Regret Minimization Based Adaptation of the Energy Detection Threshold in Body Area Networks

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***Abstract*— IEEE802.15.6 is a radio interface standard for wireless connectivity of wearable and implantable sensors and actuators located inside or in close proximity to the human body i.e., Body Area Network (BAN). Medical applications impose stringent requirements on BAN Quality of Service (QoS), including reliability and on-time availability of the sensors data. However, interference from other co-located BANs or other nearby devices sharing the same spectrum may cause unacceptable QoS degradation. The impact of such degradations can be minimized by using adaptive schemes that intelligently adjust relevant parameters at the transmitting or receiving nodes of a BAN . This paper provides a framework for low complexity regret minimization based algorithms for Energy Detection Threshold (EDT) adaptation in the transmitter node of a BAN. The nodes are assumed to be using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol according to the IEEE 802.15.6 BAN standard. Our preliminary simulation results demonstrate the performance gain of our algorithm compared to using a fixed EDT, and thus warrant future efforts in the adaptive EDT optimization as a mechanism to maintain QoS in various interference scenarios.**

Keywords-body area network; interference mitigation; CSMA; energy detection threshold

I. INTRODUCTION

A Body Area Network (BAN) consists of multiple wearable (or implantable) sensors and actuators that can establish two-way wireless communication with a controller node that is located on or in the vicinity of the body [1]. Medical applications impose stringent requirements on BAN quality of service including reliability and on-time availability of data. Since the current IEEE802.15.6 standard [2] does not consider any coordination across multiple BANs, interference from nearby BANs or other devices sharing the same spectrum could inevitably cause performance degradation, leading to unacceptable performance in a given BAN [3]. One common scenario is when several BANs are located in close proximity to each other. This could lead to cross-interference among the nodes of different BANs. Several interference mitigation strategies for such scenarios have been proposed and investigated in [4]-[5].

The CSMA/CA MAC protocol as outlined in the IEEE802.15.6 BAN standard involves the use of an Energy Detection Threshold (EDT) to determine the status of the transmission channel i.e. idle versus busy. In [6], it has been shown that the use of such static thresholds could negatively impact the performance of a system composed of multiple co-located BANs. It could also lead to starvation or unfair treatment of a node that is experiencing excessive interference due to its physical location relative to all other nodes in the system. As indicated in [6], there exists an optimal choice for the value of this threshold; however, this optimal value is heavily scenario-dependent. Specifically, when the BANs are mobile, it would be impossible to estimate the static value of this threshold in order to guarantee the optimal performance of all links in the system. In addition, even under the optimal choice of this threshold, we observed that fairness could still be a challenging issue, i.e., some sensor nodes could experience heavy backlogs or equivalently huge packet drop rates while others face virtually no delays and zero drop rate. This is a fundamental problem that is caused by having the same fixed EDT threshold to sense the channel and to make decisions on whether to go ahead with packet transmissions.

It is known that CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) transmission protocol that is based on queue length, i.e., Q-CSMA/CA, can achieve throughput optimality in some wireless networks [7]-[8]. Recent results indicate that Q-CSMA/CA-based networks can achieve a combination of near optimal throughput and low queueing delays by controlling both link transmission probability and an access probability [9]. Transmission probability on each link is chosen as an appropriate function of its queue size and access probability on each link is inversely proportional to the number of links that interfere with this link.

Theoretical analysis of Q-CSMA [9] is based on a simplified model which assumes that transmission probability on each link is a *decreasing* function of the level of interference at the receiver, and an *increasing* function of the queue size at the transmitter. The specific forms of this function is based on phenomenological arguments and simulation results. Controlling transmission probability through Energy Detection Threshold (EDT) has been proposed in [10]. While [10] demonstrated performance benefits of controlling EDT, high complexity of algorithms [10] makes practical implementation of these algorithms challenging.

This paper suggests viewing EDT adjustment algorithm as minimization of the properly defined regret. One of the benefits of this viewpoint is the ability to balance the aggregate throughput for all transmissions on one hand and certain degree of fairness on the other hand. Here, we rely on a simple implementation of the IEEE 802.15.6 CSMA/CA protocol on a simulation platform for performance evaluation of the proposed algorithms. This paper provides a mathematical framework with simulation results which indicate potential benefits of queue size & observed interference based EDT adaptation in IEEE 802.15.6 CSMA/CA.

