A Regret Matching Strategy Framework for Inter-BAN Interference Mitigation

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Abstract—**A Body Area Network (BAN) is a radio standard for wireless connectivity of wearable and implantable sensors located inside or in close proximity to the human body. Medical and some other applications impose stringent constraints on battery powered BAN reliability, quality of service, and power consumption. However, lack of coordination among multiple co-located BANs in the current BAN standard may cause unacceptable deterioration of BAN reliability and quality of service due to high levels of inter-BAN interference. Assuming Time Division Multiple Access (TDMA), this paper proposes inter-BAN interference mitigation with regret matching based transmission scheduling algorithm. This scheduling algorithm uses pattern of past interference for implicit coordination between different BAN transmissions. Simulation results demonstrate potential benefits of the proposed scheduling algorithm for inter-BAN interference mitigation.**

Keywords- body area network, interference mitigation, regret matching scheduling

I. INTRODUCTION

Body Area Networks (BANs) consist of multiple wearable or implantable sensors that can establish two-way wireless communication with a controller node that could be either worn or located in the vicinity of the body [1]. Assuming Time Division Multiple Access (TDMA) protocol, transmissions between the controller and body sensors can be perfectly coordinated within each BAN. However, currently there are no mechanisms for transmission coordination across multiple adjacent BANs. This could lead to excessive interference when several BANs are operating in close proximity to each other. This inter-BAN interference may result in unacceptably low performance for some BAN applications such as physiological signal monitoring [2, 3].

Assuming a TDMA-based intra-BAN communication, this paper investigates the impact of regret matching transmission scheduling algorithms on inter-BAN interference. This scheduling strategy uses pattern of past interference for implicit coordination between transmissions by different BANs. Regret matching has been proposed in [4] as a learning algorithm converging to a correlated equilibrium in the corresponding non-cooperative game; and later has been shown in [5]-[6] to be effective for interference mitigation in wireless communication. BANs offer a specific set of communication challenges, including power limitations, stringent reliability requirements, and highly variable wireless channel. We view each BAN as a strategic agent attempting to minimize its individual cost, which is a measure of the interference experienced during a frame, by choosing time slots for transmission. A correlated equilibrium (in which different BANs coordinate their transmissions) could result in a lower level of interference than a Nash equilibrium, which assumes un-coordinated transmissions. In this study, we address high wireless channel variability by considering "first order regret matching scheduling algorithms," which assume that each BAN chooses its transmission scheduling for the upcoming frame only on the basis of the interference experienced during the last frame.

The paper is organized as follows. Section II describes the system model. Section III introduces class of regret matching scheduling algorithms, and defines specific algorithms that have been simulated. Section IV describes the simulation setup. Section V describes and discusses some preliminary simulation results. Finally, Section VI briefly summarizes our results and outlines plans for future research.

II. SYSTEM MODEL

Consider a system of N BANs, where each BAN has a star topology connecting the controller with several sensor nodes. Assuming that each BAN $n=1,..,N$ is using a TDMA protocol for intra-BAN communication, where each frame comprised of L time slots, the success probability of receiving transmitted data at node d of BAN n in a slot l of frame m depends on the corresponding Signal to Noise and Interference Ratio

$$SNIR_{nd}^{lm} = p_{nd}^{lm} \big/ (\sigma_{nd}^2 + I_{nd}^{lm}), \qquad (1)$$

where p_{nd}^{lm}, σ_{nd}^2, and I_{nd}^{lm} are the corresponding received power, the power of the exogenous noise, and inter-BAN interference power respectively. Reliable BAN operation requires elimination or at least sufficient reduction of the inter-BAN interference I_{nd}^{lm}. Here we propose achieving this by a regret matching scheduling strategy, which does not require explicit coordination between different BANs. We make a number of simplifying assumptions, some of which can be relaxed at a later stage, e.g., we assume that throughout the observed history the powers of exogenous noise σ_{nd}^2 are fixed.

