A Repeated Game Approach for Interference Mitigation of Priority-Based Body Area Networks

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***Abstract*—In this paper, we address the issue of interference between Wireless Body Area Networks(WBANs) with different medical emergency levels. The inter-WBAN interference could potentially degrade the Quality of Service (QoS) performance of sensor nodes. Furthermore, such interference leads to a fatal situation when WBANs belong to patients with different emergency condition. A game-theoretic scheme is proposed to tackle the inter-WBAN interference issue and improve the reliability of data for WBANs with different emergency levels. We formulate the interference between WBANs as "infinite repeated game" and model the emergency levels using the heterogeneous discount factors. We propose a "grim" strategy for the repeated game and investigate the conditions in which this strategy holds "Subgame Perfect Equilibrium" property. Finally, we evaluate the performance of our approach using simulation model.**

I. Introduction

Wireless Body Area Networks (WBAN) has emerged as a promising technology for pervasive healthcare systems and remote monitoring applications. A WBAN is comprised of multiple sensor nodes deployed on, in or around the human body and a central coordinator which schedules the data transmission of sensor nodes. Sensor nodes are utilized to monitor the vital signs of the patient such as heart rate, body temperature, etc. The sensor nodes regularly sample the medical data and transmit it to the coordinator via the wireless channel using technologies such as Zigbee and Bluetooth, UWB, etc [1]. Eventually, the central coordinator will send the data to the medical center to be processed by the medical staff. Therefore, doctors and nurses will be able to monitor the health condition of the patients remotely. The WBAN technology is cost efficient has a tremendous potential to significantly improve the quality of healthcare system. As an example, [2] studied the effect of specific treatment on Parkinson disease using a WBAN composed of several accelerometer sensor nodes.

Meeting the potential of WBAN systems requires considering a multitude of technical challenges. Some of these challenges such as limited processing, memory constraints and scarce energy capacity are shared between WBAN and other types of sensor networks. However, the WBANs with medical applications are the source of additional performance issues. The signal "interference" is among the most challenging problems in WBAN design which is due to concurrent data transmission of sensor nodes which are in the vicinity of each other. There exists two types of signal interference in a network of multiple WBANs: (i) *intra*-WBAN and (ii) *inter*-WBAN interference. The intra-WABN interference occurs due to concurrent data transmission of sensor nodes belonging to a single WBAN. Such interference has been studied extensively and could be resolved by the proper resource allocation schemes such as TDMA scheduling and optimal power allocation [3], [4]. The inter-WBAN interference is related to the interference between two or more WBANs which are in the vicinity of each other in a crowded area such as hospital. In a crowded environment, the simultaneous data transmission of multiple independent WBANs leads to a severe packet loss. Simulation results in [5] shows that inter-WBAN interference is a serious phenomenon and could cause a real threat to the overall performance of a netwrok of multiple WBANs. Particularly, such interference might result in catastrophic consequences when each WBAN is assigned a different priority level. The heterogeneous priorities may result from several factors such as signal quality, battery lifetime, packet loss and etc. In the medical applications, different priorities are mainly due to the health condition of the patients. Clearly, sensor nodes of a patient in trauma condition are required to transmit their data with relatively higher probability in contrast with others in normal condition. The existence of inter-WBAN interference would make the priority-based resource allocation a challenging task. One solution to this problem is to find a scheduling mechanism which ensures that the WBAN with critical situation transmits its data earlier. However, the WBANs are usually independent of each other and are not guaranteed to adhere to such scheduling discipline. Therefore, we need a mechanism to mitigate the inter-WBAN interference in an area of multiple autonomous WBANs with different emergency situations.