The paper is organized as follows. Section II describes our system model and relevant assumptions. Section III proposes the EDT adjustment algorithm along with our performance metrics. Section IV describes the simulation scenarios. Simulation results are discussed in section V. Finally, conclusions and future research plans are presented in section VI.

II. SYSTEM MODEL

Consider a system comprised of N adjacent BANs. Each BAN consists of one coordinator and several sensor nodes in a star topology specified in the IEEE 802.15.6 standard. According to this standard, communication between the coordinator and the body sensors is handled by the CSMA/CA transmission protocol, which operates as follows. The access to the channel is managed by the coordinator through the establishment of SuperFrames (SF). Duration of all SFs are bounded by a beacon period of the same length. Figure 1 shows the general SF structure. Each SF is divided into Exclusive Access Phases (EAP1, EAP2), Random Access Phases (RAP1, RAP2), Managed Access Phases (MAP) and a Contention Access Phase (CAP). In EAP, RAP, CAP periods nodes in a BAN contend for resource allocation using either slotted aloha or CSMA/CA access procedure. The EAPs are used to transfer high-priority or emergency traffic, while RAPs and CAP are used for regular traffic communication. The MAP period is used for uplink, downlink, bi-link allocation intervals and for polling resource allocation. Depending on the application requirements, the coordinator can disable any of these periods by setting the duration length to zero.

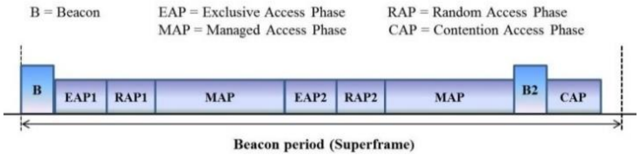

Figure 1. IEEE 802.15.6 Superframe Structure [9]

According to IEEE802.15.6 CSMA MAC protocol, time in a SF is divided into slots with duration of 145 µsec. When a node needs to transmit a data packet, a back-off counter (BC) is chosen randomly within the interval [1, CW], where CW ∈ [CWmin, CWmax]. The values of CWmin and CWmax depend on the traffic type priority. Then, the channel is sensed for a time period pSIFS (Short Inter Frame Spacing) of 75µsec to determine whether it is idle. If the channel is determined to be idle for this period, the BC (corresponding to the node) is decremented by one for each idle slot that follows. Once the BC has reached zero, the node transmits the corresponding data packet. On the other hand, if the channel is sensed to be busy, the BC is locked until the channel becomes idle again for the entire duration of a pSIFS. A node assessment of the transmission channel (i.e. idle/free) is done according to the Clear Channel.

Assessment (CCA) Mode 1 is described in the standard document [2]. It involves the use of an EDT threshold. If the node's receiver detects any energy in the selected frequency channel above the EDT threshold, the channel is determined to be busy; vice versa, the idle channel status corresponds to no energy detection above the EDT threshold. According to the standard, the minimum EDT threshold should be set to values such that the received power is no less than 10 dB above the receiver sensitivity for the lowest data rate within the band of interest.

Due to inter-BAN as well as exogenous interference, a static value for the EDT threshold can lead to starvation or unfair treatment of a particular node. To demonstrate this, we have extended our simulation platform presented in [3] and implemented a simplified CSMA/CA MAC protocol as outline by the IEEE 802.15.6 standard. We consider a system comprised of N BANs. Each BAN consists of one controller and several sensor nodes (i.e. star topology according to the IEEE 802.15.6 standard). For each BAN $k = 1,..,N$, the Signal to Interference plus Noise ratio (SINR) at the receiver node $i = 1,...,M$ with respect to signal transmitted by node $l \neq i$ is

$$SNIR^t_{kl \to i} = p^t_{kl} \xi^t_{kl \to i} \big/ [(\sigma^t_{ki})^2 + I^t_{ki}] \tag{2}$$

where p^k_l is the transmission power by node l of BAN k, σ^2_{ik} is the noise power at the receiving node i of BAN k, ξ^k_{li} is channel attenuation from a transmitting node l in BAN k to the receiver node i in BAN k, and I_{ik} is interference at node i of BAN k.

