Interference Aware Adaptive Clear Channel Assessment for Improving ZigBee Packet Transmission under Wi-Fi Interference

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***Abstract*—The low-power, low-rate ZigBee/IEEE 802.15.4 wireless sensor network (WSN) is vulnerable to the interference from a collocated wireless local area network (WLAN), which operates with considerably higher power in the same 2.4GHz Industrial, Scientific, and Medical (ISM) band. In this paper, a novel and effective Interference Aware Adaptive Clear Channel Assessment (IAACCA) technique is proposed to countermeasure the presence of interference with consequence to improve the performance of packet transmission between ZigBee nodes. The performance evaluation has been done through experimentation performed on a testbed implemented by the authors.**

***Keywords*—wireless sensor network; coexistence; clear channel assessment.**

I. INTRODUCTION

ZigBee is a standard-based wireless technology for low-cost and low-power wireless sensor networks (WSN). It is easy to implement and can be widely used in various applications, products, or services for a broad range of markets such as consumer electronics, energy management, healthcare, and home/building/industrial automation. ZigBee devices are operating at Industrial, Science and Medial (ISM) unlicensed band, which is heavily used by many unlicensed products such as microwave ovens, cordless phones, IEEE 802.11b/g/n Wi-Fi wireless local area networks (WLAN) and Bluetooth wireless personal area networks (WPAN). There are already confirmed interference problems between collocated devices of different nature [1, 2], and the expectation is that the problem will worsen as the density of such devices per square meter increases. Among all interferers, 802.11b/g/n WLAN can cause ZigBee networks the most severe problem due to the considerably higher level of transmit power it uses, increasing volume of traffic it carries, and the pervasive deployment of its devices. Therefore, it is important to understand and quantify how the interfering Wi-Fi devices impact the performance of ZigBee packet transmission and design effective counter-measuring techniques for performance improvement.

In recent years, the coexistence issues between IEEE 802.11b/g/n WLAN and ZigBee/IEEE 802.15.4 WSN have been extensively studied in quite a few papers (e.g. [1]-[7]). [1] and [2] performed comprehensive experimental measurements on the performance degradation between collocated IEEE 802.11g/n and IEEE 802.15.4 networks. In [3]-[6], analytical models and approaches have been proposed to analyze the performance of ZigBee network subjected to the interference generated by Wi-Fi and Bluetooth nodes. [7] studied the impact of clear channel assessment (CCA) mode on the performance of a ZigBee network operating in collocation with an interfering Wi-Fi network via analysis and simulation.

In addition, there are quite a few performance improvement schemes proposed recently in the open literature, which address the interference problem between WLAN and ZigBee/IEEE 802.15.4 WSN (e.g. [8]-[16]). Frequency agility-based interference avoidance algorithms (e.g. [8] - [10]) utilize interference detection (e.g. energy detection or frame error rate) and active scan to perform smart channel selection. These methods need to interact with the network coordinator for interference detection and/or for coordinating the change of operating channel. Switching the operating channel of the entire WSN cluster generates considerable extra cost (e.g. power consumption, delay, possible loss of frames) to the network. Particularly, when there are several WLAN access points (APs) in the vicinity operating at different channels, channel switching might happen very often, leading to unstable WSN operation. [11] proposed a technique to adaptively optimize the CCA energy detection (ED) thresholds of IEEE 802.15.4 WSN in order to mitigate interference from IEEE 802.11b/g WLAN. The ED threshold is adaptively increased or decreased according to the rate packet transmissions are aborted due to the channel been detected as busy. However, we observed in our experiments that in many cases only a very small portion of ZigBee packets are denied access to the channel, while the packet loss rate (PLR) is very high because of collision with Wi-Fi packets. When the channel is detected to be idle by CCA, the packet is sent out immediately but still has a good chance of colliding with a Wi-Fi packet, because ZigBee packets have considerably longer transmission times compared to those of Wi-Fi packets (this is due to the considerable difference of transmission speeds between ZigBee and modern Wi-Fi such as IEEE 802.11b/g/n). Regardless of being able to reduce the number of aborted packet transmissions, the proposed approach cannot reduce the packet loss due to collisions. In [12] and [13], performance improvement schemes based on adjusting the parameters of the exponential backoff algorithm were proposed. These schemes do not have the capability of exploiting the free-of-use time and/or spectrum segments in order to make the packet

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transmission more reliable. In [14], an adaptive collocated-collaborative coexistence mechanism that utilizes the received signal strength indication (RSSI) and channel utilization information contained in WLAN's beacon frame was proposed. This scheme needs the collaboration between WLAN and ZigBee network, which is not easy and flexible for practical low cost implementation. This collaboration will generate extra costs not only to ZigBee devices but to the WLAN nodes as well. [15] proposed to perform an additional CCA carrier sensing (CS) for more accurate determination of whether a data packet should be transmitted after the acknowledgement packet or not. However, this algorithm only addressed a very special circumstance of CCA failure that applies to slotted CSMA/CA. The preliminary adaptive mechanism presented in our previous research [16] achieves performance improvement by selecting CCA mode or ED threshold value adaptively according to varying Wi-Fi interference. However, this mechanism requires some initial testing to determine the best performed CCA mode and ED threshold, and can only be applied in certain scenarios where varying external interference results in performance tradeoff between transmission buffer overflow and collision loss.

