Impact of the Energy Detection Threshold on Performance of the IEEE 802.15.6 CSMA/CA

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Abstract—**A Body Area Network (BAN) is a radio interface standard for wireless connectivity of wearable and implantable sensors located inside or in close proximity to the human body. Medical applications requirements impose stringent constraints on the reliability, and quality of service performance in these networks. Interference from other co-located BANs or nearby devices that share the same spectrum could greatly impact the data link reliability in these networks. Specifically, the CSMA/CA MAC protocol as outlined in the IEEE802.15.6 BAN standard involves the use of an energy detection threshold to determine the status of the transmission channel i.e. idle versus busy. In this paper, we would like to show that the use of such static thresholds could negatively impact the performance of the 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. A simulation platform is presented to highlight this problem and investigate the performance impact.**

Keywords-body area networks, CSMA MAC protocols, interference, collision avoidance

I. INTRODUCTION

A Body Area Network (BAN) consists of multiple wearable (or implantable) sensors that can establish two-way wireless communication with a controller node that is located in the vicinity of the body [1]. Considering the mobile nature of BANs, these networks are expected to coexist with other wireless devices that are operating in their proximity. However, interference from coexisting wireless networks or other nearby BANs could create problems on the reliability of the network operation. For example, when several body area networks are within close proximity of each other, inter-BAN interference may occur since no coordination across multiple networks exists in general. For these scenarios, several mitigation strategies that are applicable to the PHY layer have been proposed and studied [2,3,4]. Here, we would like to focus on the MAC layer and specifically the operation of the CSMA/CA protocol.

Consider a system comprised of several adjacent BANs. Each BAN consists of one coordinator and several sensor nodes in a star topology as outlined in the IEEE 802.15.6 standard. A CSMA/CA transmission protocol based on the standard is used for communication between the coordinator and the body sensors. At each BAN, the access to the channel is managed by the coordinator through the establishment of a SuperFrame (SF). Each SF is bounded by a beacon period of equal length. Figure 1 shows the general SF structure which 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.

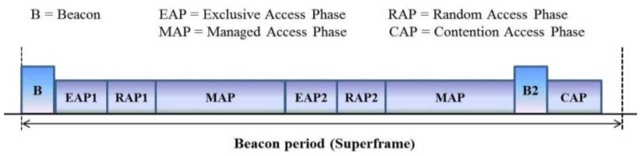

Figure 1. IEEE 802.15.6 Superframe Structure [8]

According to IEEE 802.15.6 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 described in the standard document [8]. It involves the use of an Energy Detection

(ED) threshold. If the node's receiver detects any energy in the selected frequency channel above the ED threshold, the channel is determined to be busy; vice versa, the idle channel status corresponds to no energy detection above the ED threshold. According to the standard, the minimum ED 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.

In this paper, we plan to highlight the impact of this threshold on the system performance when the system is comprised of several co-located BANs. It is shown how the static value of this threshold can lead to starvation or unfair treatment of a particular node(s) when there are potential interferers in the vicinity. To demonstrate this, we have extended our simulation platform presented in [7] and implemented a simplified CSMA/CA MAC protocol as outline by the IEEE 802.15.6 standard. The rest of this paper is organized as follows. Section II briefly describes the simulation platform and scenarios, as well as our simplified CSMA/CA protocol implementation. Section III outlines the performance results obtained through the simulation platform. Finally, conclusions and future research plans have been discussed in section IV.