To model interdependence between different BANs we assume that Interference in BAN k, I_{ik} is caused by concurrent transmissions within the same BAN k as well as within the other BANs $n \in \{1,..,N\} \setminus k$:

$$I_{ik} = \sum_{j \neq k} p^j_m \xi^j_{mi} + \sum_{k,n \neq l} p^k_n \xi^k_{ni} \tag{3}$$

where, ξ^j_{mi} is channel attenuation from a transmitting node m in BAN $j \neq k$ to the receiving node i in BAN k, and ξ^k_{ni} is the channel attenuation from a transmitting node $n \neq l$ in BAN k to the receiving node i in BAN k. For simplicity, we assume that all transmissions use the same frequency band.

III. EDT ADJUSTMENT BY REGRET MINIMIZATION

Theoretical analysis of a simplified version of Q-CSMA/CA [9] has predicted that a combination of near optimal throughput and low queueing delays can be achieved using a proper transmission probability on each link. This probability should be a *decreasing* function of the level of the interference at the receiver and an *increasing* function of the queue size at the transmitter. The specific form of this function is based on phenomenological arguments and simulation results. A natural way to control transmission probability in CSMA/CA is by adjusting the EDT. Setting the EDT "too low" results in a very conservative transmission strategy, i.e. few packet transmissions or equivalently higher delays or packet drop rate. On the other hand, setting EDT "too high" results in very aggressive transmission strategy, which will lead into higher interference and further packet losses for other links in the system.

Developing specific low complexity adjustment algorithms for the EDT, based on the observable information, is an extremely challenging problem. The observability problem is due to transmitter inability to directly observe interference level I at the receiver. Assuming for simplicity that interference at the transmitter is $(1+\chi)I$, where χ is some (hopefully "small") random variable indicating correlation with the interference at the receiver. Using a fixed EDT effectively implies a transmission probability $\Pr ob\{(1+\chi) \le EDT/I\}$, which is a decreasing function of the interference I at the receiver.

In addition to the level of interference $(1+\chi)I$, the relevant observable information at the transmitter include probability of successful packet delivery and packet queuing at the transmitter. Assume that π represents the probability of a transmitted packet that is not correctly received at the intended receiver (i.e. probability of receiving a NACK at the transmitter). High values of π indicates that interference at the receiver is "too high," and EDT at the transmitting node should be lowered. Also, following theoretical guidelines [9], it is natural to attempt to reduce queuing delays by making EDT an increasing function of the queue size Q.

Consider the following form of EDT dependency on π and Q:

$$EDT = \frac{1+\psi_Q(Q)}{1+\psi_\pi(\pi)} I\,, \tag{4}$$

where $\psi_Q(Q)$ and $\psi_\pi(\pi)$ are non-negative and increasing functions of Q and π respectively. Specific selection of functions $\psi_Q(Q)$ and $\psi_\pi(\pi)$ affects tradeoff between competing requirements for the aggregate throughput for all transmissions on one hand, and fairness on the other hand.

Since interference level I at a receiver is determined by all uncoordinated transmissions occurring in the proximity to this receiver, attempt to assign EDT according to (4) for the duration of a SuperFrame is always associated with some error. Assuming that assignment (4) intended to optimize some performance criterion, error in this assignment results in loss in this performance criterion. The loss can be quantified by the following quadratic function:

$$l = \left(EDT - \frac{1+\psi_Q(Q)}{1+\psi_\pi(\pi)} I \right)^2 . \tag{5}$$

For each transmitter n, loss (5) depends on EDT assignments for all transmitting nodes $\mathbf{EDT}$ in the system:

$$l_n(\mathbf{EDT}) = \left(EDT_n - \frac{1+\psi_Q(Q_n)}{1+\psi_\pi(\pi_n)} I_n(\mathbf{EDT}) \right)^2 . \tag{6}$$

The socially optimal assignments minimize the aggregate loss:

$$\mathbf{EDT}^{opt} = \arg\min_{\mathbf{EDT}} \sum_{n,} l_n(\mathbf{EDT}) . \tag{7}$$

Since social optimization (7) cannot be performed due to lack of coordination between different transmissions, we consider a "selfish" framework, where each transmitter n chooses EDT_n in attempt to minimize its individual loss (6):

$$EDT_n^* = \arg\min_{EDT_n} \left(EDT_n - \frac{1+\psi_Q(Q_n)}{1+\psi_\pi(\pi_n)} I_n(\mathbf{EDT}) \right)^2 . \tag{8}$$

This selfish optimization framework has natural interpretation as a non-cooperative game of different transmitters attempting to minimize their individual losses (6). From this perspective, optimization (8) yields a corresponding pure Nash equilibrium.