Motivated by the above, in this research, a novel and effective Interference Aware Adaptive Clear Channel Assessment (IAACCA) technique is proposed to improve the performance of ZigBee packet transmission under the interference of collocated Wi-Fi connection. The proposed technique has been implemented in Crossbow MICAz motes, and a ZigBee WSN and IEEE 802.11g WLAN collocation testbed is established and used to experimentally evaluate its performance. Extensive performance evaluation experiments were carried out and the results show that IAACCA can significantly improve the performance of ZigBee packet transmission when operating in close proximity with a WLAN.

The remainder of this paper is structured as follows. In Section II, the testbed and system parameters are introduced. Section III presents the proposed IAACCA scheme. The experimental results are presented and analyzed in Section IV. Finally, conclusions are drawn in Section V.

II. TESTBED AND EXPERIMENT SETUP

Since theoretical analysis and computer simulation often have the risk of leaving the impact of hidden factors on the performance unaccounted because of the simplified models and assumptions they used, we pursue this research by implementing a testbed, using the existing off-the-shelf computing and communication devices as platforms to implement the proposed technique and run extensive experiments to evaluate its performance under various conditions. Such testbed provides an effective compromise between simulation and deployment, and supports experimentation with actual devices in a realistic environment so as to capture the realism those simulations miss.

The testbed consists of ZigBee motes and Wi-Fi nodes. As shown in Fig. 1, a laptop running Distributed Internet Traffic Generator (D-ITG) [17] is connected to an Ethernet port of an IEEE 802.11 b/g/n wireless router (WR) (ASUS RT-N16 router) which serves as Wi-Fi traffic source/transmitter. A Dell Inspiron 1545 laptop with Dell Wireless 1515 (IEEE 802.11 a/g/n) WLAN half mini-Card (Atheros) installed is used as Wi-Fi sink node. WR is used as Wi-Fi transmitter because it provides stable transmission power and can be set to operate at different transmit power levels with the DD-WRT [18] OpenSource router firmware, thus enabling control on the interference strength applied to the ZigBee packet transmissions. One Crossbow MICAz mote equipped with IEEE 802.15.4-compliant CC2420 transceiver is used as ZigBee client, transmitting IEEE 802.15.4 traffic with different packet sizes, packet generation rates and inter-departure time (IDT) distributions to the ZigBee coordinator, which is a MICAz mote installed on a Crossbow MIB600 programming board. A PC is connected to the MIB600 board, collecting the received data from the ZigBee coordinator. Custom ZigBee client and coordinator software programs were developed and run on the MICAz motes. The client software samples the RSSI in the motes for monitoring the external interference and noise level, and allows controlling the packet size, generation rate and IDT distribution. In addition, the ED threshold and transmit power of the motes can be adjusted as needed. The coordinator software collects the received data packets and performs statistic tasks such as calculating the number of received packets, cancellation packets, and so on.

The results reported in this contribution involve the existence of one active IEEE 802.11g Wi-Fi connection and one active ZigBee connection. The distance between WR and the ZigBee source mote is 1m and the distance between the Dell laptop and the ZigBee coordinator is 2m. There is a strong line-of-sight path between the ZigBee source mote and coordinator, with a distance of 1.5m. In our testbed, the traffic generating laptop and the experimental data collecting PC are connected by Ethernet cable to the WR and the ZigBee coordinator respectively. Thus their distances can be ignored and have no impact on the testing results. The Wi-Fi router uses 50 mW transmitting and generates IEEE 802.11g traffic; the transmitting mote sets the power to 0 dBm when sending out its IEEE 802.15.4 packets.

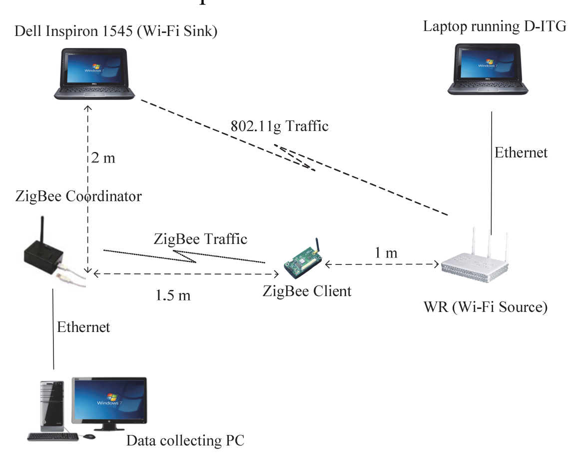

Figure 1. Testbed setup for studying Zigbee packet transmission under collocated Wi-Fi interference.

