A Queue-Size & Channel Quality Based Adaptation of the Energy Detection Threshold in IEEE802.15.6 CSMA/CA

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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 data. However, interference from other co-located BANs or other nearby devices sharing the same spectrum, e.g., due to BAN mobility, may cause unacceptable QoS degradation. This paper suggests that the impact of such QoS degradations can be minimized with a queue-size and channel quality based adaptation of the Energy Detection Threshold (EDT) at the transmitting nodes. Guided by known results for Q-CSMA/CA, we propose an adaptive EDT algorithm for use in 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 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 [2]. 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 [3]-[4].

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 [5]-[6]. 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 [7]. 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 [7] is based on a simplified model which assumes that transmission probability on each link l during each time slot is

$$\pi_l = \alpha_l \beta_l \tag{1}$$

where "access probability" α_l is a *decreasing* function of the level of interference at the receiver, and "queue-sensitive transmission probability" β_l is an *increasing* function of the queue size at the transmitter. The specific form of access probability α_l is based on phenomenological arguments and simulation results, e.g., [7] suggests $\alpha_l = 1/(d_l + 1)$, where d_l is the number of links interfering with the transmission on link l. In the simplified model [7], the throughput optimality is rigorously guaranteed for queue-sensitive transmission probability $\beta_l = e^{w_l}/(1+e^{w_l})$ with weight functions w_l of the form $w(q) = \log(1+q)/g(q)$, where $g(q)$ can be a function that increases arbitrarily slowly, e.g., $w(q) = [\log(1+q)]^{1-\varepsilon}$ for any small positive ε.

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 [8], 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 [8], there exists an optimal choice for the value of this threshold; however, this optimal value is heavily scenario-dependent. In other words, when the BANs are mobile, it would be impossible to estimate and adjust 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.

Using the underlying concept in Q-CSMA protocol, this paper proposes a queue length and channel quality based EDT adaptation algorithm in the IEEE802.15.6 CSMA/CA to combat performance degradation in multiple adjacent BANs scenarios. The motivation for our work is as follows. A low EDT will result in fewer transmissions for a transmitting node; effectively making the node too conservative to access the channel. On the other hand, a high EDT would imply higher availability of the channel; and therefore, would result in more aggressive transmissions. Thus, even if retransmission probabilities are kept constant, variations in EDT control the number of transmissions in the system indirectly affecting the total system interference and link throughout. The complexity of various inter-BAN wireless channels and their variations due to inherent mobility of these networks could lead to unfairness considering each node's specific QoS requirements. This unfairness can be mitigated by allowing each transmitting node to adjust its EDT independently.

Since our system model is more complicated compared to the one considered for Q-CSMA analysis, here we have only relied on a simulation platform to investigate the performance of various queue-size and channel quality based EDT algorithms. This platform allows us to evaluate the average packet delays and packet drop rates for several interfering BANs in various static and mobile scenarios for a given EDT adaptation strategy. This paper reports initial simulation results which indicate potential benefits and warrant future investigation of queue size & channel quality 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.

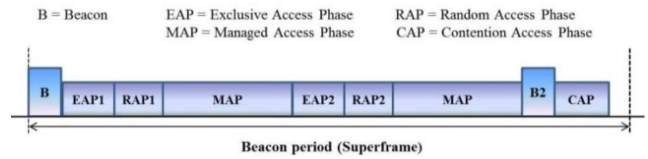

Figure 1. IEEE 802.15.6 Superframe Structure [9]

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 [9]. 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 [2] 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

$$SNIR_{li}^{k} = p_l^k \xi_{li}^k / (\sigma_{ik}^2 + I_{ik}) \quad (2)$$

where p_l^k is the transmission power by node l of BAN k, σ_{ik}^2 is the noise power at the receiving node i of BAN k, ξ_{li}^k 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 $n \in \{1,..,N\} \setminus k$:

$$I_{ik} = \sum_{j \neq k} p_m^j \xi_{mi}^j + \sum_{k,n \neq l} p_n^k \xi_{ni}^k \quad (3)$$

where, ξ_{mi}^j is channel attenuation from a transmitting node m in BAN $j \neq k$ to the receiving node i in BAN k, and ξ_{ni}^k 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 Algorithm & Motivation

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. 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. Our objective is to study the impact of a Queue-size and channel quality based Energy Detection Threshold on the performance of a system consisting of multiple adjacent BANs. Using the underlying concepts in Q-CSMA and experimentation with different EDT adjustment strategies, we propose the following algorithm.

