a utility-based game theory model that is a function of two variables: transmission power and data rate to address interference and packet contentions. The transmitter chooses the value of the transmit power and data rate to maximize energy efficiency whilst meeting the packet delivery ratio (PDR) requirements. Since the transmitter’s action will be a function of the choice of data rate and transmit power. Therefore, the two parameters need to be executed jointly.

According to experimental results, an increase in data rate can result in WBAN’s packet delivery ratio degradation in the same SINR regime. However, the length of payload transmission time is also related to the WBAN’s data rate, so that higher data rate may also reduce the intra-WBAN packet collision possibility as the transmission time is reduced accordingly, and thus mitigate interference. Furthermore, the proposed game theoretic algorithm handles packet re-transmissions, until the retry limit is reached. In addition, it should be noted that all game associated calculations are made by the hub, hence there will be no extra computational cost for the sensors.

### 4.1 Game-theoretic System Model

We consider the system model of the form described in Section 2.1 where multiple WBANs are co-located. All WBANs are within each others interference range, and the corresponding transmitters always have packets to send. TDMA schemes with the same random back-off scheduling mechanism are applied for all WBANs and the minimum back off slot length cannot be changed. There are no pre-assigned priorities among different WBANs such that all links can expect identical priorities in traffic. Formally, we define the Link Adaptation Game in normal form as $G = \{N, (P, R), U\}$, notation described in the following sub-sections.

### 4.2 Players

Each co-existing WBAN is a player in the Link Adaptation Game, the player set is denoted by $N = \{1, 2, 3,...N\}$. Within each WBAN, the sensor(transmitter) adapts its power and data rate by utilizing the game-theoretic algorithms.
4.3 Action Set

We require that the data rate of WBAN $i$, $R_i$ is chosen from a discrete finite set $\mathcal{R} = \{R_{\text{min}}, \ldots, R_{\text{max}}\}$, where $R_{\text{min}}$ is the base rate and $R_{\text{max}}$ is the maximum data rate. In each packet transmission, and variations in $R_i$ result in variations in packet delivery ratio (PDR). In addition, each WBAN can adjust its power $P_i \in [P_{\text{min}}, P_{\text{max}}]$. Thus the action selected by any player $i$ is defined as the pair $A_i = (P_i, R_i)$, where $P_i$ is the transmit power of player $i$ and $R_i$ is the data rate of player $i$. The aggregation of all players action is denoted as $A = (P, R) = \{A_1, A_2, \ldots, A_n\}$.

4.4 Utility Function

It is obvious that each player is always trying to maximizing its own utility. However, due to the non-cooperative nature of this game, it is easy to see that in an attempt to maximize its own benefits at any cost, each WBAN is likely to consume maximum power, and the highest data rate. This will also create excessive interference, leading to performance degradation. A pricing mechanism is then also introduced to penalize the use of excessive power. The utility function of each player is defined as follows:

$$U(P, R) = -C(P) + \ln(1 + \text{PDR}(P, R)) + G(R),$$

where,

$$C(P) = c \cdot P^g$$

$$G(R) = -q \cdot \frac{1}{R}$$

the coefficients in the cost function $c, g, q$ are positive constants that can be tuned depending on channel conditions. The linear cost function (where the exponent $g = 1$) is commonly used in the literature, however, in the proposed game $g$ are generally greater than 1 to provide strictly concavity. $c, q$ are constant non-negative weighting factors.

In equation (9), a sigmoid approximation of PDR is introduced. This model has been shown to be capable of approximating the PDR versus SINR of a wireless channel. Here, the SINR is defined as:

$$\gamma_i = \frac{h_{ii} P_i}{\sum_{j=1, j \neq i}^{N} h_{ij} P_j + \sigma^2},$$

where, $h_{ij}$ represents the channel attenuation between WBAN $i$ and WBAN $j$. $h_{ii}$ denotes the on-body channel attenuation in WBAN $i$. $\sigma$ is the noise gain. The sigmoid PDR function of SINR is presented as follows:

$$\text{PDR} = \exp\left(\alpha \cdot \gamma^\beta\right)$$

Fig. 7 shows the comparison between approximated and simulated PDR vs. SINR for different data rate ($R_1 \sim R_5$) respectively. The sets of parameters $\alpha, \beta$ of the sigmoid model in the equation above that best approximate the simulation curves are selected by computer-aided search and summarized in Table 3:

| Data Rate   | $\alpha$  | $\beta$ |
|-------------|------------|----------|
| $R_1 = 25.6$ kbps | -100.02   | -3.66    |
| $R_2 = 51.2$ kbps | -214.95   | -2.82    |
| $R_3 = 76.8$ kbps | -663.69   | -2.79    |
| $R_4 = 102.4$ kbps | -1182.7   | -2.73    |
| $R_5 = 128.0$ kbps | -1433.5   | -2.58    |
4.5 Nash Equilibrium

The Nash equilibrium is a set of strategies that guarantee the best response of each player with respect to the chosen utility. In the proposed non-cooperative game, the game is played by rational players, which implies that every player adopts the strategy achieving the Nash Equilibrium.

