Application of Link Adaptation in Body Area Networks

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***Abstract*— A Body Area Network (BAN) is a wireless protocol for connectivity of wearable and implantable sensors located inside, on the surface or near the human body. Medical applications requirements impose stringent constraints on the reliability, and quality of service (QoS) performance in these networks. Interference from other co-located BANs or nearby devices that share the same spectrum could greatly impact the communication link reliability in these networks. Link adaptation (LA) schemes can be an efficient alternative to preserve link quality in high interference environments. This paper proposes a low complexity link adaptation strategy to mitigate cross-interference in scenarios where multiple BANs are operating adjacent to each other. Each BAN is assumed to be using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol as outlined by the IEEE 802.15.6 Standard, where different modulation schemes are available at the physical layer. Each node selects the appropriate modulation scheme based on the experienced channel quality indicated by the received Signal-to- Interference and Noise Ratio (SINR). System performance is evaluated in terms of Packet Delivery Ratio (PDR) per link. Simulation results demonstrate significant improvement in the performance and highlight potential benefits of using link adaptation schemes for BAN applications.**

Keywords - Body Area Networks, CSMA/CA MAC protocols, interference, link adaptation

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. To maintain the link quality (i.e. desired signal to interference and noise ratio (SINR)) efficient power control mechanisms have been proposed [2, 3]. However, implementation of such mechanisms for BAN applications could be very challenging, particularly in fast changing scenarios when the SINR is varying due to the unpredictable movement of individual nodes and BANs in general.

Consider a system comprised of several adjacent BANs. The operating frequency of each BAN is considered to be 2.4 GHz (i.e. ISM frequency band) [4]. 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. In this paper, we investigate the use of Link Adaptation (LA) as a mean to mitigate the resulting cross-interference and reduce packet losses when several BANs are in close vicinity of each other.

Link adaptation is a technique that is routinely used in cellular networks [5]. Nodes employing LA could change their modulation/coding scheme (and therefore transmission bit rate) based on the experience channel quality. The possibility of selecting different transmission rates in networks using contention-based protocols (such as IEEE802.11) has already been investigated [6, 7, 8]. The main objective of introducing LA is to increase the throughput in the network. There are also a few studies on the performance of LA in 802.15.4 and 802.15.6 networks; however, all of them focus on a single WBAN scenario [9,10,16]. In this paper, we investigate the performance of LA for a system composed of multiple adjacent BANs. We assume that sensor nodes can choose different modulation schemes at the physical layer (PHY). To study the performance, we simply extended the simulation platform presented in our previous works [11,12] by including 2 and 3 levels LA schemes. We evaluate the improvement in Packet Delivery Ratio (PDR) when LA is used.

The rest of this paper is organized as follows. Section II summarizes the relevant PHY and MAC protocols features as indicated in the IEEE802.15.6. It also illustrates our proposed strategy to adaptively change the link bit rate through estimation of SINR over time. Section III briefly describes the scenarios and the metrics used to evaluate the system performance. Results obtained through extensive simulations

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are presented in Section IV. Finally, conclusions and future research plans are discussed in section V.

II. LINK ADAPTATION

Table I summarizes the different modulation and coding schemes (MCSs) defined for the 2.4 GHz ISM band as specified in the IEEE 802.15.6.

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 I. IEEE 802.15.6 Modulation and Coding Schemes for the 2.4 GHz

Sensitivity (P_{Rmin}) as well as the minimum Signal to Interference Ratio ($SIR_{|min}$) values were evaluated in [10].

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. According to CSMA/CA 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 75 μsec 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 [13].

In order to increase link usage efficiency and transmission reliability, here we propose using an adaptive modulation scheme based on the experienced channel quality at each node. We consider both 2-level and 3-level link adaptations where the transmitting node switches between MCS2 and MCS3 (for 2-level) and between MCS1, MCS2 and MCS3 (for 3-level) adaptations. We assume that each node uses MCS3 when interference is negligible (or equivalently the experienced SINR is high). We also assume that the coordinator of each BAN is capable of measuring the SINR every time it is receiving a packet from one of the sensor nodes. At the beginning of SF n the coordinator, by means of a sliding window, evaluates the average SINR per link experienced over the past 'm' SFs according to:

$$Avg\ SINR_{dB} = 10\log_{10}\frac{1}{m}\left(\sum_{i=n-1-m}^{n-1} Avg\ SINR/link\ in\ SF_i\right) \quad (1)$$

where

$$Avg\ SINR/\ link\ in\ SF_i = \frac{1}{N_{Tx}}\sum_{n=1}^{N_{Tx}} SINR_{lj,n}^{k}$$

is the average over the SINR values of the received packets during N_{Tx} transmissions by the coordinator j of BAN k during SF i for transmitting node $l \in$ BAN k.