Fig. 2 shows the bandwidth allocation of WLAN and ZigBee at the ISM band. By scanning all the Wi-Fi channels, it is found that ZigBee channel 20 (2.449-2.451GHz) is not "contaminated" by interference from any other Wi-Fi APs in the building. To minimize the interference from other coexisting WLANs, ZigBee channel 20 is used as our ZigBee operating channel. In addition, since ZigBee channel 20 is located within the range of Wi-Fi's channel 9 (2.441-2.463GHz) where the power spectral density is the strongest, Wi-Fi channel 9 is used with the WR of our testbed to investigate the ZigBee packet transmission performance in the worst case scenario.

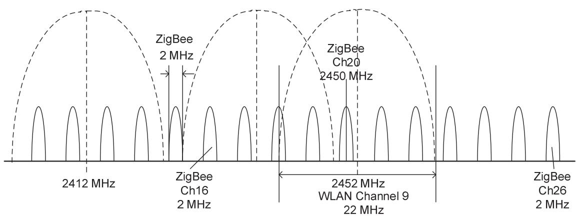

Figure 2. Bandwidth allocation of WLAN and ZigBee at 2.4 GHz band.

III. INTERFERENCE AWARE ADAPTIVE CLEAR CHANNEL ASSESSMENT TECHNIQUE

A new technique we have named Interference Aware Adaptive Clear Channel Assessment (IAACCA) is proposed to improve the performance of ZigBee packet loss rate when there is varying interference from the collocated Wi-Fi system. CCA is performed before the transmission of each ZigBee packet in order to decide whether the medium is busy or not. The default CCA mode of CC2420 of MICAz motes adopts both carrier sense and energy detection (CS-ED) with -77 dBm threshold. The proposed IAACCA scheme adopts the default CCA mode of CS-ED, with the emphasis placed on improving the ED mechanism. With ED, CCA shall report a busy medium upon detecting any energy above the ED threshold (P_{th}). Use of the ED option improves coexistence by allowing transmission backoff if the channel is occupied by any device, regardless of the communication protocol it may use. The proposed IAACCA scheme makes use of the inter-arrival time occurring between two subsequent ZigBee packet transmissions to perform estimations of the external interference level.

In the proposed IAACCA scheme, a full cycle of channel assessment consists of N channel assessment periods (CAPs). Channel assessment starts after a ZigBee packet transmission. Two types of channel assessment are performed during each CAP. One is the estimation of the length of channel's idle period (EL) and the other is spectrum sensing (SS). The purpose of estimating the channel's idle period is to find out if it is long enough to accommodate the transmission of a ZigBee packet. The EL values are used to determine whether there is a need to shorten the ZigBee packet's payload size and consequently the size of the packet. On the other hand, spectrum sensing is used to search for ZigBee channels that are at better condition than the one in use, in order to switch when necessary. It is noted that the channel sensing scheme we developed is different from the approach used in the current devices when selecting operational channel as well as those proposed in earlier publications (e.g. [8] - [10]). Switching to a better quality channel should be activated when the estimated length of currently used channel's idle period is too short to accommodate the transmission of ZigBee packets of minimum size, i.e., the size of header plus minimum payload that is required by the corresponding applications.

During the EL of each CAP, the transmitting mote continuously acquires a certain number (N_d) of RSSI readings of the current channel at time interval t_s and compares them with a pre-defined threshold P_{th}. The mote then calculates the maximum number (n_m) of successive RSSI measurements (among the N_d readings) where the measured value is lower than P_{th}. It is noted that up to 2 above-threshold RSSI readings which appear amidst a series of consecutive below-threshold RSSI readings will be ignored in order to avoid misjudgment caused by some sudden and brief energy fluctuation (e.g. a WLAN client scanning through all channels in search of an AP). This helps isolate the presence of consistent interference. The maximum length of channel idle period in this detection can be calculated as $T_{idle} = n_m \bullet t_s$. We denote the current ZigBee packet transmission duration as t_{cur_pkt} and the minimum acceptable ZigBee packet transmission duration as t_{min_pkt}. Since the PLR might be still acceptable even when the measured idle period is not long enough for the full length of the transmitted ZigBee packets, an empirical constant c ($0 < c < 1$) is also introduced to assist with the decision to adjust ZigBee's packet size. Obviously, the value of c is mostly influenced by the strength of the interference signal and the PLR requirement. After N CAPs, if the average length of channel idle period $\overline{T_{idle}}$ is larger than $c \bullet t_{cur\_pkt}$, it is decided that the channel is in good condition and no changes of packet size or operational channel are needed. If the average value satisfies $\{ c \bullet t_{min\_pkt} \leq \overline{T_{idle}} \leq c \bullet t_{cur\_pkt} \}$, it is decided that the channel is not in a good condition in terms of accommodating the current packet size, but remains good enough for supporting shorter packet sizes. Therefore the transmitting mote will shorten the packet to have a time duration of t_{min_pkt}. It should be noted that if the motes are powerful enough in terms of computation power, the packet size can be adjusted more precisely, setting the packet's transmission time to a value in-between t_{min_pkt} but smaller than $\overline{T_{idle}}/c$. If an increase in the length of channel idle period becomes detected in the following cycles of channel assessment, making $\overline{T_{idle}}$ larger than $c \bullet t_{cur\_pkt}$, the packet length can be restored to its original size in order to improve the transmission efficiency. If the $\overline{T_{idle}}$ is even less than $c \bullet t_{min\_pkt}$, the transmitting mote concludes that adjustment of packet size cannot help the connection to remain/become reliable and subsequently tries to locate another channel with better transmission conditions to switch, by following a policy elaborated in the following paragraph.