**Definition 1.** Let \( A^* = (P^*, R^*) \) be the Nash Equilibrium in the Link Adaptation Game, then for every \( i \in N \):

\[
U(P^*_i, R^*_i) \geq U((P_i, R_i), P^*_{-i}, R^*_{-i}),
\]

where, \((P_{-i}, R_{-i})\) represents all other player strategies except for player \( i \). At the end of every transmission (say \( t \)), players update their next transmit power and rate jointly to maximize the outcome of adapting the utility function based on the current SINR:

\[
\{P_i(t + 1), R_i(t + 1)\} = \arg \max U \{(P_i(t), R_i(t)), P^*_{-i}, R^*_{-i}\}
\]

The action profile \( P^* = (P^*_1, P^*_2, P^*_3 ... P^*_n) \) for \( n \geq 2 \) is a Nash Equilibrium, is the best response towards \( P^*_{-i} \).

4.6 Existence and uniqueness of the Nash equilibrium

The existence and uniqueness of the Nash Equilibrium of the proposed game are proved as follows:

**Lemma 1.** The action space \( \overline{A} = (P, R) \) is not a convex set. However, under the condition that \( R \) is fixed, \( \overline{A} = (P, R) \) is a convex set.

**Proof.** We simply choose two points, \( A_1 = (P_{\text{max}}, R_1) \), \( A_2 = (P_{\text{max}}, R_2) \) that have the same power component. A line connecting these points consists of only two points \( A_1, A_2 \) themselves. The intervening points on this line do not belong to \( (P, R) \). Hence, \( (P, R) \) is not convex. However, suppose the data rate is fixed at, say \( R_1 \). We note that a convex combination \( A' = \lambda A'_1 + (1 - \lambda)A'_2, \lambda \in [0, 1], \) where \( A'_1 = (P_1, R_1) \), \( A'_2 = (P_2, R_1) \) are any two arbitrarily selected actions in \( A \), such that \( P_{\text{min}} < P_1, P_2 < P_{\text{max}} \) belongs to the set \( \overline{A} \). Hence the set \( \overline{A} \) is convex when \( R \) is fixed.

**Theorem 2.** (Existence) The game \( G \) admits at least one Nash Equilibrium, when assuming \( R \) is fixed.
Thus we transform the game to a potential game denoted by \( G \), which provides useful properties concerning the justification of Nash Equilibrium. The utility function leads to the uniqueness of the Nash Equilibrium solution over the action space as proved in Lemma 1. The utility function \( U \) is continuous for all \( P_i \in [P^\text{min}_i, P^\text{max}_i] \). As the first derivative of the utility function \( U \) is well defined as:

\[
\delta U_i \over \delta P_i = -c \cdot g^{p_{-1}} + \left( 1 - \frac{1}{(1 + \text{PDR}_i)} \right) \alpha \beta \gamma_i^\beta P_i^\beta,
\]

where \( \frac{|h_i(k_i)|^2}{I_i} = \frac{w_i}{P_i^2} \), therefore, as \( P_i \in [P^\text{min}_i, P^\text{max}_i] \) is real and the PDR is non-zero, the Theorem 2 is proved.

**Theorem** 3. (Uniqueness): The Nash Equilibrium in each stage of the game \( G \) is unique, and independent of history so it is a unique sub-game perfect equilibrium.

**Proof.** The second derivative of \( U(\cdot) \) is shown to be always negative \( \forall i \), so that \( U(\cdot) \) is strictly concave.

\[
\frac{\delta^2 U_i}{\delta P_i^2} = -c \cdot g(g - 1)P_i^{g-2} + \left( 1 - \frac{1}{(1 + \text{PDR}_i)} \right) \gamma_i^\beta \alpha \beta (\beta - 1)/P_i^2 - \frac{\text{PDR}_i}{(1 + \text{PDR}_i)^2} \alpha^2 \beta^2 \gamma_i^{2\beta} / P_i^2,
\]

where PDR is always positive and between (0,1), and the term \( (\beta - 1) \) is less than 0. In addition \( w \) is positive, thus \( \frac{\delta^2 U_i}{\delta P_i^2} < 0 \). Therefore the utility function has a global maximum at \( P^*_i \) which occurs at the point where \( \frac{\delta U_i}{\delta P_i} = 0 \).

However, in practice, the data rate \( R \) is not always fixed. Hence, we need to make sure that the game only admits a unique Nash Equilibrium solution over the action space \( \bar{A} \). As the concavity of the utility function leads to the uniqueness of the Nash Equilibrium, we use the concept of potential game[22], which provides useful properties concerning the justification of Nash equilibrium.

### 4.7 Forming a Potential Game

For game \( G \), when at high PDR regime (where the system usually operates), we can obtain the following approximation by using Taylor expansion for the last term in the utility function (13):

\[
\ln(1 + \text{PDR}(A_i, A_{-i})) = \ln(1 + \exp(\alpha \cdot \gamma_i^\beta)) \approx \ln(2) + \frac{\alpha \cdot \gamma_i^\beta}{2} + \frac{(\alpha \cdot \gamma_i^\beta)^2}{8} \ldots
\]

Substitute this approximation into the utility function (only takes the first order term), we can get the new game with utility function defined as:

\[
U_{P_i}(P, R) = -c \cdot p_i^g + q \cdot \frac{1}{R_i} + \ln(2) + \frac{\alpha(R_i) \cdot \gamma_i^\beta(R_i)}{2} \approx U(P, R)
\]

Thus we transform the game \( G \) to a potential game denoted by \( G_P = \{N, A, U_P\} \), where \( U_P \) is the new utility function.