After receiving four consecutive successful packet delivery acknowledgments (ACKs), the transmitting node raises the EDT at the beginning of the next SF as follows:

$$EDT = EDT + \Delta[\log_2(1+\delta q)+1], \quad (4)$$

where q is the queue size at the beginning of the current SF, and $\Delta, \delta > 0$ are some parameters. Similarly, after four consecutive unsuccessful packet deliveries (NACKs), the EDT is lowered as follows:

$$EDT = EDT - \frac{\Delta}{\log_2(1+\delta q)+1}. \quad (5)$$

Otherwise the current EDT at the transmitter stays unchanged for the next SF.

Our analysis for the proposed EDT adjustment algorithm (4)-(5) is based on the following equation approximately describing joint evolution of Energy Detection Threshold EDT_k, probability of transmission to be successful θ_k, and queue size q_k at the beginning of k-th SF:

$$EDT_{k+1} = EDT_k + [\log_2(1+\delta q_k)+1]\Delta \prod_{i=k-3}^{k} \theta_i - \frac{\Delta}{\log_2(1+\delta q_k)+1} \prod_{i=k-3}^{k} (1-\theta_i). \quad (6)$$

In equilibrium, when $EDT_k = EDT$, $\theta_k = \theta$, and $q_k = q$ are independent of k, we obtain from (6) the following relation between the steady-state probability of transmission success θ, and queue size q:

$$\left(\frac{\theta}{1-\theta}\right)^2 = \frac{1}{\log_2(1+\delta q)+1}. \quad (7)$$

Inverse relation between q and θ implies direct relation between q and the "steady-state" EDT since decrease in the probability of successful transmission implies increase in the level of interference. Solving (7) with respect to θ we obtain:

$$\theta = \frac{1}{1+\sqrt{\log_2(1+\delta q)+1}}. \quad (8)$$

Relation (8), plotted in Figure 2 for different values of δ, indicates that increase in the number of backlogged packets q reduces the probability of successful transmission θ.

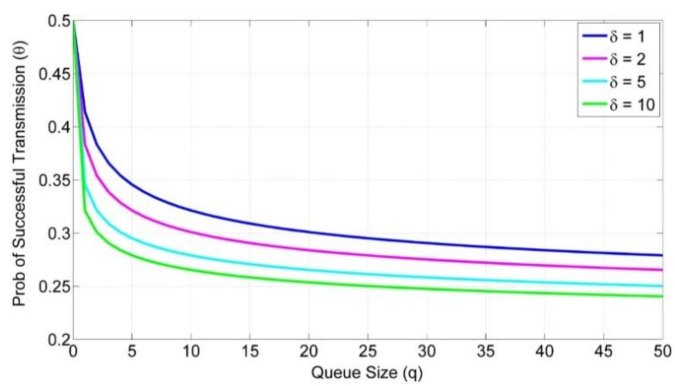

Figure 2. Probability of successful transmission vs. queue size (8)

Probability of successful transmission (8) can be also expressed as an increasing function of $SNIR = P_R/I$, where P_R is the received power and I is interference at the receiver: $\theta = \varphi(P_R/I)$. Since transmission of backlogged packets is attempted as soon as interference I falls below EDT, we assume that $\theta \approx \varphi(P_R/EDT)$, and by inversing the function φ we obtain the following approximate expression for EDT:

$$EDT \approx P_R \Big/ \varphi^{-1}\left(\frac{1}{1+\sqrt{\log_2(1+\delta q)+1}}\right). \quad (9)$$

Substituting (9) into transmission probability for a backlogged packet $\pi = \theta F(EDT)$, we obtain

$$\pi = \frac{F\left[P_R \Big/ \varphi^{-1}\left(\frac{1}{1+\sqrt{\log_2(1+\delta q)+1}} \right) \right]}{1+\sqrt{\log_2(1+\delta q)+1}}, \tag{10}$$

where $F(x) = \Pr ob(I \le x)$ is the probability distribution function of the interference at the receiver.