In this paper, we study the problem of inter-WBAN interference in the context of Game Theory. Game theory is a mathematical tool to study the interaction between multiple selfish and autonomous agents in a competitive environment. We consider each WBAN as a rational agent with its individual goal to optimally schedule its sensor nodes. We model the interaction between multiple WBANs in a crowded environment as an "infinitely repeated game". Specifically, the model considers two WBANs as selfish rational players which compete with each other to access the wireless channel for relatively long period. We assume the WBANs have different priority levels pertaining to emergency health condition of the

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patients. We make the following contributions in this paper:

- We formulate the inter-WBAN interference game as an infinite repeated game where priority is modeled by heterogeneous discount factors.
- We propose a game-theoretic distributed strategy and investigate the "Subgame Perfect Equilibria" solutions.
- We conduct several simulations to characterize the efficiency of the proposed solution. We conclude that by deploying the proposed game-theoretic approach the packet loss and energy consumption will sharply decrease.

II. System Model

In this section, we present the system model and give a detail description of our game-theoretic formulation for inter-WBAN interference.

A. Network Model

We consider a crowded area composed of two co-existing WBANs each belong to a single patient. Each WBAN consists of multiple sensor nodes and a single entity called "coordinator". Sensor nodes are deployed on, in or around the patient body and collect the vital signs and send it to the coordinator. The job of coordinator is to schedule the data transmission of sensor nodes. We assume that each sensor node operates based on the IEEE 802.15.4 standard designed for low power wireless technologies. We consider the *beacon-enabled mode* mode of 802.15.4 standard in this paper. In this mode, system time is divided into several fixed-length time slots called *superframe* which are separated by beacon messages. The coordinator initiates the superframe with a "beacon" message by broadcasting it to all sensor nodes The beacon message provides synchronization and specifies the data transmission plan for the next superframe. Each superframe is composed of two periods: *active* and *inactive*. Sensor nodes will transmit their data during the active period according to the received beacon message guideline. Then, they go to sleep during the inactive period to save the battery life. Fig. 1 shows the superframe structure in a WBAN with becaon-enabled mode:

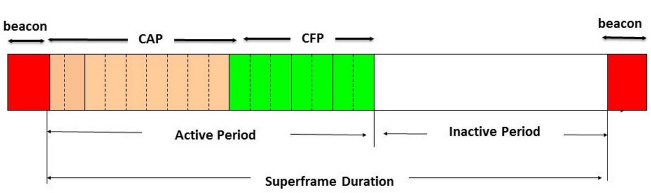

Fig. 1. Superframe Structure

Duration of active and inactive intervals in a superframe has been defined in the standards and could vary according to the application requirements. Based on the IEEE 802.15.4 standard definition, the active period of a superframe denoted by T_{sd} is:

$$T_{sd} = 960 \cdot 2^{SO} \cdot t_s, \quad 0 \leq SO \leq BO \tag{1}$$

Here, SO stands for *Superframe Order* and denotes the number of data packets that can be transmitted during active period of a single superframe. Parameter t_s is called "symbol time" which is usually equal to 16μs. Also, in time of packet collision IEEE 802.15.4 standard requires the sensor node to back off and wait for a random period of time. This is to ensure that the channel is clear of the collision and no other node is in transmission. The standard defines the back-off period denoted by T_c as:

$$T_c = \left[20 * (2^{BE} - 1) + 8\right] \cdot t_s \quad 0 \leq BE \leq 5, \tag{2}$$

Here BE stands for *Back-off Exponent* and denotes the number of random backoffs due to consecutive collisions(refer to [6] for more details).

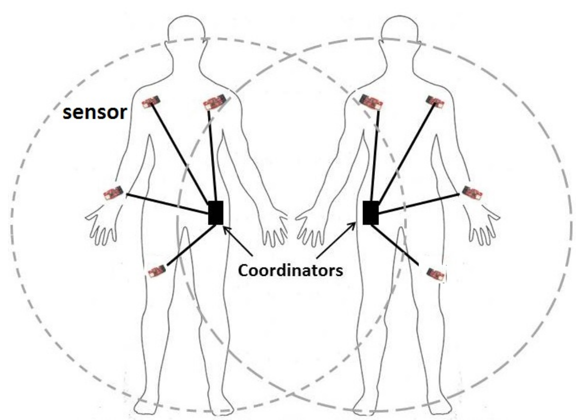

Fig. 2. WBAN interference

We assume that there exists an interference between two WBANs whenever at least one sensor is in the transmission range of the other WBAN. We assume that at anytime at most two WBANs will have signal interfere with each other. This assumption is valid since most of the WBAN standards define a 3m communication range. Fig. 2 shows an example of inter-WBAN interference among two WBANs.