II. SIMULATION PLATFORM

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). The experienced Signal to Interference plus Noise ratio (SINR) at the receiver node $i=1,...,M$ (with transmitter node $l \neq i$) of BAN $k=1,..,N$ can be expressed by:

$$SNIR_{li}^{k} = p_l^k \xi_{li}^k / (\sigma_i^2 + I_i), \qquad (1)$$

where p_l^k is the transmission power for the transmitting node $l=1,...,M$ in BAN k, σ_i^2 is the noise power at receiver i, ξ_{li}^k denotes channel attenuation from a transmitting node l in BAN k to the receiver node i in BAN k and I_i is the interference at receiver i created by other BANs $j \neq k$ and eventually by sensors of the same BAN k which are concurrently transmitting, computed as :

$$I_i = \sum_{j \neq k} p_m^j \xi_{mi}^j + \sum_{k, n \neq l} p_n^k \xi_{ni}^k \qquad (2)$$

where ξ_{mi}^j in equation (2) denotes channel attenuation from a transmitting node m in BAN $j \neq k$ to the receiver 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 receiver node i in BAN k. For simplicity, we have assumed all such transmissions are using the same frequency band. In practice, there will be a subset of the nodes that are using a common frequency band. In [6], we presented a simulation platform that can be used to assess the inter-BAN interference. Using this platform various scenarios (BAN spatial distribution, movement pattern, speed, number of nodes per BAN, and frequency of operation) can be defined.

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 [5]. Although the channel models used in the simulation platform 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. Use of MBAN frequency band will provide much cleaner wireless channels to applications in body area networks; however, inter-BAN interference could still remain as a potential source for disrupting the reliable data communication in a BAN [6]. As mentioned before, we have implemented a simplified version of the IEEE 802.15.6 CSMA/CA MAC protocol on this platform. The simplification means that only the Contention Access Phase (CAP) in the SF has been considered. We have also assumed perfect synchronization between sensor nodes and the coordinator of each BAN. This means that beacon frames are always received by all sensors i.e. there are no connectivity issues among the nodes of a single BAN. Our objective as stated before is to study the impact of the ED threshold on the multi-BAN system performance.

The first simulation scenario consist of eight BANs (each having 3 on-body sensors and one coordinator node) that are static and at a fixed distance from each other (see Fig. 2). This is intended to emulate eight people (each wearing a BAN) sitting around an oval-shaped table. Similar static scenarios such as people sitting in a bus may also be considered and it can be shown that our results are easily applicable to those scenarios as well. The second simulation scenario 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.3). Special movement patterns can be incorporated in our platform if desired. For this simulation, we have considered a simple version of the random waypoint model to represent people walking around in a building or an office.

Inter-BAN channel models used for the above scenario are based on [9, 10]. We have only used channel models associated with tangentially polarized antennas, as they result in less inter-BAN interference compared with normally polarized antennas [6]. 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 ED thresholds in the interval [-84 -

60] dBm. The lower bound (i.e. -84 dBm) has been chosen according to the minimum ED threshold 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.