Offline EDT assignment algorithm, which possesses the entire information on the actual interference, queue size, and packet delivery in the upcoming SuperFrame, can achieve negligible loss (6). However, for realistic online EDT assignment algorithms, the "regret" of not possessing this information at a Superframe T can be defined as weighted sum of losses (6) for the previous Superframes $t = 0,1,..,T-1$:

$$L_{nT}(EDT) = \sum_{t=0}^{T-1} \beta_t \left(EDT - \frac{1+\psi_Q(Q_{nt})}{1+\psi_\pi(\pi_{nt})} I_{nt} \right)^2 \tag{9}$$

with weights $0 \le \beta_0 \le \beta_1 \le ... \le 1$. Since regret (9) is a convex function of EDT, minimization

$$EDT_{nT} = \min_{EDT} L_{nT}(EDT)$$

(10)

yields unique solution

$$EDT_{nT} = \left(\sum_{t=0}^{T-1} \beta_t \right)^{-1} \sum_{t=0}^{T-1} \beta_t \frac{1+\psi_Q(Q_{nt})}{1+\psi_\pi(\pi_{nt})} I_{nt} . \tag{11}$$

In the remainder of this paper we report simulation results on some special cases of this EDT adjustment algorithm with $\psi_Q(Q) \equiv \psi_\pi(\pi) = 0$. This special cases are intended to minimize the complexity of the EDT adaptation algorithm, and possibility of their implementation with the current form of IEEE802.15.6 standard.

IV. SIMULATION SCENARIOS

Consider the following particular cases of algorithm (11):

A) Set the EDT equal to the average sensed interference over the past m SuperFrames ($m = 1,2,3, \ldots..$) Repeat the adaptation every m SuperFrames. In other words, for $k = 1,2,3, \ldots.$, calculate EDT at SuperFrame n according to:

$$EDT_n = \frac{1}{m}\sum_{i=(k-1)\times m}^{k\times m-1} I_{SF_i} \qquad (12)$$

where k× $m \leq n < k(m+1)$.

B) Using a sliding window, measure the total interference over m consecutive SuperFrames ($m = 1,2,3, \ldots.$), and set the EDT equal to the average sensed interference over the past m SuperFrames. Repeat the adaptation every SuperFrame. In other words, EDT at SuperFrame n is calculate according to:

$$EDT_n = \frac{1}{m}\sum_{i=n-1-m}^{n-1} I_{SF_i} \qquad (13)$$

C) Set the EDT to be used at SuperFrame n according to the following moving average formula:

$$EDT_n = (1-\beta)EDT_{n-1} + \beta I_{SF_{n-1}} \qquad (14)$$

where EDT_{n-1} is the EDT value during SuperFrame $n-1$, $I_{SF_{n-1}}$ is the average sensed interference over the SF $n-1$,and β represents a constant weighting factor between 0 and 1. A lower β adds more weight to the EDT in prior SFs and diminishes the impact of the sensed interference in the current frame. Conversely, higher values of β reduces the impact of EDT history. In this scheme, $1/\beta$ is the effective window size of the first order filter represented by the equation (14).

For the above methodologies, the EDT at every SF_i is bounded by upper and lower limits of EDT_{max} and EDT_{min} respectively i.e.:

$$EDT_i = \begin{cases} EDT_{max} & if\ EDT_i \geq EDT_{max} \\ EDT_{min} & if\ EDT_i \leq EDT_{min} \end{cases} \qquad (15)$$

We are also assuming that the transceiver at each node is capable of sensing and measuring total interference over m consecutive SFs ($m = 1,2,3, \ldots.$). As the functionality to do this operation is currently available in the IEEE 802.15.6 standard (See Clear Channel Assessment (CCA) Mode 1 [2]), no major complexity in terms of additional hardware is expected. The best choice of m in the above schemes depends on the channel coherence time which itself depends on the considered scenarios.

A simplified version of the IEEE 802.15.6 CSMA/CA MAC protocol, which incorporates the Contention Access Phase (CAP), has been implemented on our simulation platform [5]. We assumed perfect synchronization between sensor nodes and the coordinator of each BAN. Therefore, beacon frames are always received by all sensors i.e. there are no connectivity issues among the nodes of a single BAN.