B. Game Theoretic Model of WBAN Interference

In this section, we formulate the inter-WBAN interference as an infinitely repeated game in the context of game theory. First, let us give a brief definition of infinitely repeated game.

Infinitely Repeated Game: "Infinitely Repeated game" is an extensive form of game consists of infinite repetitions of some base game called "stage game". The player strategy in a repeated game specifies as a series of actions selected at different repetitions of the game. Players receive their payoffs stage-by-stage and their objective is to select the optimal strategy which maximizes the sum of payoffs across all stages. According to literature [7], the overall payoff of the player i in an infinitely repeated game is given as:

$$U_i = (1 - \delta_i) \sum_{k=0}^{k=\infty} (\delta_i)^k R_i[k] \tag{3}$$

where $0 < \delta_i < 1$ is the discount factor of player i and $R_i[k]$ denotes the player i payoff at the repetition(stage) k of the game. The discount factors could be interpreted as an expression of time preference of the player i across the time(for complete discussion refer to [7]).

Inter-WBAN interference Game: We formulate the interference between WBANs with different emergency levels using the infinitely repeated game. In particular, we utilize the heterogeneous discount factors to model the emergency priority of different WBANs. Consider an infinitely repeated game between two WBANs P and I which are in the proximity of each other. Assume WBAN P and I have discount factors δ_P and δ_I representing different patients' emergency level. The game involves infinite repetitions of a single stage game played at the beginning of each superframe. At each stage game, the WBAN players compete with each other to occupy the following superframe. Next, we describe the stage game strategies and payoffs.

Stage Game: The stage game is an interaction between two autonomous WBAN players at the beginning of each superframe. Each WBAN player selects her action from a set of two actions {S, NS}. The "S" action indicates that the coordinator will '(S)chedule' its sensor nodes to transmit data in the following sueprframe. Meanwhile, the "NS" action means the coordinator will '(N)ot (S)chedule' the sensor nodes and they could sleep in the next superframe to save the energy. If the players choose (S,NS) or (NS,S) profile, the one who selects "S" action will occupy the next superframe. Meanwhile, the other player who plays "NS" action will remain inactive and go to sleep to save energy. In the case that both players select the "S" action *i.e.* (S,S), the signal interference will occur. Then, both nodes is required to wait for a back-off period until the channel is clear. Finally, for the action profile (NS,NS) both players remain inactive and do not schedule their sensor nodes. The proposed stage game is a famoud classic game in the literature known as "Prisoners' Dilemma". Each action profile is associated with a separate payoff. Payoffs at each stage are represented by the relative allocated superframe time. In case of (S,NS) or (NS,S) the WBAN player that 'wins' the next superframe will receive a payoff equal to the superframe duration. Meanwhile, the other player will receive the same value with negative sign showing the relative time loss. In case of (S,S) profile the packet collision happens and WBAN layers are required to wait for a period of time. Finally, in case of (NS,NS) none of players have schedule any transmission and their payoff becomes zero with respect to each other.

One way to envisage an infinitely repeated game is to shorten the time between two consecutive stages. Therefore, we consider the minimum value of superframe denoted by T_{sd}^{min} as superframe duration payoff in our model. Using the equation (1), we have $T_{sd}^{min} = \min_{SO} T_{sd}$. Also, in the time of consecutive collisions which occurs during the signal interference, the value of BE in the formula (2) reaches its maximum. Therefore, the players' payoff in the action profile (S,S) becomes *i.e.* $T_c^{max} = \min_{BO} T_c$. Each WBAN player receives a $-T_c^{max}$ as the payoff during the collision. By replacing the desirable value of $SO = 0$ and $BE = 5$ in the equation (1) and (2) we have:

$$T_{sd}^{min} = 960t_s \quad , \quad T_c^{max} = 628t_s$$

To simplify the notation we define $\lambda = \frac{T_c^{max}}{T_{sd}^{min}}$. Then, the stage game payoff could be represented by the payoff matrix shown in Fig. 3.