Then, based on the $Avg\ SINR_{dB}$ value calculated in equation (1) the modulation scheme and the resulting bit rate for node l in the current SF n is chosen by the following algorithm:

if 2 levels LA is implemented then:
  if $Avg\ SINR_{dB}$ >= 7 dB then node l uses MCS3
    else node l uses MCS2
  end
elseif 3 levels LA is implemented then:
  if $Avg\ SINR_{dB}$ >= 7 dB then node l uses MCS3
  elseif 7dB > $Avg\ SINR_{dB}$ >= 3 dB then node l uses MCS2
    else node l uses MCS1
  end
end

The gist of our proposed strategy is to exploit possible correlation between the SINR values experienced over multiple consecutive packet transmissions in order to adaptively change the modulation, and therefore the bit rate, for each link. We assume that the information regarding the choice of MCS is included in the beacon frame that the coordinator sends to its nodes at the beginning of each SF. As energy is a significant constrain for sensors nodes in body area networks, LA schemes that do not require channel estimation at the sensor/actuator side would be desirable. This will avoid further energy consumption; and therefore, prolong the lifetime of the nodes and network.

In addition, the SINR value that is measured at the BAN's coordinator is more accurate and indicative of the actual channel conditions when most of the traffic is being transmitted from the sensor nodes (e.g. monitoring applications). When Link Adaptation is performed, the packet payload is adjusted according to the MCS used by the transmitting node. If the node is using MCS3 then one full packet can be delivered per transmission. Otherwise, if the node is using MCS2 or MCS3 half or quarter packet will be delivered per transmission respectively.

III. SIMULATION SCENARIOS, ASSUMPTIONS & PERFORMANCE METRICS

The first simulation scenario consists 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. 1). This is intended to emulate eight people (each wearing a BAN) sitting around an oval-shaped table like for example in a meeting scenario. 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.2). 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.
Intra-BAN channel models used in our simulations correspond to the 2.4 GHz ISM frequency band [14].

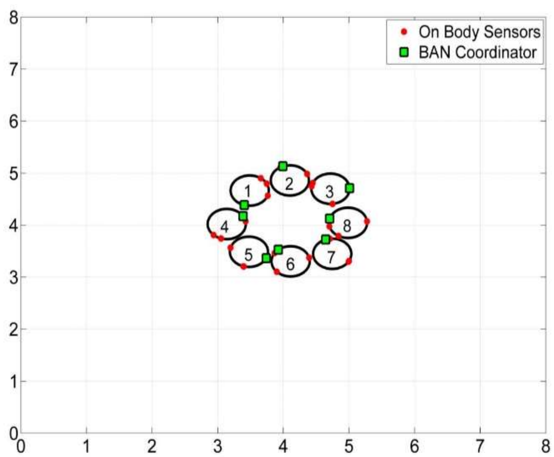

Figure 1. Multi-BAN Meeting scenario

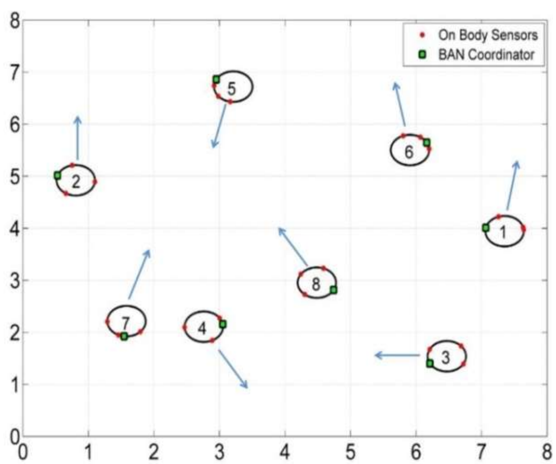

Figure 2. Eight randomly moving BANs scenario

Inter-BAN channel models used for the above scenario are based on [10,15]. We have only used channel models associated with tangentially polarized antennas, as they result in less inter-BAN interference compared with normally polarized antennas [11].