In the SS of each CAP, the transmitting mote randomly chooses one of the 16 ZigBee channels and performs the same estimation of the length of channel's idle period. It should be noted that the chosen channel can be different for each CAP. Using the collected SS results, a table of preference for the different ZigBee channels is constructed. The preference value of each channel is stored in one byte. Every time the measured T_{idle} is bigger than $c \bullet t_{cur\_pkt}$, the corresponding preference value of this channel in the table increases by 1, otherwise it remains unchanged. When any of the preference value goes over 255, i.e., the storing byte overflows, the entire preference table will be initialized with every channel's preference value reset to 0. When the transmitting mote needs to switch channel, it checks the preference table and chooses the channel with the highest preference value. Then the transmitting mote initiates a request to change its operating channel by informing the ZigBee coordinator of its preferred channel selection.

This channel assessment process is illustrated in the figure (Fig. 3) below.

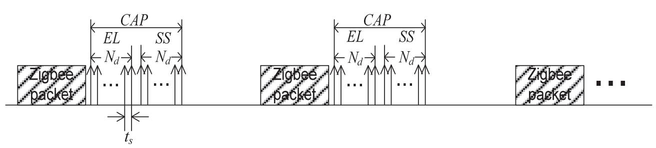

Figure 3. The new channel assessment process.

It is noted that such a full cycle of channel assessment is performed every T_{ca} seconds, depending on the needs of dealing with the changing Wi-Fi interference. For example, in an environment with very stable WLAN traffic profile, T_{ca} can be assigned a large value so as to save the energy in clear channel assessment.

The default CCA mechanism reads the RSSI value, which is an average value reflecting the signal strength during the previous 128μs, then compares it to the ED threshold. If the RSSI value is lower than the ED threshold, the channel is assumed to be idle and the ZigBee packet is transmitted right away. In the proposed IAACCA scheme, the transmitting mote increases the CCA detection accuracy by reading the RSSI value consecutively at a very short time interval of 16μs that accounts for a symbol's transmission period. This is also the period for updating the RSSI value used by CC2420. The packet transmission starts once N_s consecutive less than P_{th} RSSI readings have been counted. The value of N_s is selected randomly from within the interval $\{N_{s\_low}; N_{s\_high}\}$ (e.g. {3 and 6}) according to a uniform distribution. The values of N_{s_low} and N_{s_high} have been selected empirically. The reason to have the mote select random N_s is to avoid collisions among active motes waiting to transmit, i.e., it acts as a collision avoidance mechanism. If there aren't N_s continuous readings that satisfy the threshold requirement in N_{max} (e.g. 200) RSSI readings, the new sending mechanism will switch back to the default mode.

In the case of having to switch the channel, the transmitting mote sends a packet to the coordinator with its preferred channel number and waits for acknowledgement. The coordinator acknowledges the reception of this channel switch request and sends out the notice to the transmitting mote it communicates with, informing of the coming channel switch and indicating the selected preferred channel. The coordinator then waits for the acknowledgement from this mote. After successfully receiving acknowledgement from the transmitting mote, the coordinator starts the channel switching algorithm. It sends out N_i instruction packets which include a parameter of time interval t_{ins} between two consecutive instruction packets and a unique sequence number denoted as i. Each of these instruction packets is broadcasted and contains a request to the receiving mote to switch to the new channel. The mote will switch to the new channel after receiving one of instruction packets and wait for $(N_i - i) \bullet t_{ins}$ to start sending packets in the new channel. This algorithm can make the switching accomplished as long as one of the instruction packets is successfully received.

IV. PERFORMANCE EVALUATION RESULTS AND DISCUSSION

In order to validate the performance improvement of the proposed IAACCA mechanism, extensive experiments are performed using the testbed shown in Fig. 1. For the IAACCA scheme, the adopted values of the parameters introduced in section III are listed in Table I.