Introduce transmission indicators $\delta_{n\to d}^{lm} = 0,1$ and

$\delta^{lm}_{n\leftarrow d}=0,1$ where $\delta^{lm}_{n\to d}=1$ if the BAN n controller transmits to a sensor node d (of the same BAN) during slot l of frame m, and $\delta^{lm}_{n\to d}=0$ otherwise. Indicator $\delta^{lm}_{n\leftarrow d}=1$ if a sensor node d of BAN n transmits to the controller node (of the same BAN) during slot l of frame m, and $\delta^{lm}_{n\leftarrow d}=0$ otherwise. Note that since transmissions within each BAN are perfectly coordinated $\sum_d(\delta^{lm}_{n\to d}+\delta^{lm}_{n\leftarrow d})=0,1$. The interference at a node d of BAN n during slot l of frame m is

$$I^{lm}_{nd}=\sum_{k\neq n}\sum_{i\neq 0}(p_{k\to i}\delta^{lm}_{k\to i}\xi^{k0}_{nd}+p_{k\leftarrow i}\delta^{lm}_{k\leftarrow i}\xi^{ki}_{nd}) \qquad (2)$$

where $p_{k\to i}$ is the transmission power from the BAN k controller to its sensor i, $p_{k\leftarrow i}$ is the transmission power from BAN k sensor i to the controller, ξ^{kj}_{nd} is channel gain from a node j of BAN k to node d of BAN n, and node $j=0$ corresponds to the controller of the corresponding BAN.

We assume that in the beginning of each frame $m=1,2,..$ each BAN $n=1,..,N$ selects its transmission schedule during frame m, $s^m_n=(\delta^{lm}_{n\to d},\delta^{lm}_{n\leftarrow d})$. Note that the frames corresponding to different BANs are not necessarily aligned in time. Due to high communication reliability requirements for medical applications, we characterize BAN n overall communication performance during frame m by the maximum, i.e., the worst case scenario, interference experienced by receivers of BAN n during this frame:

$$\tilde{I}^m_n(s^m_n)=\max_{l=1,..,L}\max_d[(\delta^{lm}_{n\to d}+\delta^{lm}_{n\leftarrow d})I^{lm}_{nd}]. \qquad (3)$$

Assuming that the overall system performance during frame m can be naturally characterized by the total aggregate interference $\tilde{I}^m(s^m)=\sum_n\tilde{I}^m_n(s^m_n)$, the optimal transmission scheduling s^m_{opt} minimizes the total aggregate interference i.e. $s^m_{opt}=\arg\min_{s^m}\tilde{I}^m(s^m)$ where $s^m=(s^m_n,n=1,..,N)$.

This paper suggests that adaptive scheduling based on the observed history of interference can be equivalent to a form of implicit coordination among the BANs. Our efforts are motivated by significant potential performance advantages of coordinated wireless transmission [5, 6]. In fact, in this particular case when the total number of transmission slots by all interfering BANs within the same frame does not exceed the number of slots in the frame L, inter-BAN coordination creates the possibility for complete inter-BAN interference elimination. In a typical case when total number of slots by all interfering BANs within the same frame exceeds the number of slots in the frame L, inter-BAN coordination allows for inter-BAN interference reduction by judiciously spreading intra-BAN transmissions over the entire frame.