We firstly provide the definition of the exact potential game, and proceed to show that the game belongs to the class of exact potential games.

**Definition 2.** A game is said to be an exact potential game if there exists a function satisfying:

\[
U(S_i, S_{-i}) - U(T_i, S_{-i}) = F(S_i, S_{-i}) - F(T_i, S_{-i}),
\]

where \( F \) is called the potential function that can map the action space of the game in to a real space.
Algorithm 2 Main steps for Link Adaptation Game

1: Initializing MAC Parameters when, \( CW = CW_{min}, b = 0, w = 0 \)
2: Hub sends a beacon to sensor \( i \) with synchronization information
3: After receiving the beacon, the sensor \( i \) transmits data using the scheduled slots with \((P(t), R(t))\).
4: if Hub successfully receives the packet then
5: \(
\{P_i(t + 1), R_i(t + 1)\} = \arg \max U\{(P_i, R_i), P^*_{-i}, R^*_{-i}\}
\)
6: Sensor keeps inactive for a period of \( T_{idle} \) until the end of the superframe.
7: go to 2
8: \( i \leftarrow i + 1 \)
9: \( t \leftarrow t + 1 \)
10: close;
11: else if The transmission fails because of the interference, the sensor will not receive the ACK then
12: \( b \leftarrow b + 1 \)
13: if \( b > MaxRetransmissionLimit \) then
14: Discard The Packet
15: go to 2
16: close;
17: end if
18: The Hub choosing the transmit power and rate for next transmission by equation (14):
19: \(
\{P_i(t + 1), R_i(t + 1)\} = \arg \max U\{(P_i, R_i), P^*_{-i}, R^*_{-i}\}
\)
20: The hub calculates the backoff length
21: \( W = \lambda^b CW_{min} \)
22: \( w = \text{random}\{0, CW\} \)
23: Sensor keeps inactive for a period of \( T_{idle} \), and starts back off until the end of the superframe.
24: \( w \leftarrow w - 1 \)
25: if \( w = 0 \) then
26: go to 2
27: \( t \leftarrow t + 1 \)
28: close;
29: end if

The Game \( G_p \) is an exact potential game, with a potential function defined as:

\[
F_i(A) = \sum -cP_i^w - q \frac{1}{R_i} + \frac{\alpha(R_i) \cdot y^\beta(R_i)}{2}
\]  

(20)

Notice that we discard \( \ln(2) \) in the utility function when constructing the potential function as the constants can be canceled out. We can see that \( F \) satisfies the Definition 2.1 in [20].
\[
F_i = -cp_i^g - q \frac{1}{R_i} + \frac{\alpha(R_i) \cdot y(b(R_i))}{2} + \sum_{j \neq i} -cp_j^w - q \frac{1}{R_j} + \frac{\alpha(R_j) \cdot y(b(R_j))}{2} \\
\]

and,

\[
F(A_i, A_{-i}) - F(T_i, A_{-i}) = -cp_i^g - q \frac{1}{R_i} + \frac{\alpha(R_i) \cdot y(b(R_i))}{2} - cp_T^g - q \frac{1}{R_T} + \frac{\alpha(R_T) \cdot y(b(R_T))}{2} = U_p(A_i, A_{-i}) - U_p(T_i, A_{-i}), \tag{21}
\]

where \(T_i = (P_{T_i}, R_{T_i})\), and thus it is a potential function of the game \(G_p\). Also, game \(G_p\) is a best response potential game, which defined as:

**Definition 3.** The game \(G\) is a best-response game if and only if a potential function \(F\) exists such that,

\[
\arg \max U(A_i, A_{-i}) = \arg \max F(A_i, A_{-i}) \tag{22}
\]

According to [31], this leads to the following lemma:

**Lemma 4.** For best-response game \(G\) defined over action space \(\bar{A}\), with a potential function \(F\). If \(A \in \bar{A}\) maximizes \(F\), then it is a Nash Equilibrium for \(G\).

### 4.8 Large Midpoint Property and Discrete Concavity

For an exact potential game, the change of the potential function attributes the same amount of change in a player’s utility function due to its strategy deviation. A concave potential function guarantees that every Nash equilibrium of the game also maximizes a potential function.

Therefore, with the help of the results in [29] on discrete concavity for potential games, we can prove the uniqueness of the Nash equilibrium in \(G_p\): since the maximizer in the potential function \(F\) is unique, so is the Nash Equilibrium in game \(G\).

According to [29] the Large Midpoint Property (LMP) is defined as:

**Definition 4.** For a function defined over discrete set satisfies LMP if for any \(x, y \in X\) with \(|x - y| = 2\),

\[
\max_{|x - z| = |z - y| = 1} f(z) = \begin{cases} 
> \min \{f(x), f(y)\}, & \text{if } f(x) \neq f(y) \\
\geq f(x) = f(y), & \text{otherwise}
\end{cases} \tag{23}
\]

We show that the potential function satisfies the LMP the discrete strategy \(\bar{R}\). As the choice of data rate \([R_{\min}, R_{\max}]\) is discrete, and \(\bar{P}\) is continuous. We can have the following proposition:

**Theorem 5.** For a certain power strategy \(P \in \bar{P}\), the potential function \(F(A)\), where \(A = (P, R)\) satisfies LMP for \(R \in \bar{R}\).