TABLE I. IAACCA EXPERIMENTAL PARAMETERS

Parameters	Values
P_{th}	-77dBm
T_{ca}	2s
t_s	16μs
N	16
N_d	250
N_i	10
N_{s_low}	3
N_{s_up}	6
N_{max}	200
c	0.8
t_{ins}	100ms

The ZigBee source mote generates traffic with constant packet rate and packet length. After each packet transmission, the source mote waits for acknowledgement (ACK) from the coordinator. If no ACK is received within a set time frame, the source mote retransmits the packet once. The D-ITG traffic generator running on the laptop generates UDP traffic with different packet payload, packet rate and IDT distribution, which are then fed into the WR for generating various interfering 802.11g Wi-Fi traffic. Such different interfering IEEE 802.11g UDP traffic is hereafter described and characterized by the packet payload size, packet rate, and the IDT distribution when generated by D-ITG. It is noted that data segments with payload size larger than 1500 bytes will be fragmented at MAC layer and then sent out in subsequently transmitted frames.

In the following, the ZigBee packet transmission performance comparisons between IAACCA and the default CCA mechanisms in terms of PLR are illustrated and discussed. It should be noted that, since switching the operating channel of the entire WSN generates considerable extra cost to the network and also for the purpose of performing a fair comparison between the proposed IAACCA and the default CCA mechanisms, the channel switching function of IAACCA is disabled for our experiments shown in Figs. 4-14. The experimental results when employing channel switching function are discussed at the end of this section. For the conciseness of notation, in all figures hereafter, we denote IAACCA with 50-byte packet as A50 and with 100-byte packet as A100; and denote default CCA with 50-byte packet as D50 and with 100-byte packet as D100. All the data bars are marked with a 95% confidence interval.

Figs. 4-8 illustrate the performance of ZigBee packet transmission with a constant packet rate of 50 packets/second in terms of PLR under different Wi-Fi interferences. In Fig. 4, the D-ITG is set to generate UDP packet sequences having constant packet IDT at the rate of 500 packets/second. Performance was evaluated for three different payload sizes: 900 bytes, indicated in Fig. 4 as test 1; 1400 bytes, indicated as test 2; and 1800 bytes, indicated as test 3. Fig. 5 depicts the ZigBee transmission performance under interfering UDP traffic with packet payload size of 1400 bytes and different packet rates, namely, 300 packets/second (test 4), 400 packets/second (test 5), and 600 packets/second (test 6). In test 4 and test 5, the PLRs are almost the same although test 4 has a lower volume of interference than test 5. The reason is that in both cases, the channel idle duration is long enough for accommodating a 100-byte ZigBee packet.

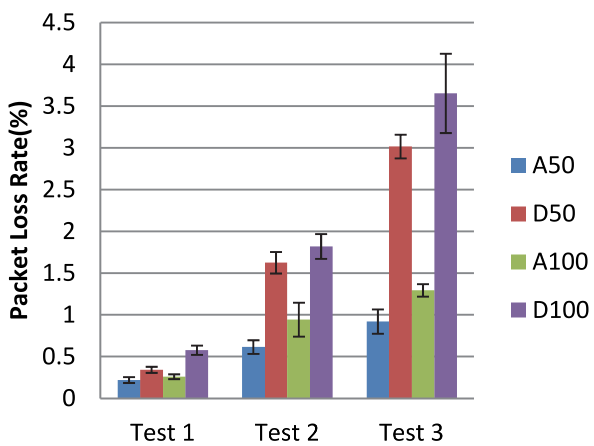

Figure 4. ZigBee PLR perfomance with default CCA or with IAACCA, in the presence of different interfering traffic with packet payload sizes of 900 bytes (test 1), 1400 bytes (test 2), and 1800 bytes (test 3).

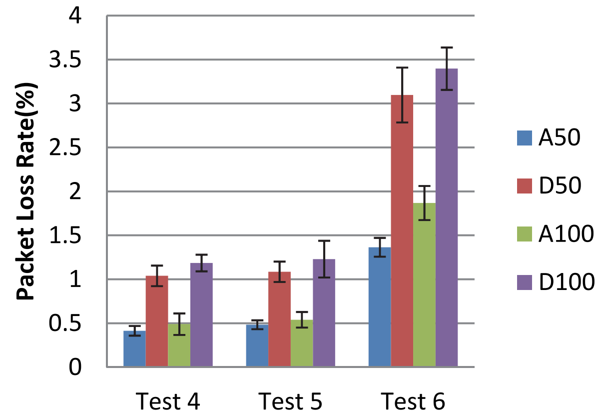

Figure 5. ZigBee PLR perfomance with default CCA or with IAACCA, in the presence of different interfering traffic with packet generation rates of 300 packets/second (test 4), 400 packets/second (test 5), and 600 packets/second (test 6).