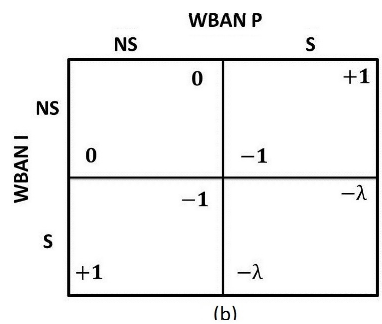

Fig. 3. interference matrix

The matrix in Fig. 3 is achieved after dividing the payoffs in the original payoff matrix by the value of T_{sd}^{min}.

Heterogeneous Discount Factors: In the our model, we define the discount factor as a subjective probability of WBAN player continues to be alive on the next superframe(stage game). Therefore, the player with relatively smaller discount factor has less chance of staying alive in the next stage game. Assume that the WBAN player I has higher emergency priority relative to the WBAN player P. Then we have *i.e.* $0 < \delta_I < \delta_P < 1$ In other words, the WBAN player with higher emergency level will be assigned a relative smaller discount factor. To best of our knowledge, this is the first work which uses the concept of heterogeneous discount factors to represent the emergency levels in sensor networks.

Now, the question may arise: *what is the optimum strategy given the above formulated game?* We seek an answer to this question by finding a suitable strategy which leads to mutual benefit for both WBAN players in the next section.

III. Existence of Equilibria

In a single stage game, game theory defines the equilibrium as an action profile where no player has incentive to unilaterally change her action. In the context of repeated games, the equilibrium point extends to new concept called "Sub-game Perfect Equilibrium(SPE)". A strategy holds the SPE property if it represents an equilibrium at any stage game of the repeated game. Folk theorem[8] assists us in finding the SPE points for an infinitely repeated game of *identical* discount factors. Nevertheless, Lehrer *et al.* in his seminal paper [9] showed that the Folk theorem does not extend to the case when players have heterogeneous discount factors. It is because, for such games players can benefit from inter-temporal "trade". That is, a relatively impatient player (*i.e.* a player with smaller discount factor) cares more about the rewards in present while the patient player cares more about the rewards received in the future comparatively. Thus, the patient player finds it rational to play the action profile that gives larger rewards to an impatient player in the time periods close to the present; in exchange, the impatient player promises to play action profiles that yield the patient player larger rewards in future. We utilize the "inter-temporal" trade property to propose a SPE strategy for inter-WBAN interference game. We denote this strategy by σ and describe it below:

Strategy σ: We divide the system time into two distinct phases. During the first phase, players agree to play a pair of actions which benefits the impatient WBAN player I for a period of K superframe. Then, after K superframe the players switch to the second phase where they play a set of actions which is beneficial to WBAN P. In the second phase, WBAN P switches between "NS" and "S" action by assigning the arbitrary probabilities $\frac{1}{2} - e$ and $\frac{1}{2} + e$ respectively, where $0 < e < \frac{1}{2}$. Meanwhile, the WBAN I remains inactive by taking the "NS" action. We defer the derivation of the value of e and K later in this section. Any deviation from this strategy will be punished by the opponent via permanent shift to the "S" action for the rest of the game. Therefore, according to the payoff matrix the result of deviation leads to the payoff $(-\lambda, -\lambda)$ for both players in the rest of the game.

This strategy is known as "grim" strategy in the context of repeated games. Note that, it is necessary for the parameter e to be strictly less than $\frac{1}{2}$. Otherwise, player I finds it beneficial to switch to "S" in the second phase, since he/she achieves a payoff of -1 which is less than its minmax value($-\lambda$). Next theorem shows that this strategy is feasible by deriving specific regime under which the strategy σ holds the SPE property.