**Proof.** See in Appendix B.

This leads to the following proposition:

**Proposition 6.** Suppose that \(A = (P, R)\) satisfies LMP for \(R \in \bar{R}\). Then, only if \(F(A = (P, R_x), A_{-i}) \geq F(A = (P, R_y), A_{-i})\) for all \(y\), \(F(A = (P, R_x), A_{-i}) \geq F(A = (P, R_y), A_{-i})\) for all \(|x - y| \leq 1\)
This means that if LMP is satisfied for a discrete potential function, then the local optimality in the potential function implies global optimality. Thus, when at a certain transmit power level, only one maximizer exists over the discrete set of data rate. The proof of the Proposition 6 is shown in Appendix C.

As Theorem 3 shows that when $R$ is fixed, the utility function admits one optimizer (maximizer). Hence, for exact potential game, the potential function also admits unique maximizer. Thus we have

**Theorem 7.** The maximizer in the action space $A$, namely $A^\circ = \arg \max F(A_i, A_{-i})$ is unique and:

$$F(A^\circ, A_{-i}) = \max \{ F((P^*_{min}, R_{min}), A_{-i}), \ldots F((P^*_{max}, R_{max}), A_{-i}) \},$$  \hspace{1cm} (24)

where, $P^*_x$ is the maximizer when $R = R_x$.

To show that the equilibrium of the propose potential game is unique, it is sufficient to prove that the set of maximizers of the potential function is singleton. Therefore, the best-response for the potential game $G$, $A^\ast = (P^*, R^*)$ is equals to $A^\circ$, which is also unique.

4.9 Game Efficiency

The Nash Equilibrium solution of each individual BAN in the game $G$ is the maximization of its own utility. This leads to the problem of efficiency of the network. More specifically, for a network without a central coordinator, the fairness of the system may degrade due to selfish actions of the players. Thus, it is important to investigate the equilibrium efficiency among the co-existing WBANs. The social welfare reflects the fairness and efficiency of the system’s best response, considering all individuals utility combined.

**Definition 5.** The social welfare is defined by the aggregation sum of each WBAN’s utility function as:

$$\Omega(A) = \sum_{i=0}^{n} U_i(A) \hspace{1cm} (25)$$

The maximization of the social welfare is the social optimum, which represents the social fairness among the system. The price of anarchy (PoA) is used to measure the inefficiency of equilibriums among selfish players. With finite number of players in game $G$, the PoA $^1$ is defined as the ration of the highest value of social welfare (social optimum) to the NE (as the Nash Equilibrium in $G$ is unique) of the game:

$$\text{PoA} = \frac{\Omega(A_{opt})}{\Omega(A^\ast)} \geq 1, \hspace{1cm} (26)$$

where $A_{opt} = \arg \max \Omega(A)$ is the global optimum solution.

5 THE ADAPTIVE BACKOFF GAME

By implementing the proposed back-off algorithms, the collision during the frame transmission can possibly be avoided. Because, before each transmission, each WBAN waits for a random time, based on Contention Window size. This mechanism space out repeated retransmissions of the data in each WBAN. Generally, each WBAN is able to tune their transmission probability by modifying the back-off control parameters, such as $CW_{min}$ value and maximum back-off stages ($m$ value).

---

$^1$Since the Nash Equilibrium is unique, the the price of anarchy equals to the price of stability(PoS)
Therefore, each WBAN can dynamically choose a suitable contention window size according to the contention level of current network in order to effectively improve system performance.

However, due to the non-cooperative nature of the system, each selfish player attempts to increase its utility by increasing its transmission probability or equivalent by decreasing its contention window size. Increasing the transmission probability by one player encourages other players to shorten their contention window sizes, which increases collisions, thus the delay and packets drop ratios are also increased. Here, we proposed the Contention Game $G_{CW}$ based on the aforementioned MAC layer scheduling, which aims to balance the trade-off between packet delay and system throughput.

In the Contention Game, the action selected by any player is their minimum contention windows size $CW_{\text{min}}$, where $CW_{\text{min}}$ is the action space. As described by the Markov Model, by changing the contention window size, players transmission probability can be adjusted accordingly. As, in a high PDR regime, we have the following approximation:

$$\tau \approx \frac{1}{p_f \cdot CW_{\text{min}} + 1},$$  \hspace{1cm} (27)

where $p_f$ is transmission failure probability.

Empirically, in order to get the value of $n$, each node can measure $p_f$ and $\tau$ through several counters independently. The number of coexisting WBANs can be estimated from the following equations[10]:

$$\tau_{\text{est}} = \frac{\text{TransmittedFragmentCount}}{\text{SlotCount}},$$

$$p_{\text{est}} = \frac{\text{AckFailureCount}}{\text{TransmittedFragmentCount}},$$  \hspace{1cm} (28)

where $p_{\text{est}}$ and $\tau_{\text{est}}$ denote the estimated $p_f$, failure probability respectively.