In Fig. 6, the packets generated by D-ITG have the same packet payload size of 1400 bytes and the IDT following two different random distributions, i.e., Uniform distribution between packet rate of 250 to 750 packets/second (test 7) and Exponential distribution with IDT mean of 2ms (test 8). Similarly, in Fig. 7, the generated UDP packet payload sizes follow three different random distributions, namely, Uniform distribution between 900 to 1800 bytes (test 9), Exponential distribution with mean of 1400 bytes (test 10) and Normal distribution with expected value of 1400 bytes and standard deviation of 500 (test 11). In Fig. 8, both the packet payload size and generation rate of interfering UDP traffic are randomly distributed. Test 12 adopts Uniform distributions of packet payload size between 900 to 1800 bytes and packet rate of 250 to 750 packets/second.

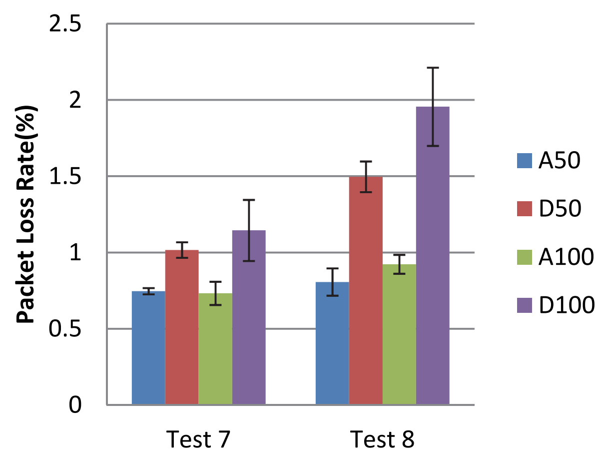

Figure 6. ZigBee PLR perfomance with default CCA or with IAACCA, in the presence of different interfering traffic with random IDT following Uniform distribution (test 7) and Exponential distribution (test 8).

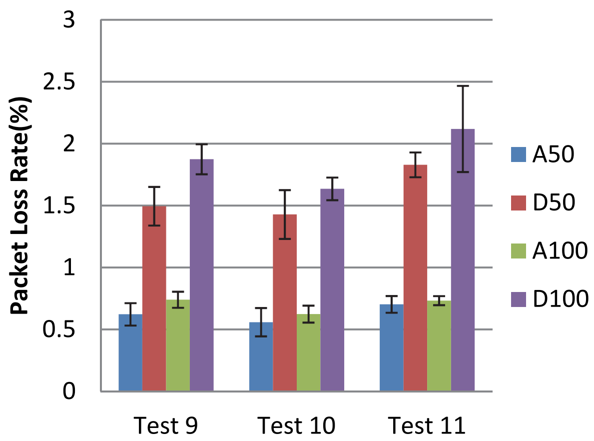

Figure 7. ZigBee PLR perfomance with default CCA or with IAACCA, in the presence of different interfering traffic with random packet payload sizes following Uniform distribution (test 9), Exponential distribution (test 10), and Normal distribution (test 11).

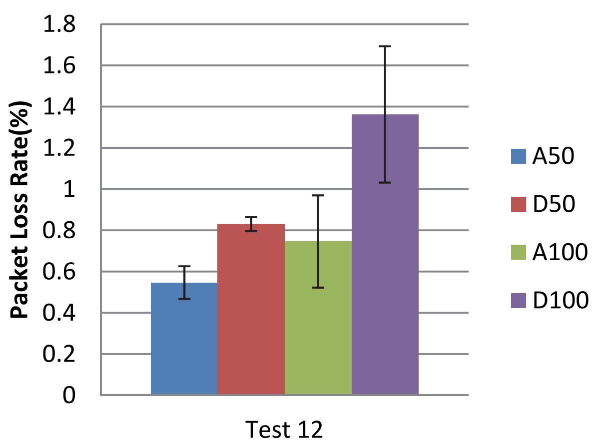

Figure 8. ZigBee PLR perfomance with default CCA or with IAACCA, in the presence of different interfering traffic with random IDT and random packet payload size both following Uniform distribution.

It can be observed from Figs. 4-8 that the proposed IAACCA mechanism achieved a much better performance compared to the default CCA. As expected, shorter packet size can reduce PLR compared to the longer one.

All experiments were repeated for ZigBee packet transmitted at a higher speed of 100 packets/second. It is noted that there is only one 128-byte transmission buffer (TXFIFO) in CC2420 for accommodating one data frame being transmitted at a given time. Therefore, a newly generated packet will be dropped if the TXFIFO is being occupied by the preceding frame that is still in the transmission process. In this set of experiments, due to the shorter ZigBee packet IDT, such TXFIFO overflow will worsen the performance of ZigBee packet transmission and the proposed IAACCA shall achieve a much better performance than the default CCA scheme. The obtained results are shown in Figs. 9-13.

