# On ZigBee Coexistence in the ISM Band: Measurements and Simulations

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***Abstract*—Wireless Sensor Network (WSN) technology enables design and implementation of novel applications that can be used to address numerous industrial, environmental, social and economical challenges. The IEEE 802.15.4 standard specifies WSN as a personal unlicensed network that operates in the Industrial, Scientific and Medical (ISM) unlicensed band. Unfortunately, this band is also available for many other wireless technologies like Bluetooth/ IEEE 802.15.1 and Wireless Local Area Networks (WLANs)/IEEE 802.11b/g. The blind coexistence between wireless technologies in the ISM band can lead to severe performance degradation due to undesired interference. This paper provides an overview on the performance of ZigBee WSNs/IEEE 802.15.4 coexisting with IEEE 802.11b/g WLANs. Through extensive measurements for packet error rate (PER), link quality indication (LQI) and received signal strength indication (RSSI) performance metrics, we were able to clarify the performance degradation due to the blind coexistence between IEEE 802.15.4 and IEEE 802.11b/g networks. We support the measurement results by extensive simulations using OPNET V.16 for large scale ZigBee WSNs coexisting with WLANs. We show that for robust operation in unlicensed bands, WSNs should be equipped with cognitive radio capability.**

***Index Terms*—ZigBee, IEEE 802.15.4, coexistence, IEEE 802.11b/g, OPNET, CC2430, cognitive radio, wireless sensor networks, ISM**

## I. Introduction

Nowadays, wireless sensor networks can be considered as the corner stone technology for many different applications. This is due to the specifications of its protocol architecture known as ZigBee. ZigBee belongs to the short range wireless technologies needed for portable and flexible connectivity [1]. The IEEE agency standardizes only the physical and MAC layers for WSNs leading to the IEEE 802.15.4 standard [2]. The main operating band for ZigBee based WSNs is the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. Since this band is unlicensed, it is shared with other technologies such as Wi-Fi, Bluetooth, Wi-Media, and microwave ovens. The blind coexistence of different devices in the same band and the overlapped spectrum of the different wireless technologies as in Fig. 1 result in mutual interference and thus performance degradation. In this paper, we investigate in details the problem of coexistence between ZigBee based wireless sensor networks and IEEE 802.11b/g WLAN networks. We specifically consider WLAN networks as they are widely deployed and have high transmission power capabilities that can excessively harm the ZigBee network performance if operated close to the sensor networks. In future smart home scenarios, both Zigbee networks and Wi-Fi networks are expected to co-exist, and thus a thorough analysis of their co-existence performance is needed. According to [4], [5], the IEEE 802.15.4 network has negligible impact on the IEEE 802.11 network performance. On the other hand, IEEE 802.11 can have a serious impact on the IEEE 802.15.4 performance, if adaptive channel allocation strategies are not considered [3], [6]. These previous papers have resorted to simple simulation models.

In this paper, we provide experimental analysis using real measurements with the CC2430 Texas Instrument hardware kits [7]. Our target is to evaluate the performance of ZigBee networks, when coexisting with WLAN networks using different metrics. We complement our indoor measurements with realistic simulations using OPNET [8] for coexistence scenarios with a larger number of sensors and interferers. The remaining of the paper is organized as follows: Section II presents a brief overview of the main characteristics of the IEEE 802.15.4 and IEEE 802.11 standards with a focus on their physical and MAC layers. The criteria used in analyzing the coexistence performance of ZigBee networks are described. In Section III, our measurement testbed setup is described. In Section IV, we present our testbed measurement results. In Section V, the OPNET simulation analysis of Zigbee coexistence in the ISM band is presented. The concept for cognitive radio wireless sensor networks for better coexistence is introduced in Section VI. Finally, we conclude the paper in Section VII.