Also, considering the aggregate inter-BAN interference profile of the considered simulated scenarios, the Energy Detection (ED) threshold used for CCA has been set to -60 dBm. This threshold is held fixed for the duration of simulation. The packet generation rate per sensor ($i.e.$ $GenRate$) varies in the interval [0 1] (Bernoulli distribution) and represents the probability that a sensor has a new packet arrival every third 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:

$$GenRate\ X \frac{Packet\ Length}{SF\ Length/3} X\ Num\ of\ Sensors\ per\ BAN$$

To obtain the results, we have also 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. System performance is evaluated in terms of Average Packet Delivery Ratio (PDR) per link which is defined as:

$$\frac{1}{n_{sens}} \sum_{j=1}^{n_{sens}} \frac{\#\ of Packets\ correctly\ received\ for\ sensor\ j}{Total\ \#\ of\ Packets\ generated\ for\ sensor\ j}$$

where n_{sens} is the number of on-body sensors in the system.

IV. RESULTS

Figure 3 shows the PDR as a function of the traffic load per BAN for three different links highlighted in the meeting scenario figure (on the upper left corner). Performance obtained with 2 levels LA approach and without LA are compared.

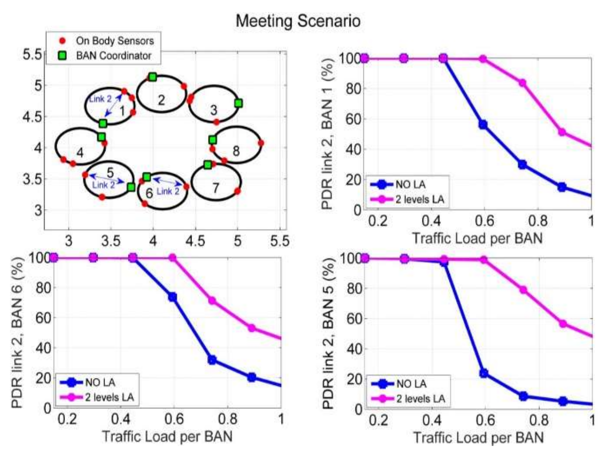

Figure 3. Packet Delivery Ratio versus Traffic Load for link #2 in BANs 1, 5 and 6 in the Meeting Scenario

Because of their locations relative to all other nodes, these links are exposed to particularly high interference. Therefore, they can significantly benefit from our proposed simple LA scheme. In fact, it is worth noting that without LA for traffic loads higher than 0.4 performance severely degrades and the PDR goes below 20% for link 2 in BAN 1 and link 2 in BAN 6 and below 5% for link 2 in BAN 5.

Average PDR over all links for the meeting scenario is shown in Figure 4. The magenta-color curve was obtained under the assumption of an optimal LA. The "optimal" here refers to the situation where each coordinator can perfectly predict the current (i.e. real time) channel conditions for each transmitting node. As this situation is not realizable, we refer to this case as a Genie-assisted LA (or simply Genie LA). Using this approach essentially enables each link to always use the MCS that leads to the highest possible PDR. The performance of this Genie-LA scheme can be considered as an ideal upper bound for all link adaptation schemes considered in this paper. Figure 4 shows that our proposed 2 levels LA strategy (red curve) leads to higher percentage of delivered packets per link compared to the no LA case (blue curve). Figure 5 and 6 show the distribution of the measured packet SINR values by the coordinator of each BAN. As observed, the large number of SINR values that exist between 3 dB and 7 dB justifies the effectiveness of our proposed 2-level LA. Average performance obtained by applying a 3 levels LA strategy does not offer noticeable gains as seen in Fig. 4. However, looking at Figures 5 and 6, for some of the BANs, (e.g. BAN 5), the number of SINR values between 0 dB and 3 dB suggests that some links might actually benefit from the implementation of a 3-level LA scheme.