III. REGRET MATCHING SCHEDULING

To account for lack of explicit inter-BAN coordination, we model transmission scheduling in BANs as a non-cooperative game, where each BAN is a strategic agent attempting to minimize its aggregate interference by choosing transmission scheduling $s^m_n=(\delta^{lm}_{n\to d},\delta^{lm}_{n\leftarrow d})$. This game-theoretic view allows for leveraging a vast body of results on learning algorithms in games for interference mitigation in BANs without explicit inter-BAN coordination. We assume that in the beginning of each frame $m=1,2,..$ each BAN $n=1,..,N$ selects its transmission scheduling for this frame $s^m_n=(\delta^{lm}_{n\to d},\delta^{lm}_{n\leftarrow d})$ in attempt to minimize the aggregate interference experienced during this frame (3). The rest of this Section describes transmission scheduling algorithm, which creates implicit inter-BAN coordination based on observed interference history during the last $M\geq 1$ frames. Parameter M selection depends on the variability of the exogenous conditions, e.g., mobility, exogenous interference and wireless channel variability, etc. Parameter M could be comparatively large if the exogenous conditions are “stable”, and should be comparatively small otherwise. Selection of parameter M, which controls the trade-off between optimality and adaptability, should be a research issue based on further investigation. The following regret matching scheduling algorithm has advantages of successful application to wireless communication [5, 6] as well as asymptotic convergence to a correlated equilibrium in the corresponding game as $m,M\to\infty$ [5]. In the beginning of each frame $m=M+1,M+2,..$ the algorithm evaluates BAN n regret

$$R^M(S^m_n,s_n)=\max\left\{\frac{1}{M}\sum_{j=m-M}^{m}[\tilde{I}^j_n(s^j_n)-\tilde{I}^j_n(s_n),0]\right\}, \qquad (4)$$

where $S^m_n=(s^j_n:j=m-M,m-M+1,..,m)$ is the actual scheduling used by BAN n during the last M frames, s_n is some feasible scheduling in BAN n during one frame, and aggregated interference during one frame $\tilde{I}^j_n(s^j_n)$ and $\tilde{I}^j_n(s_n)$ are given by (3).

Regret (4) quantifies the potential reduction in the aggregate interference experienced by BAN n if this BAN adopted some scheduling s_n instead of actual used schedules during last M frames. The regret matching algorithm adjusts BAN n scheduling s^m_n for upcoming frames starting with some initial scheduling s^1_n based on regret (4). Assuming that at frames $j=1,..,m$, BAN n used scheduling s^j_n, at the frame $m+1$, BAN n shifts to scheduling $s^{m+1}_n\neq s^m_n$ with probability

$$p^{m+1}_n(S^m_n,s^{m+1}_n)=\varepsilon R^M(S^m_n,s^{m+1}_n) \qquad (5)$$

and uses the old scheduling $s_{nm}=s_n$ with probability

$$p_n^{m+1}(S_n^m, s_n^m) = 1 - \varepsilon \sum_{s_n'^{m+1} \neq s_n^m} R^M(S_n^m, s_n^{m+1}), \qquad (6)$$

where ε is a sufficiently small positive number to ensure that all probabilities are positive and less than one.

Intuitive reasoning in the beginning of this Section suggests that a correlated equilibrium results in lower inter-BAN interference than Nash equilibria. In the rest of this paper we verify this assertion for several interfering BANs through simulations. Note that parameters ε and M control optimality/adaptability tradeoff, and their selection should be based on further investigation. Here we consider an implementation of the regret matching strategy where each BAN chooses its transmission scheduling for the upcoming frame on the basis of the experienced interference during the last M frames. An important assumption here is that each BAN node can monitor and measure the interference at each time slot and somehow report it to the controller node that is in charge of the transmission slot assignment for the whole BAN. The implementation and complexity associated with this assumption has not been considered for now, as our intention is first to evaluate the possible gain or benefit in using such algorithms. The scheduling strategy, hereafter referred to as "Minimum Interference Assignment" (MIA), is shown in Figure 1. For each BAN and in the beginning of each frame, MIA assigns frame scheduling by looking at the interference experienced during the previous M frames.