## II. Overview Of The IEEE 802.15.4 and IEEE 802.11 Standards

### A. *The IEEE 802.15.4 Standard*

The IEEE 802.15.4 standard specifies the physical(PHY) and media access control(MAC) layers for low-rate Wireless Personal Area Networks(WPANs). ZigBee standard defines the network layer for multi-hop enabled wireless PANs [2]. The IEEE 802.15.4 physical layer(PHY) offers a total of 27 channels, 1 channel in the 868 MHz band, 10 channels in the 915 MHz band, and 16 channels in the 2.4 GHz band. The raw bit rates on these three frequency bands are 20 kbps, 40 kbps, and 250 kbps, respectively. In this paper we are concerned in analysing the performance of IEEE 802.15.4 in the third band, which lies in the 2.4 GHz ISM band. The IEEE 802.15.4 MAC sub-layer deploys one of two types of channel access mechanisms, un-slotted Carrier Sense Multiple Access with Collision Avoidance(CSMA/CA) mechanism in a non-beacon enabled networks and slotted CSMA/CA mechanism in beacon-enabled networks [10].

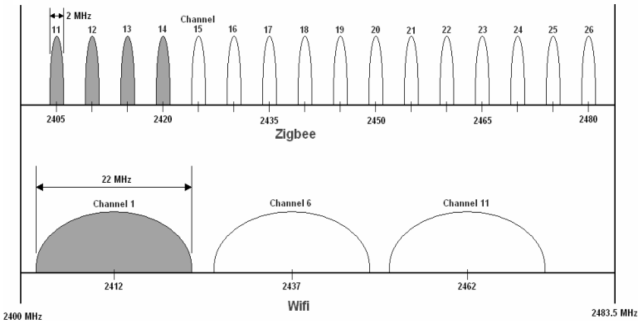


Fig. 1: The overlapping spectrum for different wireless technologies.

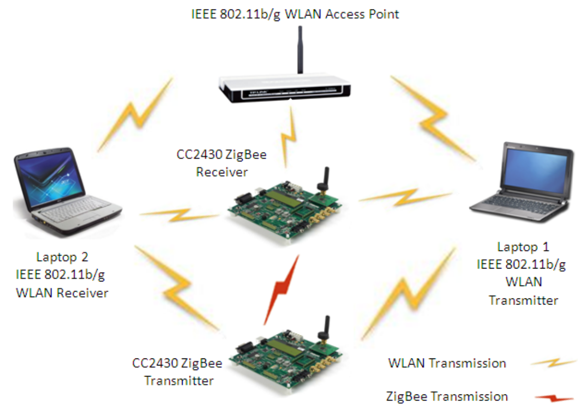


Fig. 2: Zigbee-WLAN coexistence testbed

### B. IEEE 802.11b/g Standards

The IEEE 802.11 is the standard defining the WLAN MAC layer and physical layer specifications. Both IEEE 802.11b and IEEE 802.11g amendments specify that compliant devices operate at 13 overlapping channels in the 2.4 GHz ISM band. The bandwidth of each channel is 22 MHz [11]. Different modulation techniques and air interfaces are deployed to support different data rates. For instance Complementary Code Keying (CCK) is used to provide up to 11 Mbit/s data rates and Orthogonal Frequency Division Multiplexing(OFDM) is used to provide up to 54 Mbit/s data rates.

The basic medium access mechanism of IEEE 802.11b/g, called Distributed Coordination Function(DCF), is a CSMA/CA mechanism. In addition, all individually addressed traffic uses immediate positive acknowledgement(ACK)where retransmission is scheduled by the sender if no ACK is received. An IEEE 802.11 b/g compliant station senses the channel before transmitting an initial frame. If the station recognizes that the medium is idle for a time more than or equal to a Distributed Inter Frame Space(DIFS) period, the frame will be transmitted. Otherwise, a random back-off algorithm is applied [11].

### C. ZigBee Performance Evaluation Metrics

We evaluated the performance of the ZigBee network in our coexistence measurement and simulation scenarios with the following metrics:

*1) RSSI:* It is the received signal strength. CC2430 has a built-in RSSI measurement which is indicated by a digital value read from an 8 bit register.