TransmittedFragmentCounter that counts the total number of successfully transmitted data frames, ACKFailureCounter that counts the total number of unsuccessfully transmitted data frames and the SlotCounter that counts the total number of experienced time slots. (The historical data can be used to estimate the current parameters, and the length of how far we should trace back can be adjusted accordingly).

**Algorithm 3 Main steps for Adaptive Backoff Game**

1. After execute line 19 in Algorithm 2
2. The Hub estimated the number of coexisting WBANs $n_{\text{est}}$ by using equation (28)
3. After obtain $n_{\text{est}}$. The Utility Function $V(CW_{\text{min}})$ can be constructed as a function of $w$, where the PDR is obtained as $\text{PDR}(P^*, R^*)$ from the Nash Equilibrium in the Link Adaptation Game.
4. Determine the minimum contention window size $CW_{\text{min}}$ for that given sensor, which gives the Nash Equilibrium value of the Utility Function $V(CW_{\text{min}})$
5. go to 22 in Algorithm 2

The objective of the game is to reach a trade-off in maximizing the throughput, and minimize delay. Following from the analytical model, the throughput of each WBANs is positively correlated with the Goodput(S) in equation (7). The average delay for a packet to be transmitted successfully is estimated as:

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\[ D = \sum_{i=1}^{m} P_{Bi}E[D_i] \]
\[ = \sum_{i=1}^{m-1} \left[ p_i^f (1 - p_f) \sum_{j=0}^{i} \left( \frac{W_j + 1}{2} T_{\text{slot}} + T_s \right) \right] \]
\[ + p_f^m \sum_{j=0}^{m} \left( \frac{W_j + 1}{2} T_{\text{slot}} + T_s \right), \]

where \( E[D_i] \) is the average delay in state \( i \). It is obvious that throughput, delay may have different units in different ranges, and they have to be normalized. Therefore, the utility function is defined as the following:

\[ V_i(CW_{\text{min}}) = d \cdot S - l \cdot D - P_{\text{Drop}}, \]

where \( P_{\text{Drop}} = \tau^{m+1} \) is the probability that a packet drops due to exceed maximum retry limits. The weights \( d, l \) can be adjusted based on different scenarios. The obtained results have shown that in game \( G_{CW} \), each user improves its chance of successful transmission by increasing transmission probability, whilst this increase of transmission probability causes an increase in collision probability, as well. Such collisions will cause large delay in packets transmission and energy wastage led by PDR reduction. Thus, in case of less contending nodes(or high SINR regime), the nodes should select a smaller \( CW_{\text{min}} \) as the best strategy. In the case of more contending nodes(or low SINR regime), greater \( CW_{\text{min}} \) is more appropriate in order to reduce the collision probability. The game is implemented in a similar distributed manner to the Link Adaptation Game.

5.1 Game Property

The existence and uniqueness of the Nash equilibrium point for the Adaptive Backoff game is guaranteed. The proof is given as follows.

5.1.1 Existence and uniqueness of the Nash equilibrium.

**Theorem 8.** (Existence and Uniqueness): In each stage of the game \( G_{CW} \) exists a unique Nash Equilibrium.

**Proof.** Similar with the Link Adaptation Game \( G \), the utility function in \( G_{CW} \) is differentiable and strictly concave over the convex set of the minimum contention window size \( CW_{\text{min}} \). Therefore, according to [14], the game \( G_{CW} \) admits a unique Nash Equilibrium. The details can be found in Appendix A.

5.1.2 Efficiency. Similarly with the Link Adaptation Game the social welfare of the Adaptive Backoff Game \( G_{CW} \) is defined as :

\[ \Omega_{CW} = \sum_{i=0}^{n} V_i \]

With finite number of players in game \( G_{CW} \) the PoA is defined as the ration of the highest value of social welfare (global optimization) to the NE (as the Nash Equilibrium in \( G_{CW} \) is unique) of the game:

\[ \text{PoA}_{CW} = \frac{\Omega_{CW}(B^{\text{opt}})}{\Omega_{CW}(B^*)} \geq 1, \]

where \( B^{\text{opt}} = \arg \max \Omega_{CW}(B) \) is the global optimum solution.
6 SIMULATION ANALYSIS

This section discusses the simulation results of our proposed MAC layer games in contrast with conventional schemes as well as game-theory based methods in the literatures. To evaluate and validate the performance of the proposed game, we compare throughput, energy efficiency and delay with B²RIS[12] and Adaptive CSMA/CA [32] in respect of varying numbers of consisting WBANs in our simulations. The value of MAC layer Parameters are listed as below, which is mainly based on the IEEE802.15.6 standard (described in section 2.4). In addition, a non-linear power estimation [6] is also made to measure the actual circuit energy consumptions, to provide a more realistic evaluation of the system.