The first simulation scenario consists of eight stationary BANs each having 3 on-body sensors and one coordinator node. Stationary scenarios could occur in practical situation like people sitting around a table, in a bus or a classroom. Here, we considered the meeting scenario where eight persons (each wearing a BAN) are sitting around an oval-shaped table (see Fig. 1). The operating frequency of each BAN is considered to be 2.36 GHz (i.e. MBAN frequency band) as adopted by FCC for use in indoor environment [11]-[13].

The second simulation scenario also considers eight BANs (again with 3 on-body sensor nodes and one coordinator) moving randomly in a room with a size of 8m × 8m (see Fig.2). For the motion pattern, we have considered a simple version of the random waypoint model to represent people walking around in a building or an office. Other special movement patterns can also be incorporated in our platform if desired.

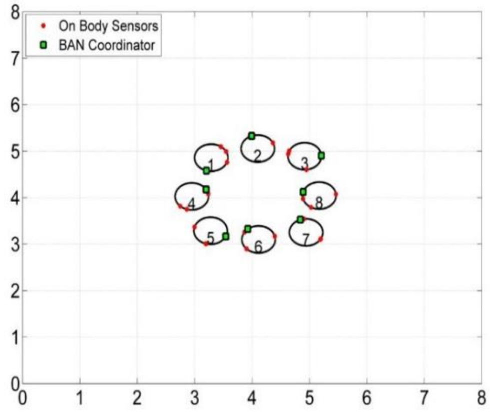

Figure 2. Sample multi-BAN meeting scenario

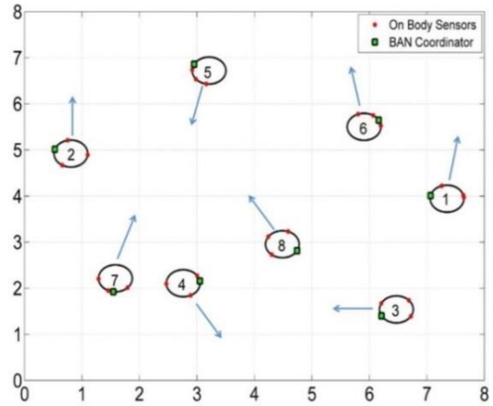

Figure 3. Sample multi-BAN random moving scenario

The traffic model used in our simulation is an i.i.d. Bernoulli with rates between 0 and 1 (packets per SF). Accordingly, traffic load per BAN is defined as:

$$GenRate \times \frac{Packet\ Length}{SuperFrame\ Length} X\ Num\ of\ Nodes\ per\ BAN$$

where $GenRate$ is the packet generation rate per sensor or equivalently the probability that a sensor has a new packet arrival at the beginning of each SF. The SuperFrame length is set to 10 msec for all BANs, and each packet is considered to have a length equal to 100 bytes. Among the different Modulation and Coding Schemes (MCSs) defined for the ISM band in the IEEE 802.15.6, we have considered MCS2 in our simulations (see table 1).

MCS	Modulation	Information Data Rate [Kbit/sec]	P_{Rmin} [dBm]	$SIR\|_{min}$ [dB]
0	π/2-DBPSK	121.4	-95	-2
1	π/2-DBPSK	242.9	-93	0
2	π/2-DBPSK	485.7	-90	3
3	π/4-DQPSK	971.4	-86	7

Table 1. IEEE 802.15.6 Modulation and Coding Schemes

The performance metrics that have been used to evaluate the proposed EDT adaptation are 1) Average Packet Delay and 2) Packet Drop Rate (PDR). Packet delay is defined as the interval of time between packet generation and its correct reception at the coordinator. Using Little's theorem, average packet delay can be computed as average number of queued packets at specific node divided by the packet generation rate. We assume infinite buffers and unlimited number of retransmissions. In order to evaluate PDR per node and average PDR across all BANs, limited queues size have also been considered for each node. Packet drop rate per link is computed as:

$$\frac{\#PacketsDropped/Link}{\#PacketsDropped/Link + \#PacketsSuccessfullyReceived/Link}$$

Our simulations assume that all nodes are using the interval associated with the traffic priority level 5 for the back-off counter. This priority level is typical for medical applications [14]. Our simulations consider EDT values to be in the interval [-84 -60] dBm. The lower bound (i.e. -84 dBm) has been chosen according to the minimum EDT criteria stated in the IEEE 802.15.6 standard. The upper bound has been derived from the aggregate inter-BAN interference profile of the scenario taken into consideration.