Theoretical analysis of the simplified model [7] suggests that transmission probability (1) should be a decreasing function of the interference level at the receiver I, and an increasing function of the queue size q. In the rest of this section we demonstrate that transmission probability (10), which is a result of algorithm (4)-(5) follows these theoretical guidelines. Since EDT adjustment algorithm (4)-(5) implies faster EDT increase (4) and slower EDT decrease (5) for larger queue sizes q, adjustment (4)-(5) results in "steady-state" $EDT = EDT(q)$ being an increasing function of q. Thus, it is sufficient to demonstrate that probability (10) is a decreasing function of the interference level I, and an increasing function of the EDT. For simplicity in our theoretical analysis we assume that relative variability of the interference level I is small, and thus $I \approx \bar{I} := E[I]$. In this case $F(I) \approx 0$ if $I \le \bar{I}$, and $F(I) \approx 1$ if $I > \bar{I}$. It is easy to verify that probability (10) is a decreasing function of $\bar{I}$ for a given EDT, and a non-decreasing function of EDT for a given $\bar{I}$ in accordance with theoretical guidelines [7].

The role of parameters δ and Δ in EDT adjustment algorithm (4)-(5) is as follows. Increase of the parameter δ increases algorithm (4)-(5) "aggressiveness" with respect to the queue size q. Step-size parameter Δ controls algorithm (4)-(5) tradeoff between adaptability to changing exogenous conditions and optimality for stationary exogenous conditions. In our simulations, we have obtained the parameters $\Delta = 0.2$, $\delta = 1$ to be the best value for the scenarios considered. We also considered a time-out window equal to eight SuperFrames (SFs) i.e., if a sensor did not transmit within eight consecutive SFs, then the node EDT threshold is raised by 1 dB. In this way, we have again tried to avoid possible starvation.

IV. Simulation Scenarios

We have measured the average packet delay across all nodes in the system for various traffic loads as a performance metric. The traffic model used is an i.i.d. Bernoulli with variable rates between 0 and 1 (packets per SF). We have evaluated the performance for various EDT in the interval [-84 -60] dBm. The lower bound (i.e. -84 dBm) has been chosen according to the minimum EDT criteria from the IEEE802.15.6 standard. The upper bound has been derived from the aggregate inter-BAN interference profile of the scenario taken into consideration.

In this preliminary study we assumed an infinite buffer along with unlimited number of packet retransmissions at each node. This assumption allows us to characterize performance by the average packet delay without concern for packet loss. The packet generation rate per sensor, i.e., $GenRate$, varies in the interval $[0,1]$ and represents the probability that a sensor has a new packet arrival at the beginning of each SF. The SF length is set to 10 msec for all BANs. Each packet is considered to have a length equal to 100 bytes. Traffic load per BAN is defined as follows:

$$L = GenRate \frac{PacketLength}{SF\ Length} \# SensorsPerBAN \cdot \tag{11}$$

Table 1 lists Modulation and Coding Schemes (MCSs) for the ISM band specified by IEEE 802.15.6 standard.

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

In our simulations, we consider MCS2. Assuming infinite buffers, system performance is evaluated in terms of the Average Packet Delay, which is defined as the interval of time between packet generation and its correct reception at the coordinator. Using Little's theorem, average packet delay is computed as follows:

$$AvePacketDelay = \frac{AveQueueLength}{PacketGenerationRate}. \tag{12}$$

We set up a simulation scenario with eight interfering BANs in a rectangular room with dimensions 8x8 meters. Each BAN has three on-body sensors and one coordinator node. The operating frequency of each BAN, i.e. MBAN frequency band, is 2.36 GHz as adopted by FCC for use in indoor environment. Although the channel models used in the simulation platform [10]-[12] correspond to the 2.4 GHz ISM frequency band, our conjecture is that these channel models are still valid for use in the MBAN frequency due to its proximity to the ISM band.

We simulated the following three scenarios. The first scenario, shown in Figure 3, includes eight static BANs.

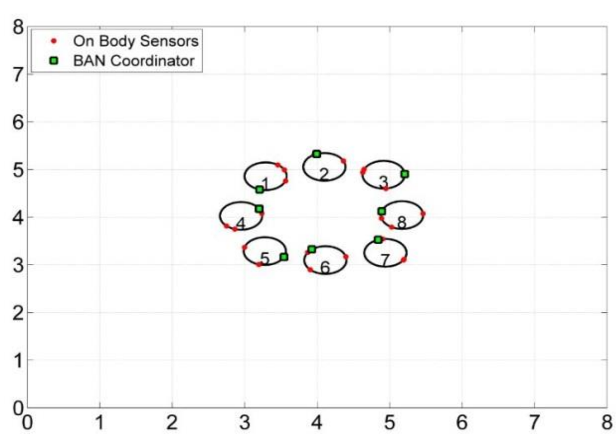

Figure 3. Scenario with stationary BANs

This scenario, which is intended to simulate eight people wearing BANs and sitting around an oval-shaped table, can be easily adjusted to simulate other static scenarios, e.g., people wearing BANs and sitting in a bus. The second scenario, shown in Figure 4, represents eight people wearing BANs and randomly walking inside a room.

