Using RTS/CTS to Enhance the Performance of IEEE 802.15.6 CSMA/CA

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***Abstract*— IEEE 802.15.6 is a radio interface standard for a 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 requirements impose stringent constraints on the reliability, and quality of service performance in these networks. Assuming CSMA/CA MAC protocol as outlined in the IEEE 802.15.6 standard Intra-BAN interference as well as interference from other co-located BANs or nearby devices sharing the same spectrum could greatly impact the data link reliability in these networks. Specifically, inter-BAN interference caused by hidden and exposed nodes could lead to higher packet delays or lower successful packet reception. In this paper, we study the use of a RTS/CTS handshake mechanism to improve the performance of IEEE 802.15.6-based CSMA/CA when multiple co-located BANs are present. Simulation results demonstrate that the introduction of RTS/CTS mechanism is able to significantly reduce packet collisions, resulting in a tangible improvement in system performance.**

Keywords- body area networks, CSMA MAC protocols, interference, RTS/CTS handshake

I. INTRODUCION

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. With the anticipated widespread commercial use of this technology, it is conceivable that there will be scenarios where multiple people wearing BANs are in close proximity of each other. Such multi-BAN scenarios combined with complexity and variability of the transmission channels in these networks could lead to instances of the hidden & exposed node problem [2].

In wireless networks, the hidden node problem occurs when a transmitting node is visible by a controller or access points but the same node is hidden from other nodes that are trying to gain access to the same controller. This situation could lead to collisions under a CSMA/CA MAC protocol which in turn leads to delay in packet transmission from the nodes. Another relevant problem in wireless networks is the exposed node problem. This problem occurs when a transmitting node is prevented from sending packets to the controller/access point because of a neighboring transmitter.

RTS/CTS handshake mechanism has been proposed as an optional mechanism to resolve collisions due to hidden node problem in IEEE 802.11 wireless networking protocol. It can also help with the exposed node problem if we assume the transmitting node can hear the CTS in most scenarios. Authors in [9,10] demonstrated that deploying RTS/CTS handshake in IEEE 802.15.6 CSMA/CA under non-saturation regime could degrade the network performance in case of poor Signal to Noise Ratio (SNR). However, the study was carried out considering a single BAN and using a non-realistic on-body channel model. For the case of several adjacent BANs, the Signal to Interference & Noise Ratio is expected to vary depending on the mobility pattern of BANs. To the best of our knowledge, the impact of RTS/CTS mechanism has not been analyzed for such scenarios. In this paper, we consider using RTS/CTS mechanism as part of the IEEE 802.15.6 CSMA/CA protocol to resolve some of the hidden/exposed node problems in multiple adjacent BAN scenarios.

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 is used for communication between the coordinator and the body sensors. Based on the location of the sensors in each BAN hidden node problem could occur when transmitting nodes cannot hear each other. This situation could happen due to body shadow (i.e. Non Line of Sight condition) even though the distance between the two nodes is not large. Figure 1(a) illustrates an example of this case. Node A can hear its corresponding coordinator C in BAN 1 as well as the coordinator D of BAN 2; but, it cannot hear node B. Similarly, node B can hear both coordinators C and D but not node A. In this case, each node (A or B) creates interference on the other node's respective coordinator; and, if this interference is high, coordinators C and D will not be able to successfully receive any packets from their corresponding transmitters.

An example of the exposed node problem for multiple co-located BANs is shown in Figure 1(b). In this case, node A can hear node B and its coordinator C in BAN 1. At the same time, node B can hear node A and its corresponding coordinator D in BAN 2. If there is a transmission between node A and coordinator C, node B after sensing the channel will mistakenly conclude that the channel is busy and will refrain from transmitting. Similar situation exists for node A, when node B starts to transmit. This situation will add to the delays experienced by the packets that are awaiting transmission from nodes A or B.