V. SIMULATION RESULTS

The average packet delay as a function of the traffic load per BAN for the meeting scenario is shown in Figure 3.

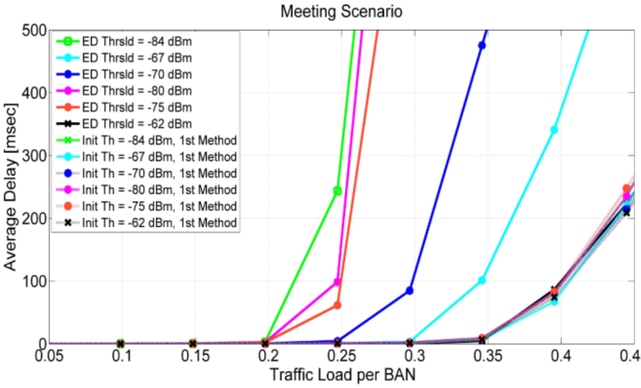

Figure 3. Average Packet Delay vs. Traffic Load for the Meeting Scenario

Graphs with solid lines refer to performance obtained with a static EDT while ones with dashed lines represent the performance obtained using the EDT adaptation scheme (12) in Section II for different starting values of the EDT. The value of 'm' has been considered to be 10. This means that the EDT is updated every 10 SuperFrames. As pointed out in [6], for static EDTs, the average packet delay is heavily dependent on the exact value of this threshold. The optimal value of the static threshold for the stationary meeting scenario is -62 dBm. This is indicated by the black solid graph in Figure 3. With our proposed adaptive strategy (12), the average packet delay performance is very close to the optimal static value. In addition, the performance is no longer dependent to the initial value of the EDT. Similar result is also observed for the random moving scenario as shown in Figure 4. Again, the average packet delay performance results achieved using adaptive scheme (12) are very close to those obtained through the optimal static threshold (-60 dBm in this case) and virtually independent of the initial value of the EDT.

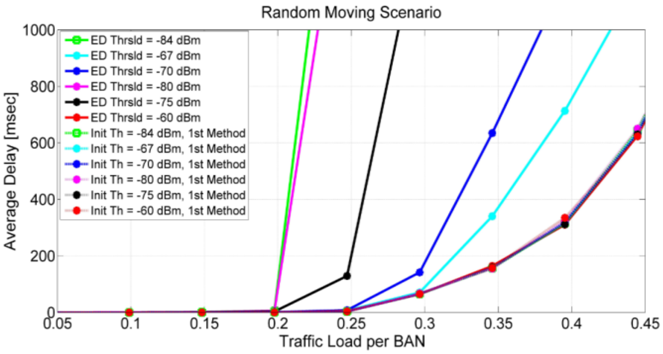

Figure 4. Average Packet Delay vs Traffic Load for Random Moving Scenario

The average packet delay performance obtained using all the adaptive EDT schemes described in Section II for both meeting and random moving scenarios have been presented in Figure 5. The results achieved by adaptive schemes (13) (i.e. sliding window) and (14) (moving average) are very close to those obtained by using adaptive scheme (12) for both scenarios.

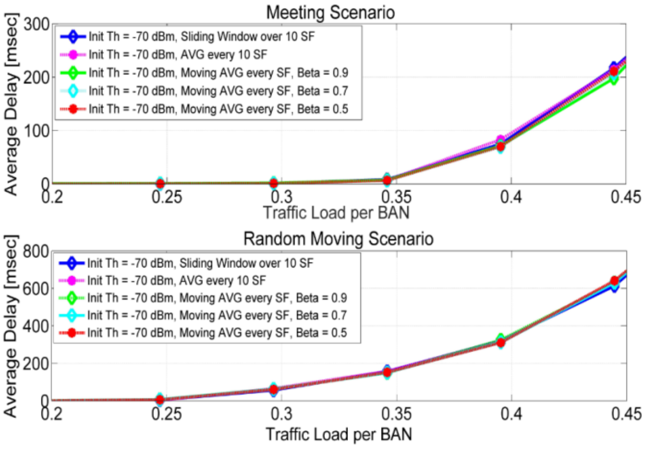

Figure 5. Average Packet Delay vs. Traffic Load

Figure 5 also highlights the performance of the moving average scheme under three different values of β. Although the results show that the difference is minimal further studies are required to determine if there exist an optimal value for this parameter.