Table 3. MAC Parameter

| Parameters              | Value      |
|-------------------------|------------|
| Superframe Length       | 80 ms      |
| Allocated Time Slot Length | 0.312 ms  |
| Minimum Data Rate       | 25.6 kbit s$^{-1}$ |
| Maximum Data Rate       | 1.28 Mbits s$^{-1}$ |
| Payload                 | 175 bytes  |
| $N_{MAC}$ Hdr           | 24 bits    |
| $N_{MAC}$ Ftr           | 24 bits    |
| $N_{Beacon}$            | 20 bytes   |
| $N_{ACK}$               | 10 bytes   |
| $CW_{min}$              | 43.75 ms   |
| MaxBackoffLimits (m)    | 4          |

6.1 Scenario 1

In this scenario, a realistic measurement [28] using small body-mounted “channel sounder” radios that operated at 2.36 Ghz is adopted in the simulation. The measurement set contains both inter-WBAN and intra-WBAN channels of the co-existing WBANs, which are measured on human wearers in many different environments, involving subjects doing a mix of distinctive everyday activities. It should also be noted that the measurements are re-sampled by the parameters above, thus the channel attenuations remain constant in each superframe [7].

Figures 8 and 9 show the variation in throughput and delay, respectively, with different numbers of WBAN co-existing. Fig. 8 shows that the throughput is much reduced with more WBANs in the system as the collision probability is increased. In B²IRS, the packets are rescheduled in a collision-free manner, hence no interference occurs. The proposed games provide lower delay and higher throughput compared with other methods. The Adaptive Backoff Game outperforms the Link Adaptation Game in terms of delay and average throughput although the Link Adaptation Game is superior in terms of power consumption and PDR. However, when larger number of WBANs are co-located the advantage of the contention window length game will be more obvious, which is shown in the next section.

6.2 Scenario 2

The measurement set used can only provide channel gain of up to 6 WBANs coexisting, computer-simulated channels are also needed to obtain performance analysis under crowded environment where many more WBANs are co-located.
In the simulation, both intra-BAN and inter-BAN channels are modeled. It is assumed that up to 15 WBANs with the same topology are coexisting and moving randomly within a $6 \times 6 \, m^2$ square area. The walking speed of the WBAN wearer is modeled as $0.5 \pm 0.1 \, m/s$, which is updated every 1 ms. The channel attenuation is modeled as $h_i^j = A_t(d_o/d_i)^{(2.5/2)}A_{SE}A_{SC}$, where the path loss exponent is 2.5. $d_i^j$ represents the distance between BAN $i$ and $j$, and the reference distance $d_o = 5m$ corresponds to a channel attenuation of 50 dB. The shadowing effect $A_{SE}$ is assumed to be 42dB, and a Jakes model with Doppler spread of 1.1 Hz as the $CN(0, 1)$ Rayleigh distributed small scale fading $A_{SC}$ between WBANs. Gamma fading with a mean 65 dB attenuation, a shape parameter of 1.31, and a scale parameter of 0.562 is employed for the on-body channels.
Fig. 10. PDR performance of the proposed games compared to other methods under Realistic Measurement Channel Sets.

Fig. 11. Circuit power consumption of the proposed games compared to other methods under Realistic Measurement Channel Sets.

Basically, for the proposed methods, less than 10% of the packets are blocked. Again, PDR performances of $B^2$IRS and adaptive CSMA/CA are better than others, because of the low collision probabilities in these two methods.

In Figure 13, there is increasing delay with increase in the number of co-located WBANs. Amongst three game-theory-based methods, Social Optimal PHY Game has the highest delay due to large re-transmissions. The Adaptive Backoff Game provides smallest packet delay, and the delay time is increased a small amount at higher interference regime. At the same time, $B^2$IRS has the largest delay due to complexity of beacon re-scheduling when greater number of WBANs are co-existing.

As described in Figure 14, when more than 4 WBANs co-exiting, the Adaptive Backoff Game can provides higher throughput. Both two proposed methods have significantly larger throughput.
respects to other methods, as higher date rate are more preferable in the game at relative better channel conditions.

By applying the non-linear circuit power mapping [6], the circuit power consumptions can be estimated. The proposed Link Adaptation Game method provides the lowest power consumption in terms of Joules per bit (J/bit). The B²IRS consumes 10 times more power per bit transmitted. However, the Adaptive Backoff Game uses slightly larger power than the Link Adaptation Game. This is because, in the Adaptive Backoff Game, when the contention windows size is small, more packets are transmitted concurrently, hence the transmitter uses larger power to achieve reasonable PDR.

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6.3 Efficiency of the Game

Social efficiency is a key measurement for a reliable and efficient game design. We evaluate the Price of Anarchy (PoA) of the two prosed games by implementing a Monte Carlo simulation on time varying channels, where an interior point approach is applied to find the centralized (global) optimum of the social welfare. Although, different WBANs decide their actions in different time slots, we assume the global maximization point is solved instantaneously despite MAC layer scheduling.