Theorem 1. *The strategy σ is a SPE strategy for the WBAN interference game given the following conditions:*

(i) $\delta_I > \dfrac{1-\lambda(e+\frac{1}{2})}{(1+\lambda).(\frac{1}{2}-e)}$

(ii) $(\delta_P)^K > \dfrac{1-\lambda}{\frac{3}{2}+e}$

(iii) $\delta_P > \dfrac{\frac{1}{2}-e}{1+\lambda}$

Proof. In order to prove the existence of SPE property, we must give a set of conditions in which players do not benefit from a single deviation at any stage at first or second phase. Player I does not benefit from any deviation in the first phase since it receives the maximum payoff. WBAN I does have incentive to deviate in the second phase if

$$(1-\delta_I)\left[(\frac{1}{2}-e)+(\frac{1}{2}+e)(-\lambda)+\sum_{k=1}^{\infty}(\delta_I)^k.(-\lambda)\right] < (1-\delta_I)\left[\sum_{k=0}^{\infty}(\delta_I)^k\left[(\frac{1}{2}-e).0+(\frac{1}{2}+e).(-1)\right]\right] \quad (4)$$

which after simple algebra [1]: reduces to the condition (i). Similarly, the inequalities (5) and (6) show the necessary conditions that player P will not deviate in the first and second phase respectively:

$$(1-\delta_P)\left[-\lambda+\sum_{k=1}^{\infty}(\delta_P)^k.(-\lambda)\right] < (1-(\delta_P)^K).(-1)+(\delta_P)^K\left[(\frac{1}{2}-e).0+(\frac{1}{2}+e).(1)\right] \quad (5)$$

$$(1-\delta_P)\left[1+\sum_{k=1}^{\infty}(\delta_P)^k.(-\lambda)\right] < (\frac{1}{2}+e).(1) \quad (6)$$

which reduce to the condition (ii) and (iii). Therefore, if condition (i),(ii) and (iii) hold together, no player is eager to deviate from the strategy σ at any stage and SPE property exists. □

Thus, the proposed σ strategy establishes an infinite repeated game only if three conditions in the Theorem 1 always hold. The satisfaction of these inequities strictly depends on the value of parameters K and e which are determined primarily by WBAN I and P respectively. Next, we investigate the optimal value for these parameters.

Optimum value of K: The parameter K specifies the superframe number in which players switch to the second phase. The maximum of K is a desirable value for player I. Player I could maximize K only to the point that prevents player P from deviation at the first phase. A simple algebra on the inequality (ii) of Theorem 1 gives the following upper bound for the value of K:

$$K \leq \frac{\log\frac{1-\lambda}{e+\frac{3}{2}}}{\log\delta_P} \quad (7)$$

This upper bond is the desirable K value for the player I. We use this value to calculate the number of superframes dedicated to the WBAN player I in our implementation in the section IV.

Optimum value of e**:** Recall that player P was responsible to determine the probability of data transmission in the second phase. Player P seeks to maximize its payoff in the second phase. Therefore, P will maximize the scheduling probability in the second phase to the point that prevents the player I from deviation. The inequality (i) of the theorem 1 gives a proper upper bound on the value of e. Using simple algebra, we have:

$$e \leq \frac{2\delta_I-1}{\delta_I-\frac{\lambda}{\lambda+1}}-\frac{3}{2} \quad (8)$$

Therefore, player P chooses the above upper bound as the optimum value of the parameter e. Also notice that, the both inequalities (i) and (ii) in 1 also give lower bounds on the

[1]The formula for computing the infinite sums is $\sum_{t=T_1}^{T_2}\delta^t = \frac{\delta^{T_1}-\delta^{T_2+1}}{1-\delta}$ which, in particular, is valid for $T2=\infty$ when δ is close to 1. See the [7] for a derivation of this formula.

TABLE I
WBAN SENSOR NODES SPECIFICATION

Parameters	Value
Number of WBANs	2
Number of sensor types	5 (rates: 0.12, 5, 35,43,72 Kbps)
Transmission power	-15dB
MAC Protocol	IEEE 802.15.4 standard
Wireless interference model	Measurement-based

value of e. However, these bound are always lower than the the one derived in inequality (8).

IV. Performance Evaluation

In this section, we conduct several simulations to study the equilibria properties of the WBAN interference game.