*2) LQI:* It is the link quality indicator. The LQI measurement is a characterization of the strength and/or quality of a received packet, as defined by IEEE 802.15.4 [2]. The LQI value is limited to the range 0 through 255.

*3) PER/PLR:* It is the packet error rate. The IEEE 802.15.4 system uses packets for all its communications. The sensitivity limit specified by [2] is based on Packet Error Rate(PER) measurements instead of bit error rates(BER). This is a more realistic measurement of the true RF performance since it mirrors the actual system level and link level performance.

*4) End-to-end delay:* The end-to-end delay of the target network can be defined as the total delay between creation and reception of application packets generated by this network.

*5) Media Access Delay:* The media access delay is defined as the sum of queuing delays and contention delays of the data frames transmitted by the target 802.15.4 MAC.

## III. Zigbee-WLAN Coexistence Measurement Setup

According to the IEEE 802.11 and IEEE 802.15.4 standards, the output power for 802.15.4 devices approaches 0 dBm, however, the output power of IEEE 802.11b/g devices is usually 15 dBm or above [2], [11]. Both technologies deploy a listen-before-send before each transmission. However, the sensing duration for 802.11b devices is 10 $\mu$sec while that of 802.15.4 devices is much larger and equal 192 $\mu$sec. The large difference in the sensing duration negatively affects the collision probabilities between their packets. The effect of interference caused by IEEE 802.11b/g WLAN to ZigBee nodes is a function of both the transmitted WLAN power and the communication distance. In our measurement testbed, the WLAN network and the ZigBee sensor network blindly coexist in the same band and location. The WLAN network consists of two laptops and one WLAN access point. The ZigBee sensor network is constructed with the CC2430 System-on-Chip solution for IEEE 802.15.4/ZigBee [7]. The CC2430 modules implement a ZigBee coordinator (receiver) and an end device(transmitter). Our measurement testbed is illustrated in Fig. 2.

### A. The IEEE 802.11 Network Specifications

For the IEEE802.11 WLAN network, we used a point to point transmission link where the maximum physical layer bit rate can be adjusted to either 11Mbps (IEEE802.11b) or 54 Mbps (IEEE 802.11g). We used a TP-LINK TL-WA500G access point that supports a transmission power ranging from 0 up to 20dBm through a 3dBi detachable omni-directional antenna [13]. The access point supports variable packet lengths that varies from 256 to 2346 bytes. The beacon interval is adjusted to 100 msec. Between the two laptops, the access

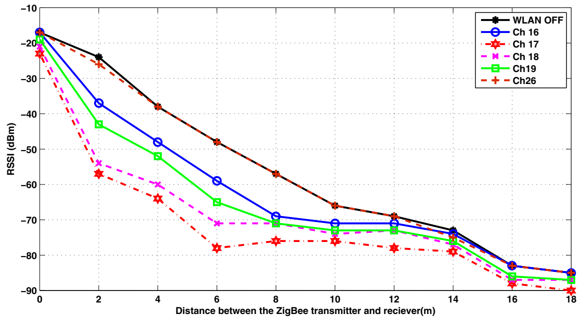


Fig. 3: RSSI versus the distance between ZigBee nodes and coordinator at fixed WLAN to ZigBee coordinator interference

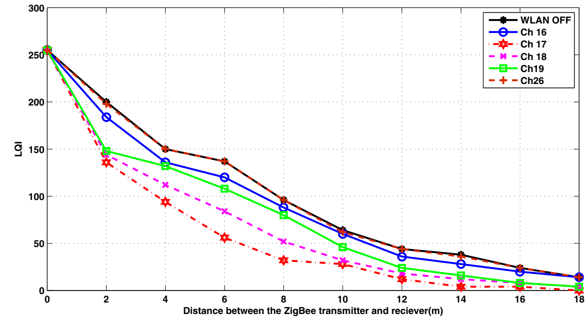


Fig. 4: LQI versus the distance between ZigBee nodes and coordinator at fixed WLAN to ZigBee coordinator interference

point is used to relay the traffic between them. Over the wireless link, UDP packets are continuously sent using the Iperf tool [14], on channel 6.