Figs. 16 and 17 above illustrate the PoA for different numbers of co-existing WBANs. It can be seen that the loss due to decentralization is relatively small as PoA $\rightarrow 1$. Also, in general, the system waste less than 10% of their welfare in terms of utility for not being coordinated from both
Fig. 16 and Fig. 17. Meanwhile, we introduce a new metrics $L, L_{CW}$:

$$L = \exp\left(\frac{\Omega(A^\kappa)}{\Omega(A^*)}\right),$$

and,

$$L_{CW} = \exp\left(\frac{\Omega_{CW}(B^\kappa)}{\Omega_{CW}(B^*)}\right),$$

where $A^\kappa \in \overline{A}$, $A^\kappa = \arg\min\Omega(A)$, and $B^\kappa \in \overline{B}$, $B^\kappa = \arg\min\Omega_{CW}(B)$. $L, L_{CW}$ correlated with the ratio of the worst value of the social welfare and the maximum value of the social welfare in game $G$ and $G_{CW}$ respectively (we take the exponential as sometime the value of utility function can be negative). These two metrics represent the gap between the system’s best possible performance and the worst case scenario. The comparison between $L, L_{CW}$ and $\exp\left(\frac{1}{\text{PoA}}\right)$ and $\exp\left(\frac{1}{\text{PoA}_{CW}}\right)$ provides some insight of how stable the Nash equilibrium is across iterations of the game. Hence, in Table 4,
Table 4. Comparison of \( \exp\left(\frac{1}{\text{PoA}}\right) \) and the mean value of \( L \)

| No. of WBANs | \( L \)   | \( \exp\left(\frac{1}{\text{PoA}}\right) \) |
|--------------|----------|---------------------------------|
| 2            | 6.832e-32 | 2.718                           |
| 5            | 4.252e-32 | 2.704                           |
| 8            | 2.291e-32 | 2.562                           |
| 11           | 2.728e-32 | 2.549                           |
| 14           | 1.141e-32 | 2.542                           |

Table 5. Comparison of \( \exp\left(\frac{1}{\text{PoA}_{CW}}\right) \) and the mean value of \( L_{CW} \)

| No. of WBANs | \( L_{CW} \) | \( \exp\left(\frac{1}{\text{PoA}_{CW}}\right) \) |
|--------------|--------------|---------------------------------|
| 2            | 2.2445       | 2.7056                           |
| 5            | 2.0317       | 2.7175                           |
| 8            | 1.5793       | 2.7183                           |
| 11           | 1.5746       | 2.7183                           |
| 14           | 1.5864       | 2.7183                           |

we illustrate the comparison between the mean value of \( L \) and \( \exp\left(\frac{1}{\text{PoA}}\right) \) when different number of WBANs are co-located. Meanwhile, the comparison between \( L_{CW} \) and \( \exp\left(\frac{1}{\text{PoA}_{CW}}\right) \) is depicted in Table 5.

Comparing with \( \exp\left(\frac{1}{\text{PoA}}\right) \), \( L \) is much more smaller. It is because the social welfare varies a significant amount over the action space. Thus, in Link Adaptation Game, the system is socially stable as the deviation from the social optimum solution is small. On the other hand, in contention game, the values of \( L_{CW} \) are relatively large. However, it can be seen that, the \( \text{PoA}_{CW} \) is close to 1, which represents complete stability of the game.

7 CONCLUSION

An insightful game theory model has been proposed to adaptively adjust transmit power and data rate to mitigate inter-WBAN interference level while reducing overall energy consumption. The model is based on a novel contention-based MAC layer protocol with special back-off mechanism, which reduces packet collision probability. Besides, another game that can optimize the length of back-off is proposed in order to reduce average delay and increase system throughput. To compare with some alternative state-of-art approaches, we conducted several simulations for both empirical and simulated channels. The simulation results reveal that the proposed methods outperform state-of-art, in terms of energy consumption, and overall quality-of-service (QoS).

Although, both of the proposed methods have \( \text{PoA} \rightarrow 1 \) and are very close to the social optimum, such optimum is not guaranteed at the game’s Nash Equilibrium. If such a guarantee could be provided that would be a further significant advance. Furthermore, as described above, in the MAC layer protocol, the length of back-off period is randomly chosen. However, even without prediction of the global channel state (channel gains), such randomness can provide efficient collision avoidance. But more precise allocation can be made if channel state information can be accurately predicted. Thus, current further work includes channel prediction, potentially improving overall throughput by offering a reduction in packet collision rate. Meanwhile, machine learning, such as reinforcement learning, is also regarded as a further potential improvement.
Appendix A  PROOF OF THEOREM 8
Firstly, the utility function (30) denoted as:
\[ V = d \cdot S - c \cdot D - P_{\text{Drop}} \]  
(35)

It can be seen that the first derivative of the utility function is continuous:
\[
\frac{d \cdot \partial S}{\partial \text{CW}} = \frac{\partial S}{\partial \tau} \frac{\partial \tau}{\partial \text{CW}}
\]
\[
= \frac{\partial \tau}{\partial \text{CW}} \cdot \left( (1 - P) T_{\text{payload}} [T_{\text{slot}} + \tau(T_s - T_{\text{slot}})] - (T_s - T_{\text{slot}}) \tau (1 - P) T_{\text{payload}} \right) \frac{1}{[T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^2}
\]
\[
= -(a \text{CW} + 1)^{-2} \frac{d(1 - P) T_{\text{payload}} T_{\text{slot}}}{[T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^2}
\]

Hence, according to [27], in this contention game, the Nash equilibrium exists.
\[
\frac{d \cdot \partial^2 S}{\partial \text{CW}^2} = \frac{2d(1 - P) T_{\text{payload}} T_{\text{slot}}([T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^2)\tau^2(T_s - T_{\text{slot}})}{[T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^4}
\]
\[
+ 2\tau^3 \frac{d(1 - P) T_{\text{payload}} T_{\text{slot}}}{[T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^2}
\]