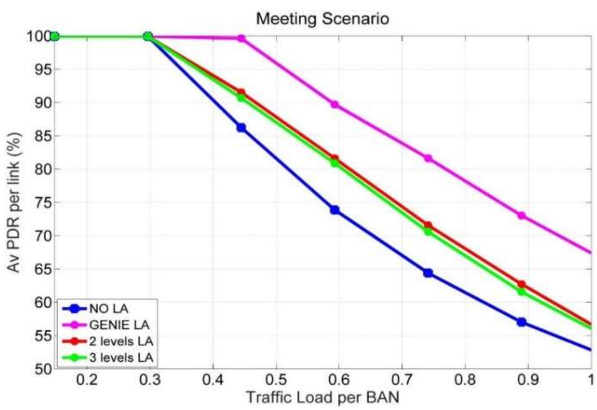

Figure 4. Average Packet Delivery Ratio versus Traffic Load for the Meeting Scenario

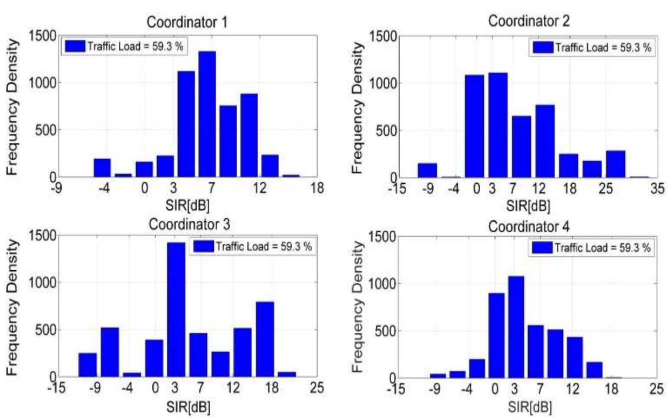

Figure 5. Distribution of the SINR values for coordinators 1- 4

Figure 7 shows the PDR performance for two different links in the system (i.e. link 1 in BAN 3 and link 1 in BAN 5). As observed, for these links the 3-level LA performs slightly better compared to the 2-level LA scheme. There is much more noticeable gain for link 1 in BAN 5. In general, and due to fading/shadowing conditions and the interference that a given sensor node is experiencing, 3-level LA scheme could still offer noticeable gains in certain circumstances.

Figure 8 displays the average PDR obtained with 2 and 3 levels LA schemes as well as with the Genie-LA approach for the random moving scenario. In this scenario, the inter-BAN interference and therefore the SINR, is highly variable due to the unpredictable movement of the BANs inside the room. Therefore, estimating link quality will be more challenging. Our simple proposed methodology still exhibits some gain compared to no link adaptation scenario.

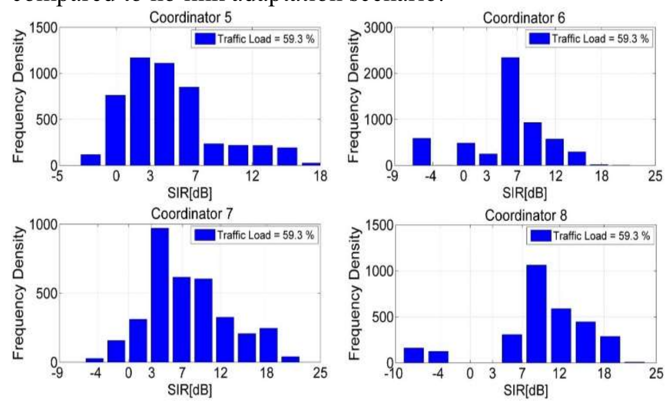

Figure 6. Distribution of the SINR values for coordinators 5-8

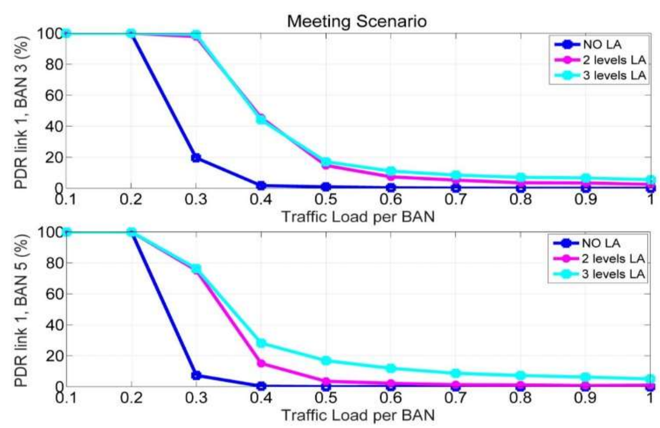

Figure 7. Packet Delivery Ratio VS Traffic Load for link 1 in BAN 3 and link 1 in BAN 5 for Meeting Scenario