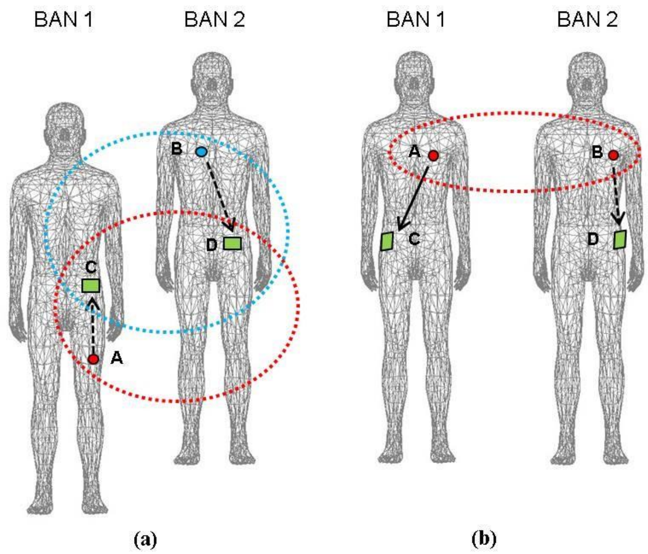

Figure 1. Example of (a) Hidden and (b) Exposed node problem in a multi-BAN system

Hidden and exposed node problems in multi-BAN scenarios can negatively impact links throughput or experienced packet delay. The inter-BAN interference (caused by hidden/exposed nodes) can either lead to an increase in the number of collisions or affect the channel sensing process of the CSMA/CA protocol under IEEE 802.15.6. In this paper, we propose using RTS/CTS handshake mechanism to eliminate this problem and enhance the performance of the IEEE 802.15.6 CSMA/CA protocol. We provide extensive simulation analysis to quantify the amount of gain in average packet delay and packet delivery ratio for several scenarios.

The rest of this paper is organized as follows. Section II briefly describes the implementation of RTS/CTS mechanism within the IEEE 802.15.6 CSMA/CA MAC protocol along with relevant parameters and simulation scenarios considered for performance evaluation. Section III provides the Packet Delivery Ratio (PDR) and average delay performance results obtained through our multi-BAN simulation platform [3, 7]. Finally, conclusions and future research plans have been discussed in section IV.

II. RTS/CTS IMPLEMENTATION

A simulation platform that can be used to study and measure inter-BAN interference among multiple adjacent body area networks has been presented in [7]. In [3], we implemented a simplified version of the IEEE 802.15.6 CSMA/CA protocol on this platform and investigated the impact of the energy detection threshold in a multi-BAN environment. The simplification refers to the fact that only the Contention Access Phase (CAP) in a Super-Frame (SF) was considered. In addition, perfect synchronization between sensor nodes and the coordinator of each BAN was assumed. This means that beacon frames are always received by all sensor nodes i.e. there are no connectivity issues among the nodes of a single BAN.

Here, we propose to modify the CSMA/CA protocol by incorporating a RTS/CTS mechanism for packets transmission as follows. When a BAN node needs to transmit a data packet, a back-off counter (BC) is chosen randomly within the interval [1 CW], where CW ∈ [CWmin CWmax]. CWmin and CWmax depend on the traffic type priority. Then, if the channel is determined to be idle for an interval of time equal to pSIFS (Short Inter Frame Spacing), the BC (corresponding to the node) is decremented by one for each idle slot that follows. Once the BC reaches zero, the node sends an RTS signal to the coordinator to indicate that it is ready for transmission. If the current Signal-to-Interference & Noise Ratio (SINR) for the link is assessed to be above the minimum required SINR, then the coordinator replies to the node with a CTS signal. The duration of RTS/CTS exchange has been considered to be one CSMA slot, i.e. 145 μsec. Longer durations, equivalent to the length of several slots, were also considered but the results were essentially unaffected. When the node receives the CTS, then it starts transmitting the corresponding data packet in the next time slot. If the node does not receive the CTS, it will keep repeating the above procedure until it gets a permission (i.e. CTS) from the receiver to transmit. A node assessment of the transmission channel (i.e. idle/busy) is done according to the Clear Channel Assessment (CCA) Mode 1 described in the standard document which involves the use of an Energy Detection (ED) threshold [8].

Hidden and exposed node problems taken into account in this paper are those caused by nodes that are located on different adjacent BANs. Within each BAN, it is assumed there are no hidden node problems. This means that all sensor nodes of a BAN can hear transmissions from one another. However, simultaneous transmissions might still occur if these sensor nodes set their BC to the same random value. Our results in the next section will show that a small size for the interval associated with the back-off counter could indeed lead to a high percentage of simultaneous transmissions by the sensor nodes of a single BAN.