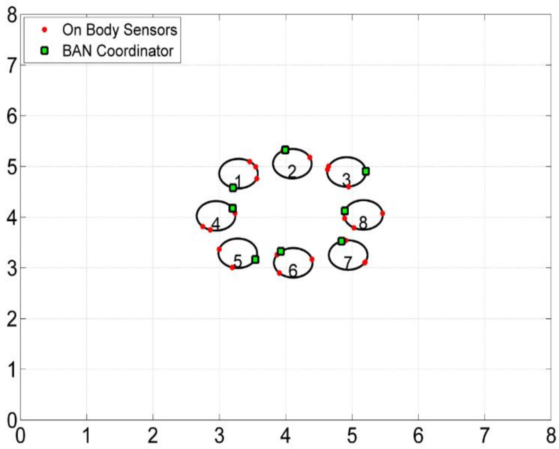

Figure 2. Sample multi-BAN Meeting scenario

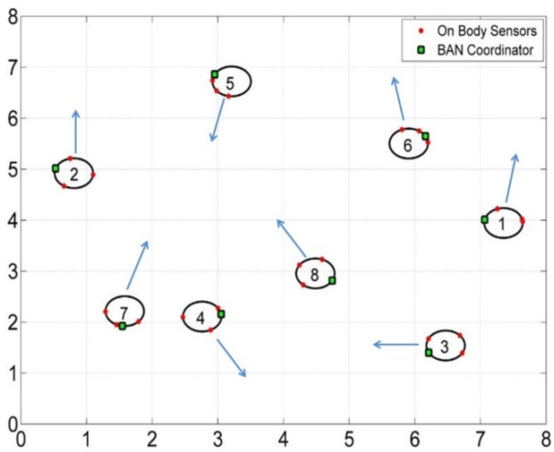

Figure 3. Sample multi-BAN random moving scenario

III. PERFORMANCE RESULTS

To obtain the results, we have simply assumed an infinite size queue (to accommodate the backlogged traffic) along with an unlimited number of retransmissions for the arrival traffic at each node of a BAN. This will allow us to evaluate the average packet delay without incurring any packet drops. Results for limited number of retransmissions and the impact on the packet drop rates will be discussed later. 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:

$$GenRate\ X\ \frac{Packet\ Length}{SF\ Length}\ X\ Num\ of\ Sensors\ per\ BAN$$

Among the different Modulation and Coding Schemes (MCSs) defined for the ISM band (see table 1), we considered MCS2 in our simulations.

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

System performance is evaluated in terms of the following metrics: Average Packet Delay and Packet Drop Rate. 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 follows:

$$Average\ Packet\ Delay = \frac{Average\ \#\ of Packets\ per\ Queue}{Packet\ Generation\ Rate}$$

Similarly, packet drop rate per link can be computed as:

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

Figure 4 shows the average packet delay as a function of the traffic load per BAN. Here, it has been assumed that are no hidden node problem within each BAN. Therefore simultaneous transmissions within the same BAN may occur only if sensor nodes set their BC to the same random value. On the other hand, simultaneous transmissions at different adjacent BANs may indeed occur, and this in fact depends on the Energy Detection (ED) threshold that has been set for the sensor nodes. As observed, the value of an ED threshold could have a significant impact on the system performance. For low threshold values (corresponding to the range -84 dBm to -75 dBm in our example), the average packet delay tends to rapidly increase for relatively lower values of the traffic load. This is due to the fact that the low values of the ED thresholds make transmitting nodes to be more conservative, and therefore, hold off on any possible transmissions if they sense even slight amount of inter-BAN interference. This could result into large delays (i.e. waiting time in the queue) that each packet experiences before it even gets the chance to be transmitted.

Similarly, for high values of the ED threshold, nodes will become more aggressive and could transmit their waiting packets irrespective of the high existing inter-BAN interference. This, in turn, will increase the possibility of unsuccessful receptions (e.g. collisions) at the receiver which means further retransmissions will be required. Obviously, this will add to the total delay experienced by the packet.

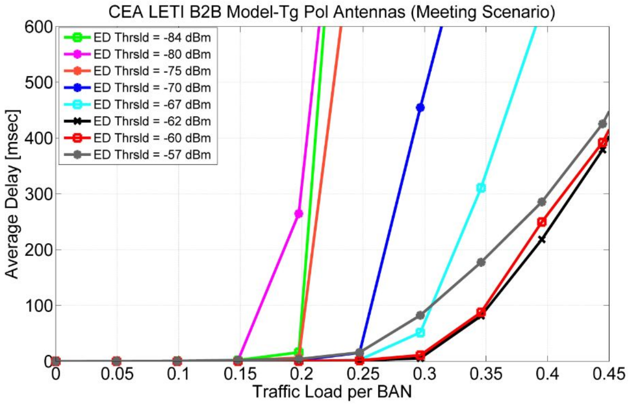

Figure 4. Average Packet Delay vs Traffic Load for the Meeting Scenario

As the results in Fig. 4 shows, the optimal value of the ED threshold is -62 dBm. In general, this optimal value depends on the exact scenario details including the relative position of each sensor at each BAN, number of nodes, the channel conditions, etc. However, our argument is that the choice of this value could make a significant impact on the quality of service experienced by a node as evident in Figure 4.