### *B. The ZigBee Network Specifications*

The IEEE 802.15.4 network was implemented using two SmartRF04 EB boards with a Chipcon CC2430 RF Transceiver [7] and two CC2430EM boards with appropriate antennas. The transceiver was controlled via IAR Embedded Workbench for 8051 and can be controlled also using the Texas Instruments Flash Programmer as an alternative to IAR [14]. In order to get the measurements, we set the 802.15.4 transceiver to send packets periodically at 250 Kbps. The 802.15.4 channels that carry ZigBee traffic are adjusted to channels 16, 17, 18 and 19 with their center frequencies 2.430, 2.435, 2.440, and 2.445, respectively. These frequencies overlap with channel 6 for WLAN technology. We also test the performance when the ZigBee network operates on channel 26 which does not overlap with the WLAN transmissions, as illustrated in Fig. 1. Before each packet transmission, the 802.15.4 transmitter listens to the channel during two consecutive slots, to sense the energy on the channel. Only when the channel is sensed free a transmission may occur.

### *C. Measurement Test Scenarios*

The measurements in this paper are done in an indoor environment. (The buildings are concrete buildings and emulate a smart home scenario where both WLAN and sensor networks are expected to coexist.) All wireless links in the indoor environment are assumed to be in line of sight. We measure the impact of the distance between the ZigBee receiver and the WLAN transmitter on each of the performance metrics mentioned above. We also measure the impact of the different sizes of the WLAN transmission packets on the performance metrics of the ZigBee network. We compare the performance of the ZigBee network when coexisting with either IEEE 802.11b or IEEE 802.11g WLANs.

## IV. ZigBee Coexistence Measurement Results

In this section the measurements obtained from the testbed shown in Fig. 2 will be analysed. The testbed consists of a

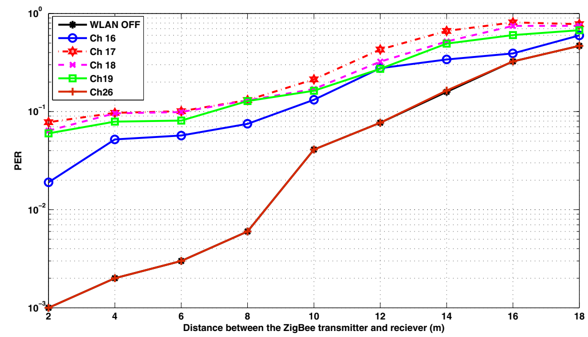


Fig. 5: PER versus the distance between ZigBee nodes and coordinator at fixed WLAN to ZigBee coordinator interference

single WLAN network and a ZigBee network. The WLAN consists of two laptops and one access point to relay the traffic between them. The traffic used is UDP stream transmitted continuously from one laptop to the other using $IPERF$ software [14]. The ZigBee network consists of two ZigBee display kits CC2430. In the measurement scenarios, 10000 ZigBee data packets are continuously transmitted from one ZigBee kit (end device) to the other kit (Coordinator). All our results are extracted directly from the LCD monitor of ZigBee kits and from the Texas Instrument packet sniffer software [16].

### *A. Scenario 1*

In this scenario, we consider the case of fixed interference to the ZigBee coordinator, but variable received power from its ZigBee nodes. The distance between the WLAN and the ZigBee coordinator is fixed to 10 meters and the distance between the ZigBee end device and the coordinator is varied. The access point is adjusted to operate as IEEE 802.11g AP on channel number 6 with the packet size adjusted to 2346 bytes and the ZigBee network is adjusted to operate on one of the channels 16, 17, 18, 19, or 26. Channels 16, 17, 18 and 19 overlap with the WLAN operation channel 6, while ZigBee channel 26 does not overlap with channel 6. The performance metrics tested are PER, LQI, and RSSI.