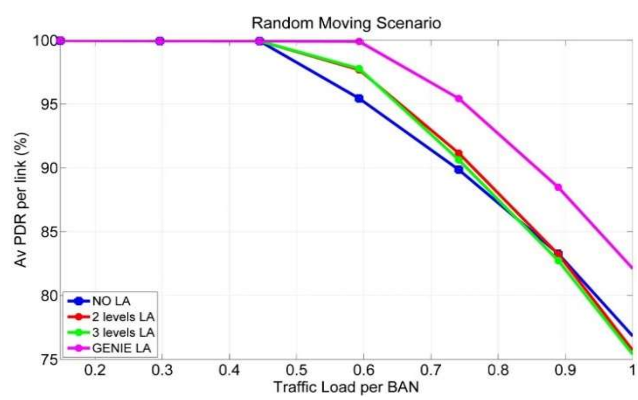

Figure 8. Average Packet Delivery Ratio versus Traffic Load for Random Moving Scenario

Similar to the meeting scenario, there exist several links, for instance those reported in Fig. 9, that can still highly benefit from the implementation of our proposed simple LA scheme. These gains are not properly reflected in the average PDR performance for the whole system. Also, the possible gain under the genie LA scheme (i.e. the magenta-color curve in Fig. 8) indicate the potential for improvement by using more sophisticated link adaptation approaches.

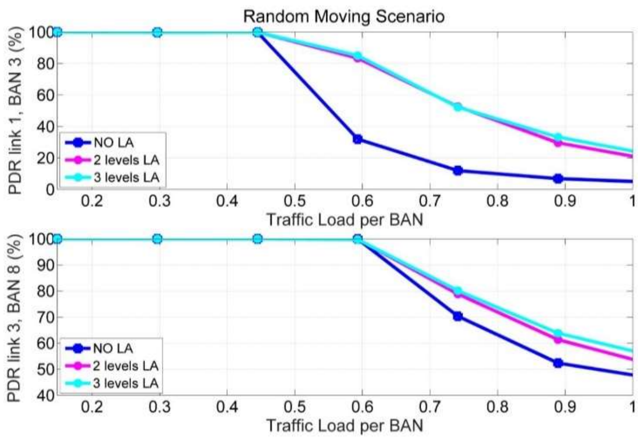

Figure 9. Packet Delivery Ratio versus Traffic Load for link #1 in BAN 3 and link #3 in BAN 8 for the Random Moving Scenario

V. CONCLUSIONS

In this study, we proposed and investigated the effectiveness of using simple link adaptation schemes to mitigate cross-interference in a system composed of several adjacent BANs. Nodes were assumed to use the CSMA/CA MAC protocol and different modulations and coding schemes as defined in the IEEE 802.15.6 Standard document. Our proposed LA strategy adapts the modulation & coding scheme and therefore the transmission bit rate based on the estimated channel quality. The channel quality is estimated by observing the history of SINR values experienced at the coordinator node during several consecutive packet receptions. In this way, channel estimation is not performed at the sensor node where energy constraints are more severe. The simulation results suggest that in case of high interference level scenario our LA strategy could result in noticeable improvements in terms of packet delivery ratio. The achievable gain for individual links that are experiencing poor SINR could be significant. More comprehensive studies are needed to optimize the parameters (e.g. length of the time window, '*m*', over which the SIR per link is averaged) involved in our proposed algorithm.

As shown in Figure 4, the genie LA boundary indicates that there is possibility of achieving more gain by using better LA schemes. However, limited energy constraints of sensor nodes could make developing low complexity LA schemes a challenge. In the future, we plan to study and develop more sophisticated LA schemes for multi-BAN scenarios to narrow the performance gap with the genie-LA bound. In addition, we conjecture that a combination of the link and energy detection threshold adaptations could lead to even better performance. Several such strategies are currently under investigation.

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