Setup: We simulated a network composed of two interfering WBANs using Castalia[10] simulator. Castalia is a network simulator generally designed for a network of low-power embedded devices such as WBAN. In our simulation, each WBAN is composed of five sensor nodes and a single WBAN coordinator as shown in Fig. 2. The sensor nodes from 1 to 5 belong to WBAN I while sensor nodes 6 to 10 belong to WBAN P. Table I shows the type and configuration parameters of sensor nodes used in our simulation. Each network in our simulation is implemented based on the IEEE 802.15.4 MAC standard which has been released specifically for Wireless Body Area Networks. All sensor nodes adopt Castalia WBAN radio standard. We compare the proposed scheduling technique to the original scheduling model used in the IEEE 802.15.4 model.

Interference Modeling: In order to implement a realistic scenario, we need to consider the interference both within a single WBAN as well as across different WBANs. Castalia provides an interference model within a single WBAN base on real measurement-based data. For intra-WBN interference, we use a pathloss map that Castalia provides for body sensor networks. For inter-WBAN interference, we considered the path loss in the free space which is around 40dB according to [11]. Thus, the large scale fading model(across WBANs) is simulated by adding a 40 dB offset to the mean path loss. Another important aspect of the wireless channel is the temporal variation due to rapid changes in environments. To make our simulation more realistic we utilize the Castalia implementation of temporal variation.

Number of interference: Fig. 5 shows the number of received packets failed due to the interference. Note that, since in 802.15.4 standard there are 12 senor nodes in the interference range of each other, the number of packet breakdown will increase sharply with respect to the time. However, in the proposed solution each WBANs is allocated a separate phase to send data regardless of the neighbor interference.

Energy Consumption: Next, we study the energy consumed by the sensor nodes. In our proposed scheduling, only a single WBAN is allowed to schedule the sensor nodes during each phase of an infinite repeated game. Therefore, the WBAN coordinator with inactive state orders its sensor nodes to set their radio to sleep mode during the inactive period and save the battery lifetime. However, in the original scheme sensor needs to be active all the time. Fig. shows the proposed algorithm has dramatically decreased the energy consumption of the sensor nodes. Note that, the coordinator nodes (#0 and #6) always remain active for the purpose of inter-WBAN communications.

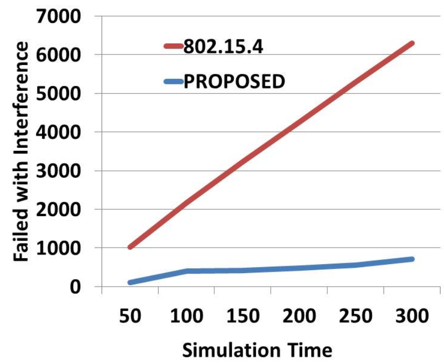

Fig. 4. Number of packets failed due to interference

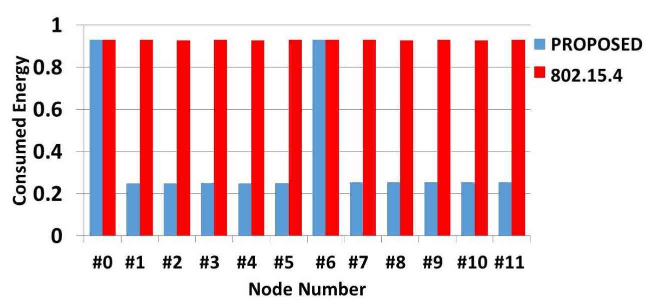

Fig. 5. Node Energy Consumption

V. Conclusion

This paper studies the inter-WBA interference in a network of two WBANs with different emergency levels. We model the interference between two WBANs as an infinitely repeated game with heterogeneous discount factors. A game-theoretic solution is proposed to prevent the occurrence of the signal interference. We propose a ”grim” strategy for the formulated game and show that it has Sub Game perfect Equilibrium(SPE) property under a specific regime. Finally, we test the proposed approach by simulating the model using a WBAN-specific simulator and compare it with IEEE 802.15.4 standards. The results show that our algorithm could decrease the packet loss due to interference as well as saving battery life time.

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