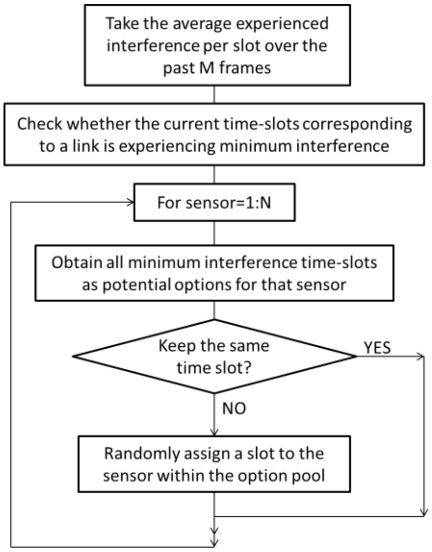

Figure 1. Minimum Interference Assignment (MIA) scheduling strategy

IV. SIMULATION SETUP

To emulate inter-BAN interference, we used the platform discussed in [10]. Each BAN includes a coordinator along with a variable number of sensor nodes. Graphically, this is shown in Figure 2, where circles represent BANs. The green square in each BAN indicates the controller node and small red circles denote body sensors. Each BAN in this system is capable of moving in a given direction and with a definable speed. This is meant to imitate several people (wearing BAN) walking randomly (or with a desired pattern) inside a room.

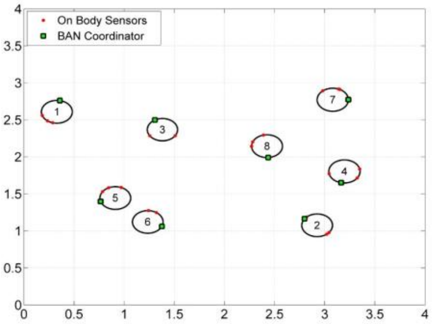

Figure 2. Sample multi-BAN scenario in a 4 m x 4 m rectangular room

An essential component of the above simulation platform is the channel model across various nodes of the BANs. Several statistical channel models that represent on-body and BAN-to-BAN propagations have been used to create channel realizations that are needed to evaluate inter-BAN interference [7, 8]. These statistical channels models have been obtained using measurements at 2.4 GHz. The recently announced MBAN spectrum by FCC [9] uses a frequency band that is very close to 2.4 GHz and it is intended for on-body sensors within hospitals or other indoor environments. Therefore, we have selected this frequency as the first candidate to study possible inter-BAN interference issues. Further details about this platform can be found in [10].

V. SIMULATION RESULTS

To demonstrate the effectiveness of our slot assignment strategies, we have created a scenario where average interference is expected to rise for all nodes in the system. In this way, we can observe whether the proposed assignment strategy can improve the communication link reliability or equivalently decrease possible outages due to interference in a consistent manner. Figure 3 shows a scenario with eight BANs forming a circle and moving toward the circle center. As BANs gets physically closer, the amount of interference will increase and this in turn will affect the quality of the communication link at each BAN. Figure 4 plots the system outage probability, i.e., probability that the experienced SIR does not exceed a given threshold, for the circle scenario shown in Figure 3 and different parameters M representing the number of past frames used for the algorithm adaptation.

The outage probability is evaluated as Cumulative Distribution Function (CDF) of the experienced SIR as different BANs relocate according to the circle scenario. Figure 4 demonstrates that compared to a Static slot allocation, the MIA algorithm significantly reduces the outage probability by intelligently distributing and re-allocating simultaneous and interfering transmissions in non- or less-interfering time slots. Taking into account longer history of interference (measured by the number of past M frames) results in better performance. However, as it appears, if the minimum required SINR is below 2-3 dB, then considering longer history of interference profile does not lead to significant gain in outage probability.

The “optimal” parameter M depends on the coherence time of the inter-body channel. Unfortunately, currently sufficient information about the BAN-to-BAN wireless channels is not available. In our simulations, a coherence time of 110 msec which is roughly around 5 frame lengths have been considered. Also, in Figure 4, we have assumed correlated channels among various body-to-body links, corresponding to the multiple sensor locations on adjacent bodies.