To assess the performance of using a RTS/CTS mechanism, we have considered three simulation scenarios. The first simulation scenario consists of eight stationary BANs each having 3 on-body sensors and one coordinator node as shown in Fig. 2. The coordinator is marked by a green square while on-body sensors are shown with red circles. This scenario is intended to emulate eight people (each wearing a BAN) sitting around an oval-shaped table. Similar scenarios, such as people sitting in a bus or train can also be designed if needed. The second simulation scenario involves 8 BANs again with 3 on-body sensors and one coordinator. The BANs are moving toward each other with a fairly uniform speed (see Fig. 3). As BANs gets closer to each other, inter-BAN interference is expected to monotonically rise for all the links in the system. This is considered to be a special test scenario used to evaluate the performance of RTS/CTS under increasing cross-interference.

Figure 2. Sample multi-BAN Meeting Scenario

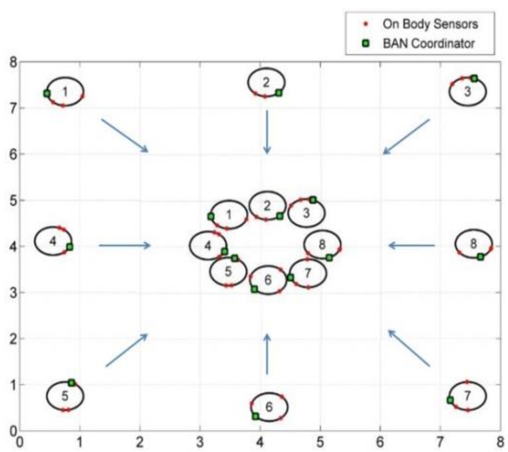

Figure 3. Sample multi-BAN Circle Scenario

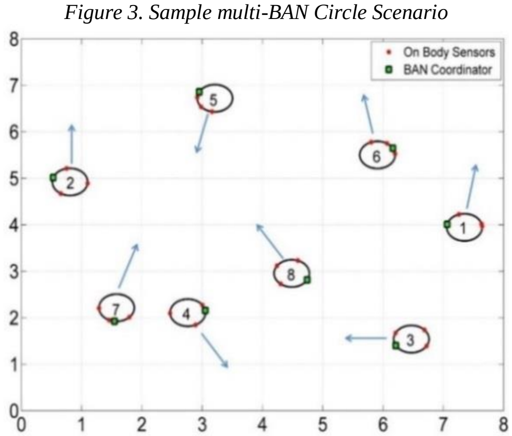

Figure 4. Sample multi-BAN Random Moving Scenario

The third simulation scenario considers the same eight BANs moving randomly in a space with dimensions 8m x 8m (see Fig. 4). 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. Other special movement patterns can be incorporated in our platform if desired.

Intra-BAN channel models used in our simulations correspond to the 2.4 GHz ISM frequency band. We assume that these channel models are also valid for use in the recently adopted MBAN frequency due to its proximity to the ISM band [4]. Inter-BAN channel models used for the above scenario are based on [5, 6]. We have only used channel models associated with tangentially polarized antennas, as they result in less inter-BAN interference compared with normally polarized antennas [7].

III. PERFORMANCE RESULTS

In our simulations, traffic at each sensor node has been modeled by a Bernoulli process. So, packet generation rate denoted by *GenRate* varies in the interval [0 1] and represents the probability that a node 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 by the following:

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

The queue size at each sensor node has been assumed to be infinite. Also, we consider an unlimited number of retransmissions for the backlogged traffic at each node of a BAN. These assumptions will allow us to evaluate the average packet delay without incurring any packet drops.

Among the different Modulation and Coding Schemes (MCSs) defined for the ISM band in the IEEE 802.15.6 standard (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

Looking at the transmission from sensor nodes to the coordinator, we evaluate the multi-BAN system performance in terms of the following metrics: Average Packet Delay, Average Number of Retransmissions per sensor and Average Packet Delivery Ratio (PDR) per BAN. 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:

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

Average number of retransmissions (ReTx) per sensor is given by:

$$\frac{1}{n}\sum_{i=1}^{n}\frac{Total\ \#\ of ReTx\ for\ sensor\ i}{Total\ \#\ of\ Transmitted\ Packets\ by\ sensor\ i}$$

where n is the total number of sensor nodes in the system. Finally, the average PDR per BAN is defined as:

$$\frac{1}{N}\sum_{j=1}^{N}\frac{\#\ of Packets\ correctly\ received\ in\ BANj}{Total\ \#\ of\ Packets\ generated\ in\ BAN\ j}$$

where N is the number of BANs in the system.