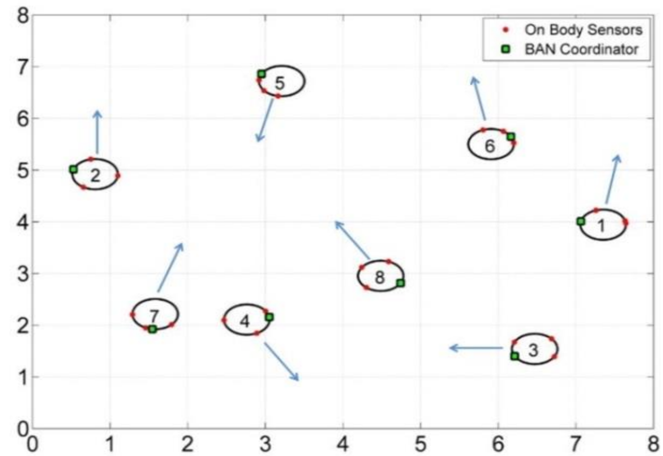

Figure 4. Scenario with eight randomly moving BANs

Initial position, speed, and reflection direction of all people are programmable within the platform.

Finally, the third scenario, shown in Figure 5, simulates eight BANs that are moving toward each other.

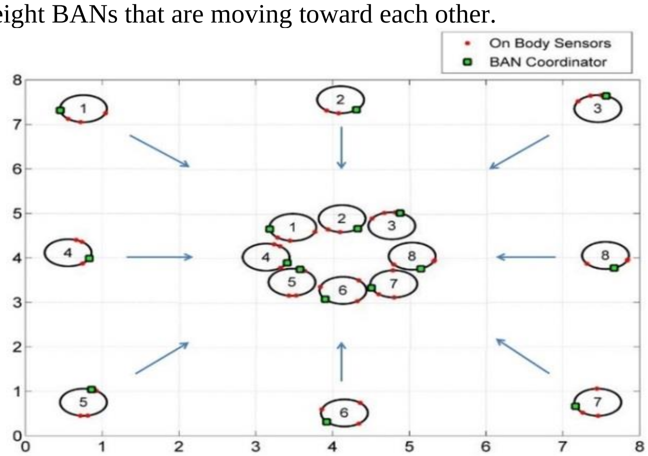

Figure 5. Stress mobility scenario

This scenario results in a monotonically increasing level of interference, and thus can be viewed as a stress scenario.

V. SIMULATION RESULTS

In this Section, initial simulation results for the EDT adaptation algorithm (4)-(5) when $\delta = 1$ are reported. The objective is to complement the qualitative motivation of the proposed algorithm with simulation based quantitative evaluation. For each scenario, the performance is compared against the case of fixed EDT as considered by the current IEEE802.15.6 standard. System performance is evaluated in terms of the Average Packet Delay (12). In addition, we have defined the following metric as a measure of fairness among the links in each multi-BAN scenario:

$$Std\left(\frac{Average\ Queue\ Size\ at\ Transmitter\ i}{Average\ Interference\ at\ Transmitter\ i}\right), \qquad (13)$$

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. This metric, which conveys a notion of proportioanl fairness, is intended to represent fair access to the channel given the level of interfernece that the transmitting nodes are experiencing. Note that smaller values of this standard deviation indicate higher degree of fairness among competing transmitters. Figures 6, 7, and 8 report simulation results for the static, random motion and special multi-BAN stress scenarios shown in Figures 3, 4, and 5 respectively.