For the random moving scenario, the average packet delay as a function of traffic load per BAN is shown in Figure 5. Although numerical results are different, similar pattern is again observed as ED threshold varies. For this scenario, as observed, -60 dB seems to be the optimal choice for low traffic load i.e. <0.4, where -57 dB provides slightly better average delays for higher traffic loads (i.e. > 0.4).

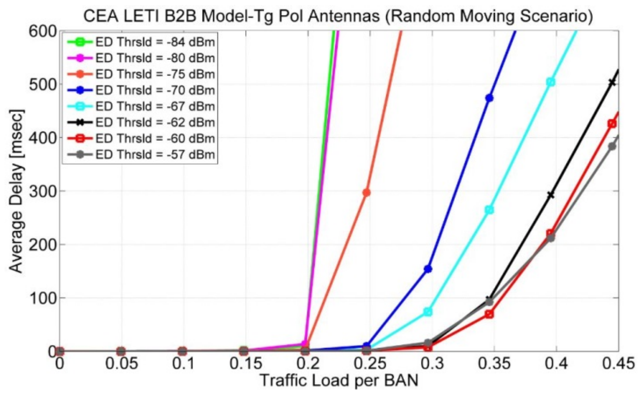

Figure 5. Average Packet Delay vs Traffic Load for the Random Moving Scenario

A look at the average queue sizes for each sensor in the system also reveals that some nodes are receiving unfair treatment in terms of accessing the channel. This is shown in Figure 6. Sensors 7, 10, 19 and 21 experience growing backlogs as traffic load increases while other sensors exhibit moderate average queue sizes.

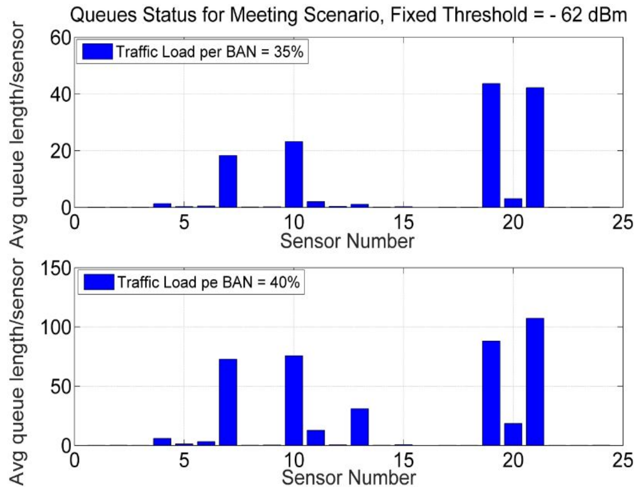

Figure 6. Average queue size per sensor for different Traffic Loads

This is another disadvantage of having static values for the ED threshold i.e. fairness cannot be maintained easily. Varying channel conditions across the system are forcing some sensors to act too conservatively or aggressively (given a fixed ED threshold); therefore, some communication links (and sensor nodes associated with those links) will perform poorly compared to others in the system. In addition, the lack of any time-out periods in the BAN Standard could translate into starvation of these nodes.

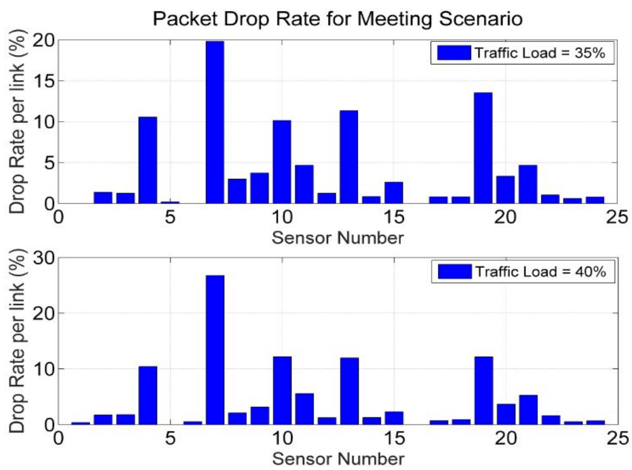

Figure 7. Packet Drop Rate per link for different Traffic Loads.