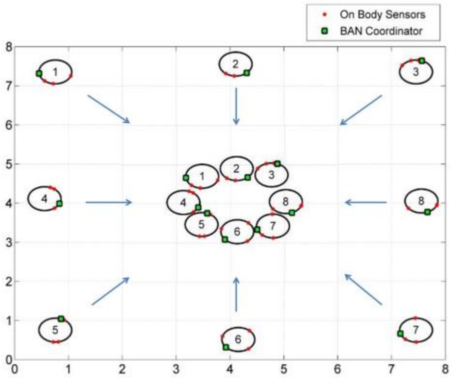

Figure 3. Sample multi-BAN scenario in an 8 m x 8 m room

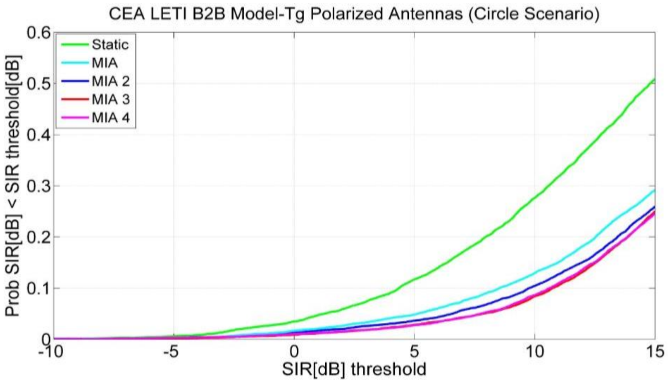

Figure 4. CDF of the experienced SIR (correlated channels)

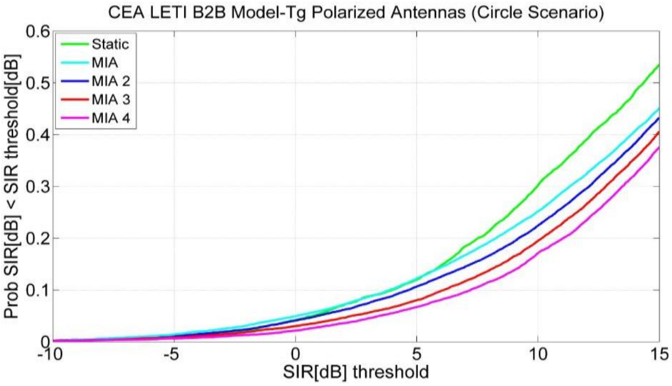

Figure 5. CDF of the experienced SIR (uncorrelated channels)

Figure 5 shows the performance of our algorithm using uncorrelated channels. As observed there is still a considerable gain compared to a static assignment. Furthermore, using higher values of M (i.e. longer interference history) could lead to more tangible gain in the outage probability in this case. For the above results, a frame size of 20 slots has been assumed. Each BAN carries 3 sensor nodes in addition to the controller. Also, it is assumed that each link in a BAN has one packet transmission during each time frame.

VI. CONCLUSION AND FUTURE RESEARCH

This paper is proposing a regret matching strategy framework to design scheduling algorithms that can mitigate inter-BAN interference without explicit inter-BAN coordination. These simulation results suggest that this adaptive scheduling may result in significant inter-BAN interference reduction in body area networks. We have used a simulation platform, which was developed for modeling inter-BAN interference and evaluation of the performance of possible mitigation strategies. Several dynamic channel models have been included in the current version of the platform; however, as more accurate models become available, they can be easily adopted by the platform and results can be re-evaluated. Our scheduling algorithm implementation achieves interference mitigation by taking advantage of the history of interference experienced by each BAN. In this preliminary study we have analyzed the performance of the scheduling strategy, when one or more frames are included in the slot assignment decision for the upcoming frame. Future research should explore performance of more sophisticated adaptive scheduling strategies, which take advantage of minimum required Signal to Noise and Interference ratio.

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