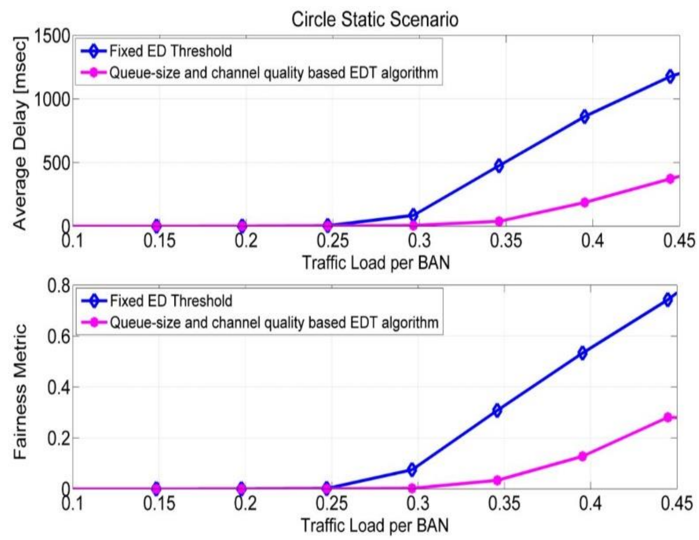

Figure 6. Average Delay and Fairness vs. load for the static scenario

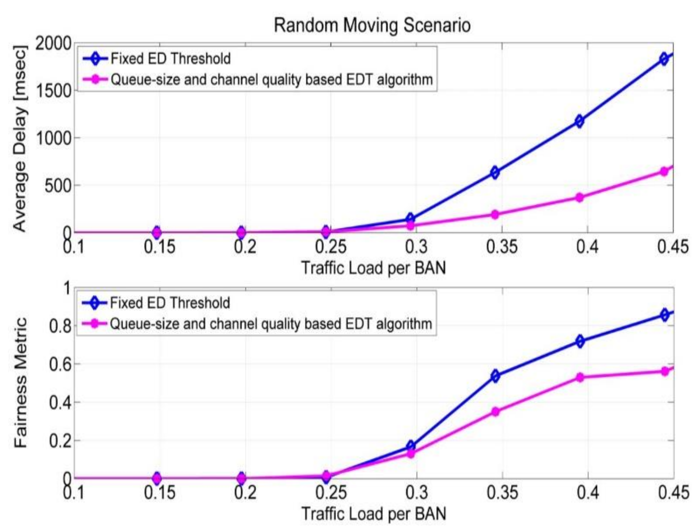

Figure 7. Average Delay and Fairness vs. load for the random motion scenario

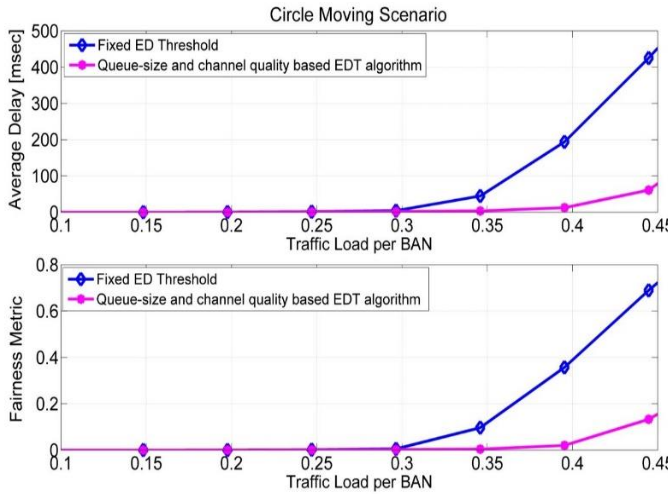

Figure 8. Average Delay and Fairness vs. load for the stress scenario

As observed in these Figures, the proposed EDT adaptation algorithm (4)-(5) outperforms the fixed EDT in all scenarios with respect to both criteria: average paket delay and fairness (13). The performance gain is more pronounced for heavier traffic load or scenarios where high cross-BAN interference could potentially disrupt the operation of several transmitting nodes. The ability of the EDT adaptation algorithm to ensure graceful performance deterioration under high inter-BAN interference is specially important for medical applications that have stringent reliability requirements.

While this Section discusses quantitative motivations for EDT adjustment algorithm (4)-(5), it does not make any claims or judgements on the proposed algorithm optimality or closeness to optimality. The significant performance gain compared to fixed EDT is intended to motivate further research on CSMA/CA with adaptive EDT.

VI. Conclusion and Future Research

Our preliminary simulation results demonstrate performance gain of the IEEE802.15.6 CSMA/CA with adaptive EDT; and therefore warrant future investigations in Q-CSMA/CA optimization for BAN applications. This gain is most significant for scenarios with heavy inter-BAN interference. Optimization of various system parameters, including queue-dependent EDT, will require 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.

In particular, theoretical analysis should provide guidance for EDT adjustment algorithm "aggressiveness" with respect to the queue size. For near-optimal EDT adjustment algorithms, theoretical analysis may also be helpful for managing inherent tradeoffs between the overall system performance and fairness for different BANs and nodes within each BAN [13]. In particular, simulations could be used to assess effects of limited number of retransmissions and the impact on the packet drop rates due to finite buffers. The ultimate goal of these efforts should be the development of practical recommendations for implementation of IEEE 802.16.5 standard.

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