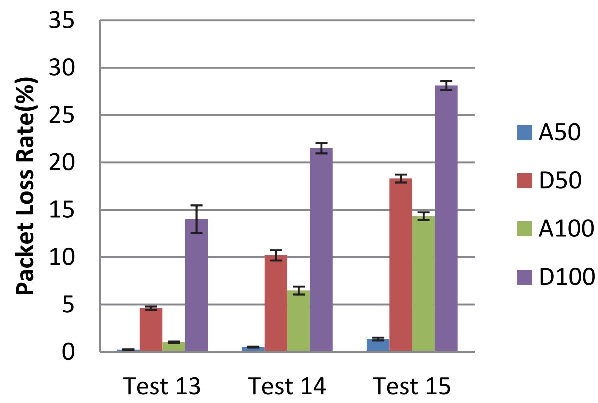

Figure 9. ZigBee PLR perfomance of 10ms IDT with default CCA or with IAACCA, in the presence of different interfering traffic with packet paylaod sizes of 900 bytes (test 13), 1400 bytes (test 14), and 1800 bytes (test 15).

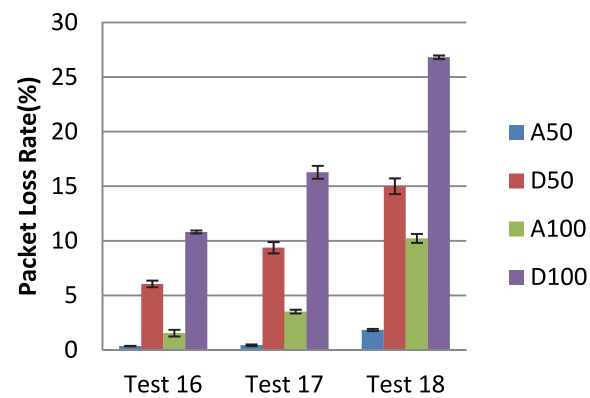

Figure 10. ZigBee PLR perfomance of 10ms IDT with default CCA or with IAACCA, in the presence of different interfering traffic with packet generationg rates of 300 packets/second (test 16), 400 packets/second (test 17), and 600 packets/second (test 18).

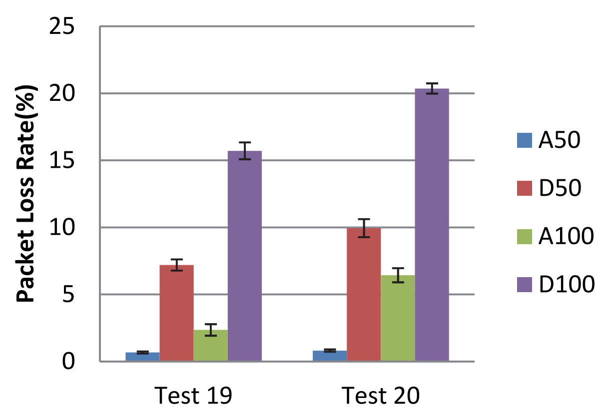

Figure 11. ZigBee PLR perfomance of 10ms IDT with default CCA or with IAACCA, in the presence of different interfering traffic with random IDT following Uniform distribution (test 19) and Exponential distribution (test 20).

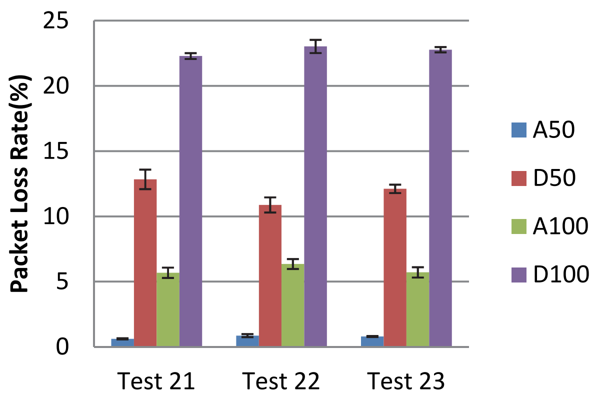

Figure 12. ZigBee PLR perfomance of 10ms IDT with default CCA or with IAACCA, in the presence of different interfering traffic with random packet payload sizes following Uniform distribution (test 21), Exponential distribution (test 22), and Normal distribution (test 23).