Figure 3 shows how the RSSI varies with the distance between the ZigBee end device and its coordinator for different operating channels. The RSSI greatly decreases as the distance between the ZigBee nodes increases. In other words, the RSSI at the ZigBee coordinator depends on the operating channel, the distance between the ZigBee nodes, and the WLAN interference power. The signal energy for each channel is concentrated around the center frequency of the channel. As a result, we observe that the ZigBee channels with a center frequency close to the center frequency of the WLAN channel suffer more decrease in their RSSI. Channel 17 and 18 are the channels with center frequencies closer to the WLAN channel center frequency, with the lowest RSSI recorded in channel 17. The degradation in the RSSI is the lowest when the WLAN is turned off or when the WLAN and ZigBee operating frequencies do not overlap. For example, we note that when the distance between the ZigBee node and coordinator is 2 meters, the WLAN interference causes more than 30 dB degradation in the received RSSI.

Figure 4 shows the LQI measurements that are extracted from the packet sniffer software. The LQI value is close to 255 when the coordinator and the end device are close to each other, and decreases as the nodes become far away from each other. Also the channels that exhibit more interference will be specified by lower value for LQI as shown in Fig. 4. At a distance of 6 meters from the ZigBee and coordinator nodes, the WLAN interference causes the LQI to degrade from around 140 to around 50.

The PER/PLR performance metrics are shown for the same interference scenario in Fig. 5. One can observe that at ZigBee coordinator-node separation of 10 meters the PER increases from about 0.05 to 0.2 due to the WLAN interference.

### B. Scenario 2

The WLAN access point is adjusted as IEEE 802.11g operating at channel 6, and the ZigBee network is adjusted at channel 17, which is the channel with the most degradation due to WLAN interference. In this scenario, the impact of the packet size of the WLAN network is tested. The same performance metrics are studied with different packet sizes. As shown in Fig. 6, the RSSI at the ZigBee coordinator is larger for smaller WLAN packet sizes. This can be explained by the increase in the probability of collision between ZigBee packets and WLAN packets with the increase in WLAN packet size. Smaller WLAN packets will lead to larger power received in the correctly received ZigBee packets. For the same reason, the LQI becomes larger with smaller packet size as shown in Fig. 7. The performance degradation with larger packet size is also tested through PER as shown in Fig. 8.

### C. Scenario 3

In this scenario, we compare the performance of the ZigBee network adjusted at channel 18 when coexisting with either IEEE 802.11b or IEEE 802.11g based WLANs. In the first test, the distance between the ZigBee coordinator and the ZigBee end device is fixed at 10 meters and the WLAN packet size is 500 bytes. As shown from PER measurements