To measure fairness among the links in each multi-BAN scenario, we have also defined the following metric:

$$Std\left(\frac{Average\ Queue\ Size\ at\ Transceiver\ i}{Average\ Interference\ at\ Transceiver\ i}\right)$$

where $Std(.)$ denotes the standard deviation of the ratios of the average queue size at each transmitting node to the average interference that the node has experienced. Note that smaller values of this standard deviation indicate higher degree of fairness among competing transmitters. Figure 6 displays this fairness metric for both meeting and random movement scenarios.

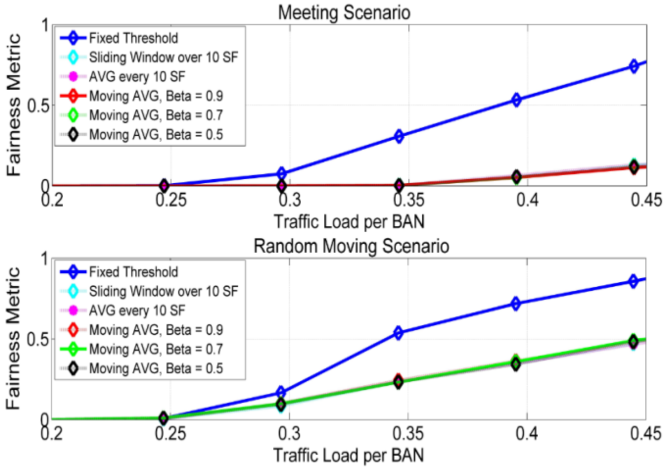

Figure 6. Fairness for Meeting and Random Moving Scenarios

Higher traffic load corresponds to higher overall inter-BAN interference and as observed the gain in fairness metric is more pronounced for higher traffic loads. The ability of the EDT adaptation to ensure graceful performance deterioration under high inter-BAN interference is specially important for medical applications that have stringent reliability requirements. For the stationary meeting scenario, all adaptive schemes seem to have an excellent fairness performance regardless of the traffic load.

We have also investigated the performance of our proposed adaptive EDT schemes considering a packet expiration time of 250 msec, which is commonly used BAN medical applications [9]. Figure 7 shows the average packet drop rate per link versus traffic load for the meeting and random moving scenarios using static and adaptive EDT.

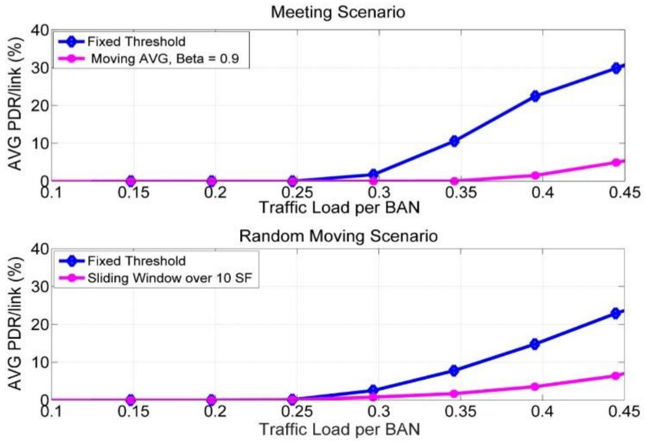

Figure 7. Packet Drop Rate vs. Traffic Load

For the random movement scenarios, the PDR with the weighted average strategy improves over 50% when traffic load exceeds 0.3. The PDR gain in the meeting scenario is even more significant. Not only the average PDR performance across all links is better with the adaptive EDT scheme but also the standard deviation of the PDR per link is much lower.

VI. CONCLUSION AND FUTURE RESEARCH

Our preliminary results warrant future investigation on optimization of adaptive EDT algorithms with respect to performance/fairness tradeoff [15]. Our current efforts is focusing on the assessment and optimization of the effect of explicit inclusion of queue size and probability of successful packet transmission in the EDT adjustment algorithm (11). We intend to achieve this goal with a combination of theoretical efforts for better understanding the achievable throughput/delay tradeoffs in combination with extensive simulations for modeling the intricacies of CSMA/CA based on IEEE 802.15.6 standard. Our ultimate goal is the development of practical recommendations for implementation of IEEE 802.16.5 standard.

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