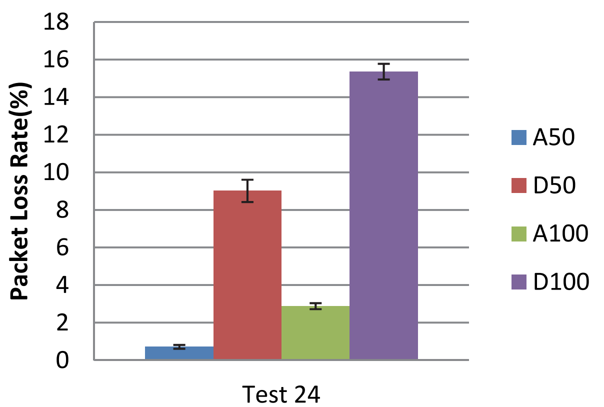

Figure 13. ZigBee PLR perfomance of 10ms IDT with default CCA or with IAACCA, in the presence of different interfering traffic with random IDT and random packet payload size both following Uniform distribution.

It can be seen from Figs. 9-13 that IAACCA achieves more significant performance improvement when ZigBee mote is transmitting at a higher packet rate. This is because the proposed IAACCA avoids the deficiency of the default CCA backoffs that could cause many packet drops due to TXFIFO overflow.

Additional experiments have been performed to address the effectiveness of the proposed packet size adaptation mechanism in IAACCA. In each of these experiments, the ZigBee transmitting node sends out a total of 10000 packets at a constant packet rate (CPR) of 20 packets/second and without retransmission. The interfering UDP traffic has a packet payload size of 1400 bytes and transmits at CPR of 600 packets/second. After 250 seconds (around halfway through the experiment), the UDP packet rate drops to 200 packets/second and maintains the same value until the end of the experiment. For convenience, we denote Th_{pkt} as the packet size adaptation threshold which equals to the transmission duration of a 100-byte ZigBee packet multiplied by *c*. We consider two ZigBee packet sizes in these experiments, i.e., 100 bytes and 50 bytes. It is observed in the experiments that the packet size adaptation mechanism works well and can adapt to the changes of interfering Wi-Fi traffic. The ZigBee transmission starts with a packet size of 100 bytes and then soon drops to 50 bytes because very short channel idle periods (below threshold Th_{pkt}) were detected. The packet size restores to the original 100 bytes after the interference decreases, i.e., idle period longer than Th_{pkt} has been detected. Fig. 14 shows an approximate 32% improvement in PLR when applying the packet size adaptation mechanism. This is particularly useful for ZigBee motes to transmit essential information with shorter packets in an environment with serious external interference to ensure acceptable PLR.

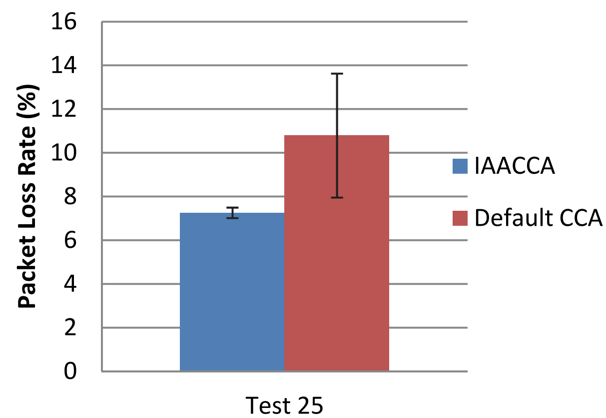

Figure 14. ZigBee perfomance comparison under interfering Wi-Fi traffic mixed of two different packet rates for IAACCA and default CCA.

Channel switching function is also tested in our testbed. It is observed that this function in IAACCA works nicely by successfully constructing a channel preference table. When the interference is getting worse, the mote and coordinator can switch to a channel that has the highest ranking in the table, i.e., has the least interference according to the results of the many spectrum sensings in the past. In our tests, since Wi-Fi channels 1, 6 and 11 are being used by other APs/WRs in the building, the ZigBee motes always switch to ZigBee channel 26 and thus experience only trivial packet loss. As mentioned in Section I, when there are several WLAN APs/WRs operating in different channels in the vicinity, channel switching might happen very often and lead to unstable WSN operation. In our proposed IAACCA scheme, switching operating channel is the last resort which only happens when the length of the channel's idle period cannot support the minimum acceptable ZigBee packet size. In addition, the channel preference table is constructed over a relatively long period of time and based on a number of spectrum sensing results, thus able to provide a better choice for selecting a channel to switch to and avoid the possible too frequent channel switching.

V. CONCLUSION

In this paper, we proposed a novel and effective Interference Aware Adaptive Clear Channel Assessment (IAACCA) technique to improve the performance of ZigBee packet transmission under Wi-Fi interference. The performance improvement has been validated and evaluated through extensive experiments carried out in our testbed. It is demonstrated from the experimental results and discussion that IAACCA can significantly improve the performance of ZigBee packet transmission in terms of packet loss rate when there is varying interference from the collocated Wi-Fi system. In addition, IAACCA has been implemented as firmware running on commercially available motes, which proves this proposed technology is easily implementable and fast deployable.

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