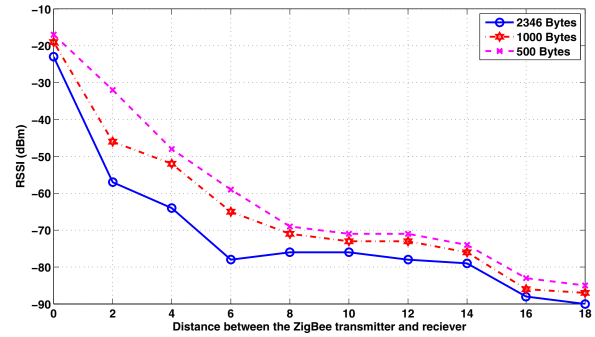


Fig. 6: ZigBee RSSI variation with different WLAN packet sizes

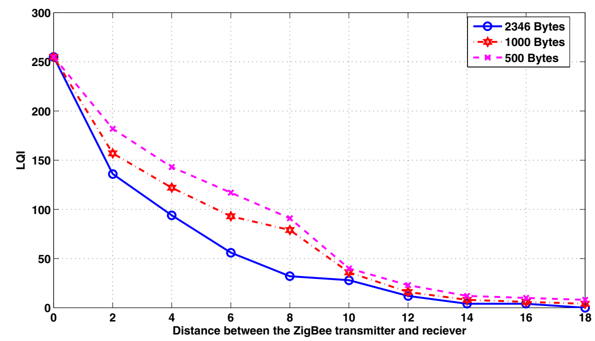


Fig. 7: ZigBee LQI variation with different WLAN packet sizes

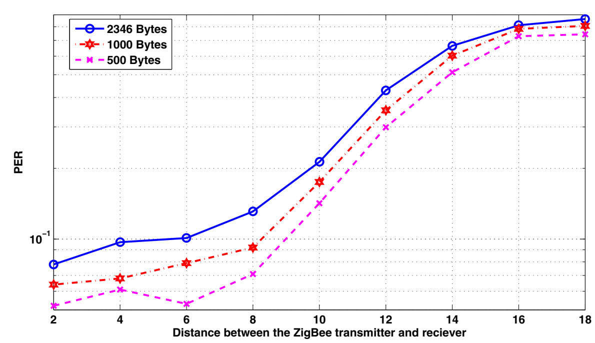


Fig. 8: ZigBee PER variation with different WLAN packet sizes

in Fig. 9, ZigBee channel 17 is the most impacted channel by the IEEE802.11b and IEEE 802.11g WLAN interference. We also note that there is more performance degradation in case of IEEE 802.11b interference. This can be explained by the shorter packet durations of IEEE 802.11g based WLANs as their data rates are higher than that of IEEE 802.11b. Thus, ZigBee has a higher packet collision probability with IEEE 802.11b than with IEEE 802.11g. Similar observations can be concluded from the PER measurements in the second test when the distance between the ZigBee coordinator and WLAN

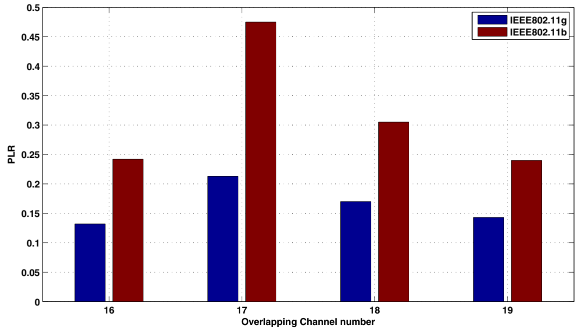


Fig. 9: Comparison of the effect of WLAN standards on the ZigBee overlapping channels

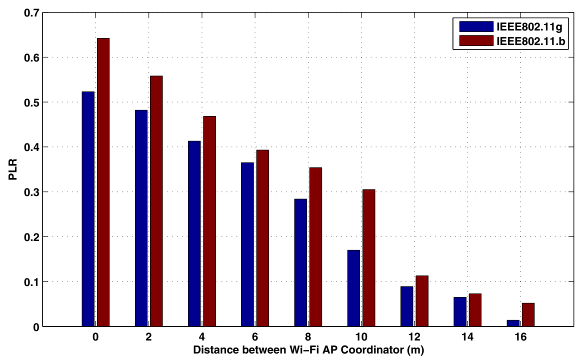


Fig. 10: PER variation with the distance between ZigBee and WLAN APs 802.11b and 802.11g

TABLE I: ZigBee network simulation parameters

| | |
|---|---|
| Application layer parameters | |
| Packet Inter arrival Time (constant) | (1,0) |
| Packet Size (bits) | 1024 |
| Start Time (uniform) | (20.21) |
| MAC layer parameters | |
| ACK | Enabled |
| ACK Wait Duration (sec) | 0.05 |
| Maximum Number of retransmissions | 5 |
| Maximum Backoff Exponent in CSMA/CA | 3 |
| Maximum Number of Backoffs in CSMA/CA | 4 |
| Channel Sensing Duration(sec) | 0.1 |
| Physical layer parameters | |
| Data rate (Kbps) | 250 |
| Packet Reception Power Threshold (dB) | -85 |
| Transmission band (GHz) | 2.4 |
| The power level for different modes (mWatt) | 1 |

TABLE II: WLAN network simulation parameters

| The WLAN network parameters | |
|---|---|
| The physical characteristics | Direct sequence |
| Data rate (Mbps) | 11 |
| Transmit power (mWatt) | 30 |
| Packet Reception power threshold (dB) | -85 |
| CTS to self option | Enabled |
| AP beacon interval (secs) | 0.02 |
| Max receiver lifetime (secs) | 0.5 |
| Buffer size (Kbits) | 256 |

AP is varied. From Fig. 10, we also observe that the PLR degradation is more severe with IEEE 802.11b interference.