Figure 5 shows the percentage of average number of simultaneous transmissions as a function of the traffic load per BAN for different User (i.e. traffic) Priorities (UP). Although, this figure displays the result for the meeting scenario, similar behavior is also observed for the circle and random moving scenarios. Those plots have been omitted for brevity. As outlined in section II, the percentage of simultaneous transmissions within a single BAN depends on the size of the interval associated with the back-off counter. As expected, a lower UP allows for wider back-off counter interval; and therefore, a lower percentage of simultaneous (i.e. colliding) transmissions.

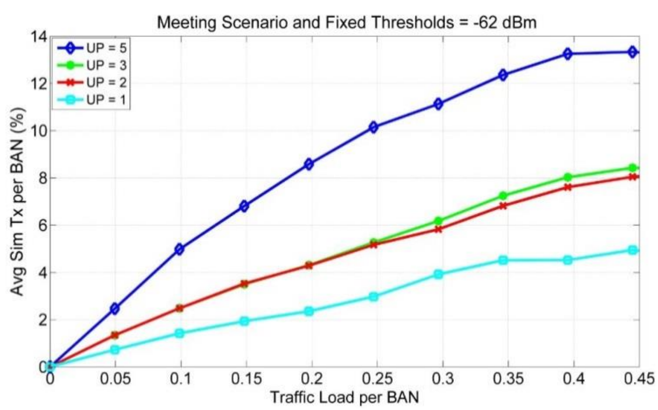

Figure 5. Percentage of simultaneous transmissions per BAN for different UPs (Meeting Scenario)

For the results presented in the following we have assumed a UP equal to 5 (e.g. medical data or other high priority traffic) for all sensors in the system. This implies a 10% to 14% simultaneous intra-BAN transmissions for traffic loads greater than 0.25. This is a significant number of collisions that a RTS/CTS mechanism can also prevent. For example, if two or more sensor nodes belonging to the same BAN are ready to transmit at the same time (i.e. all of their BCs hit zero simultaneously), then they all send a RTS signal to the coordinator. If at least one RTS signal is above the minimum required SINR level, then the coordinator will send one CTS signal to the corresponding node, and collisions will be avoided. If all received RTS signals are below the required SINR threshold, then all transmitting nodes enter the back-off process. In this way, any unnecessary transmissions that can possibly create interference for other BANs are avoided.

Figures 6 and 7 show the improvements in terms of average delay, average number of retransmissions and average PDR by implementing RTS/CTS mechanism for the meeting scenario case. The gain in performance is especially visible when traffic load is higher than 0.30. In addition to preventing simultaneous intra-BAN transmissions, RTS/CTS exchange reduces collisions and packet losses due to hidden and exposed node problems.

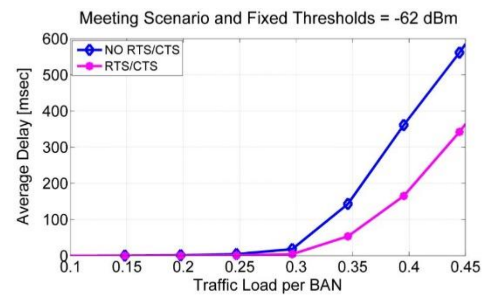

Figure 6. RTS/CTS Performance in terms of Average Delay for Meeting Scenario

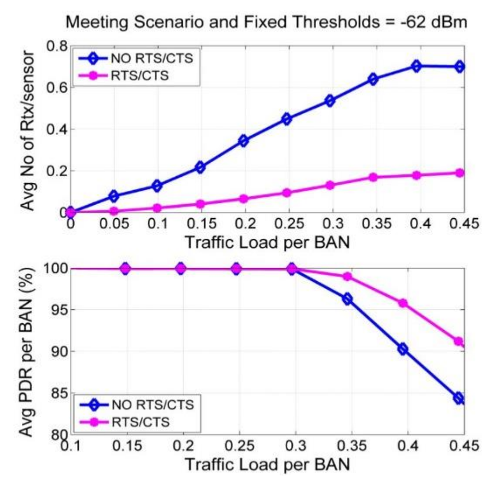

Figure 7. RTS/CTS Performance in terms of Average No of Retransmissions and Packet Delivery Ratio for Meeting Scenario