Meanwhile, delay is a linear function of the contention window size, thus \( \frac{\partial^2 P_{\text{Drop}}}{\partial \text{CW}^2} = 0 \).

\[
\frac{\partial^2 P_{\text{Drop}}}{\partial \text{CW}^2} = 2\tau^3 P^{m+1},
\]

which should always be positive. Therefore, the second order derivative of the utility function can be obtained as follows:
\[
\frac{\partial^2 u}{\partial \text{CW}^2} = -2\tau^3 P^{m+1} + 2\tau^3 \frac{d(1 - P) T_{\text{payload}} T_{\text{slot}}}{[T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^2}
\]
\[
+ 2d(1 - P) T_{\text{payload}} T_{\text{slot}}([T_{\text{slot}} + \tau(T_s - T_{\text{slot}})]^2)\tau^2(T_s - T_{\text{slot}})
\]

When \( d \) is set in a reasonable range, \( \frac{\partial^2 u}{\partial \text{CW}^2} \) will always be less than zero. Hence, the utility function is concave.

Appendix B  PROOF OF THEOREM 5
In WBAN, for any \( x, y, z \in X, ||x - y|| = 2, ||x - z|| = ||z - y|| = 1 \), we have
\[
F(A_i) = (P, R_x, A_{-i}) = -cP_q x - q \frac{1}{R_x} + \alpha(R_x) \cdot \frac{y^{\beta(R_x)}}{2} + \sum_{j \neq i} -cP_q y - q \frac{1}{R_j} + \alpha(R_j) \cdot \frac{y^{\beta(R_j)}}{2}
\]
\[
= C(P_x) + G(R_x) + H(A_i) + Q(A_{-i}),
\]
(40)

where \( H(A_i) = H((P, R_x)) = \frac{\alpha(R_x) \cdot y^{\beta(R_x)}}{2} \), \( Q(A_{-i}) = \sum_{j \neq i} -cP_q y - q \frac{1}{R_j} + \frac{\alpha(R_j) \cdot y^{\beta(R_j)}}{2} \). Meanwhile, \( F(A_x, A_{-i}) \) and \( F(A_i, A_{-i}) \) are expressed in a similar way.

Obviously, \( G(R) \) is strictly concave, and increase with \( R \). Hence, \( 2G(R_x) > G(R_x) + G(R_y) \). Also, as shown in table 3, \( 0 > 2\alpha(R_x) > \alpha(R_x) + \alpha(R_y) \). When at high PDR regime, where \( \gamma > 0dB \), as
Therefore, the potential function $F$ satisfies Lemma 1.

**Appendix C PROOF OF PROPOSITION 6**

Let $x$ satisfy $F((P, R_x), A_{-i}) \geq F((P, R_y), A_{-i})$ for all $y$ with $|x - y| \leq 1$. For $y$ with $d = |x - y| \geq 2$, we can make a sequence $x_k$ such that $x^0 = x$ and $x^d = y$ with the following steps:

$$x^{k+1} = \arg \max_{|x - z| = 1, |y - z| = d - k - 1} F((P, R_x), A_{-i})$$ (47)

Suppose $|x^k - z| = |x^{k+2} - z| = 1$, then we have $d - k = |x^k - y| = |x^k - z + z - y| \leq |z - y| + 1$. Meanwhile, $|z - y| = |z - x^{k+2} + x^{k+2} - y| \leq |z - x^{k+2}| + |x^{k+2} - y| = d - k - 1$. Therefore, $d - k - 1 = |z - y|$, which gives the following equation:

$$F((P, R_{x^{k+1}}), A_{-i}) = \max_{|x^k - z| = 1, |y - z| = d - k - 1} F((P, R_{x^k}), A_{-i}) \geq \max_{|x^k - z| = 1, |y - z| = d - k - 1} F((P, R_{x^k}), A_{-i})$$ (48)

Since $F$ satisfies LMP as proved above, for $0 \leq k \leq d - 2$:

$$\max_{|x - z| = |y - z| = 1} F((P, R_{x^{k+1}}), A_{-i}) = \begin{cases} F((P, R_{x^k}), A_{-i}) & \text{if } F((P, R_{x^k}), A_{-i}) = F((P, R_{x^{k+2}}), A_{-i}) \\ \min \{F((P, R_{x^k}), A_{-i}), F((P, R_{x^{k+2}}), A_{-i})\} & \text{otherwise} \end{cases}$$ (49)

Since $|x^0 - x^1| = 1, F((P, R_{x^0}), A_{-i}) \geq F((P, R_{x^1}), A_{-i})$. Also, by using the above properties, for all $k$ we have: $F((P, R_{x^k}), A_{-i}) \geq F((P, R_{x^{k+1}}), A_{-i})$. Thus, by induction we can have $F((P, R_x), A_{-i}) = F((P, R_{x^0}), A_{-i}) \geq F((P, R_{x^1}), A_{-i}) \geq \ldots F((P, R_{x^{d-1}}), A_{-i}) \geq F((P, R_{x^d}), A_{-i}) = F((P, R_y), A_{-i})$. 

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