So far, it has been assumed that unsuccessful packet receptions would result into retransmissions and there are no limits on the number of allowed retransmissions. Therefore, there are no packet drops. If we consider a bound for the number that a given packet is allowed to be retransmitted, we can see the impact of a static ED threshold on packets drop rate. Figure 7 shows this drop rate for the sensor nodes in the system when the maximum number of retransmissions is considered to be equal to 3. The packet drop rates in Fig. 7 corresponds to the meeting scenario shown in Figure 2. The large standard deviation of the packet drop rates across all sensors is again indicative of the unfair QoS treatments that are experienced by the nodes.

In addition to the ED threshold impact study, we have also investigated the possibility of simultaneous transmissions within the same BAN. As mentioned in section 3, in our simulations, we have assumed that there is no hidden node problem within each BAN. Therefore simultaneous transmissions within the same BAN may only occur if sensor nodes set their BC to the same random value. Considering the meeting scenario in Fig. 3, we have observed that the small size of the interval associated with the back-off counter could lead to a high percentage of simultaneous transmissions by the sensor nodes of a single BAN. Figure 8 shows this percentage for traffic loads of 0.35 and 0.4. Here, we are assuming that all 3 nodes are using the interval associated with the traffic priority level 5 (considered for medical applications). The range of simultaneous intra-BAN transmissions across all eight BANs ranges between 10 to 15 percent of total transmissions. This is a significant percentage that leads to collisions; and therefore incurs further delay in successful packet reception.

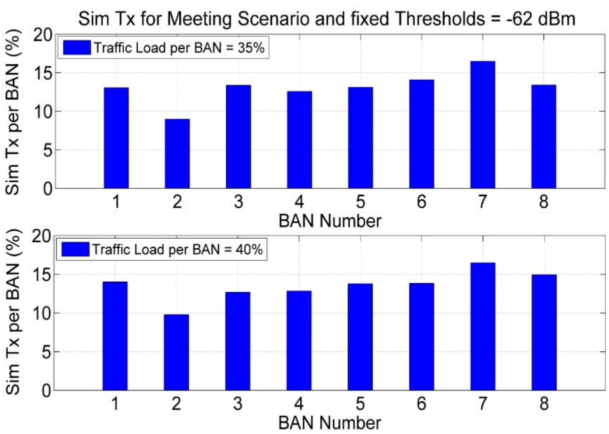

Figure 8. Simultaneous Transmissions for the Meeting Scenario

IV. CONCLUSIONS & FUTURE PLANS

The main focus of this study is the potential significant impact of the ED threshold in the IEEE802.15.6 standard on the QoS performance of various links across multiple adjacent body area networks. As discussed in the previous section, there exists an optimal choice for the value of this threshold for the example of several adjacent BANs. We have observed that this optimal value is heavily scenario-dependent. So, in normal operation of a BAN, 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. For the example considered in this paper, it was shown that 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 ED threshold to sense the channel and make decisions on whether to go ahead with packet transmissions. A system composed of multiple BANs is unlike any other network(s) configuration where a simple static threshold could be used to detect busy/idle status of a given channel. The complexity of various inter-BAN wireless channels and their variations due to inherent mobility of these networks could create unfair advantages for certain nodes to outperform others. In the meantime, some nodes could be facing near starvation scenarios.

The authors believe that the solution to this problem is through an intelligent adaptive energy detection threshold scheme, where each node can modify their corresponding ED threshold based on their assessment of their own channels. Several adaptive strategies are currently under investigation and will be presented in future publications.

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