As observed in Figure 7, for high traffic loads the average number of retransmissions per node is much lower (i.e. 20%) compared to the case with no RTS/CTS mechanism (i.e. 70%). This, in turn, results in lower average delay (i.e. waiting time) experienced by the packets in the queue and a higher PDR at each BAN (i.e. > 90%).

Figure 8 and 9 show similar results obtained for the circle and random moving scenarios. In both scenarios, the gain in using RTS/CTS handshake mechanism remains significant. Average numbers of intra-BAN simultaneous transmissions as a function of traffic load for the other two simulated scenarios are shown as a graph in the lower right quadrants of Figures 8 and 9.

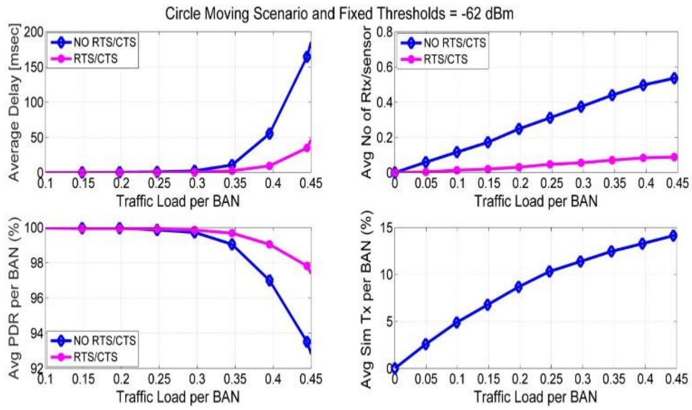

Figure 8. RTS/CTS Performance for Circle Moving Scenario

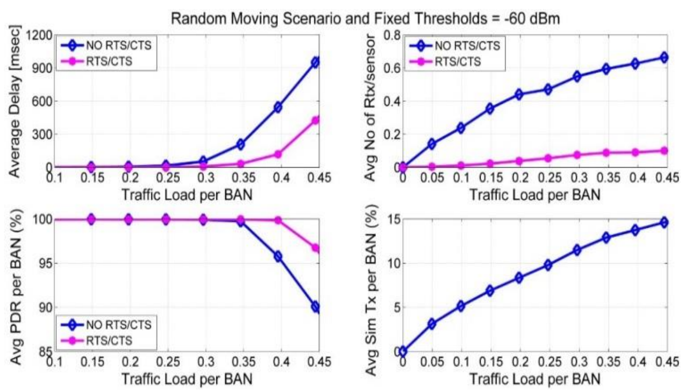

Figure 9. RTS/CTS Performance for Random Moving Scenario

IV. CONCLUSIONS

The main focus of this study is to highlight the impact of hidden and exposed node problems as well as possibility of simultaneous intra-BAN transmissions on the QoS performance of the CSMA/CA protocol of IEEE 802.15.6 for scenarios with multiple adjacent body area networks. High inter-BAN interference caused by nodes located on neighboring BANs could lead to higher average packet transmission delay and lower delivery ratio. The complexity of BAN transmission channel and natural mobility of the BANs and their individual nodes could create instances of hidden/exposed nodes problems when several BANs are in close proximity of each other. Simultaneous transmissions within the same BAN might also occur due to random selection of the same back-off counter if the size of the interval [1 CW] is small.

In this paper, we have shown that the RTS/CTS handshake mechanism in conjunction with CSMA/CA protocol is able to avoid colliding transmissions and reduce packet losses due to hidden and exposed interfering nodes in multi-BAN scenarios. Our results show that using RTS/CTS mechanism can lead to substantial reduction in number of retransmissions and significant gains in average packet delay and packet delivery ratio. The authors realize that there is an overhead cost to use a RTS/CTS mechanism and more sophisticated analysis might be required to measure the gains associated to using such handshakes protocol. However, our initial results show a noticeable advantage to use RTS/CTS in conjunction with the CSMA/CA protocol of a body area network.

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