## V. ZIGBEE COEXISTENCE OPNET SIMULATION RESULTS

In this section, we illustrate through OPNET simulations the performance degradation of the ZigBee networks when coexisting by another ZigBee network or by WLAN networks. The effect of the packet size of the interfering WLAN network on different performance metrics will be illustrated. Also the effect of the number of nodes in the interfering network will be illustrated in this section.

To enable ZigBee and WLAN coexistence in OPNET, we modified the pipeline stage of the standard ZigBee OPNET module. Tables I and II show the simulation parameters for the ZigBee and WLAN networks respectively. The target network consists of four nodes with their coordinator. The mean of the distance between these nodes and the coordinator is 5 meters. The interfering network's nodes are within an average distance of 10 meters from the coordinator of the target ZigBee network. Our performance metrics are evaluated at the coordinator of the target ZigBee network. To test coexistence, the target network and the interfering network are operating at overlapping channels(6 for WLAN and 16 for ZigBee).

We investigate the effect of the number of interfering nodes on the end-to-end delay, the media access delay (MAD) and the packet loss ratio (PLR) of the target ZigBee network in Fig. 11, Fig. 12, and 13respectively. We observe that the performance degradation due to coexisting with another Zigbee network is less severe than when coexisting with WLAN networks. When the interfering network is another ZigBee network, the same CSMA/CA mechanism of the target and interfering networks helps in decreasing the probability of packet collisions. Also the relatively small packet size decreases the probability of collision and number of packets retransmissions, which contribute to a lower end-to-end delay compared to the case when interference is from WLANs. Another observation, is that the interference impact from WLANs can be alleviated by reducing the WLAN packet size. For example, at 10 interfering nodes, the MAD and the PLR with WLAN interference is an order of magnitude worse (from $10^{-3}$ to $10^{-2}$ MAD and from $10^{-2}$ to $10^{-1}$ PLR) than with ZigBee interference.

## VI. COGNITIVE RADIO WIRELESS SENSOR NETWORKS

From both the measurements and simulation results analysed above, we observe that for ZigBee networks to mitigate interference due to coexistence in the ISM band, ZigBee networks should have cognitive radio capability [17] to enable the robust switching to vacant channels while in operation. In cases where the interference detected by the ZigBee coordinator at network formation changes or fails to reflect the interference profile of the network as a whole, ZigBee devices with their cognitive radio capability will have the ability to use their built-in spectrum sensing mechanisms to

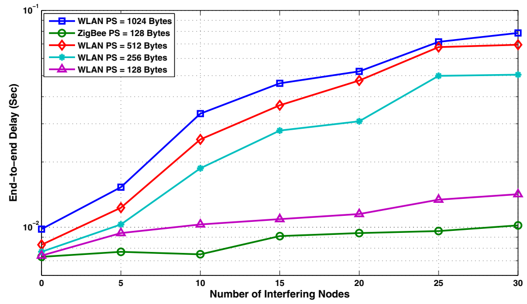


Fig. 11: Variation of ZigBee end-to-end delay with the number of nodes in the interfering WLAN/ZigBee networks

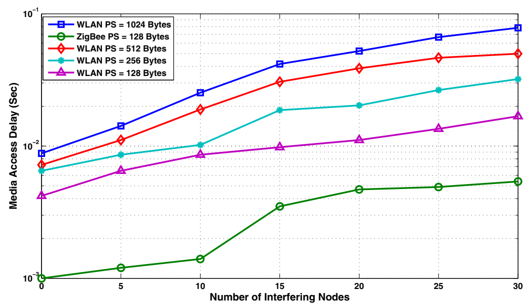


Fig. 12: Variation of ZigBee media access delay with the number of nodes in the interfering WLAN/ZigBee networks

report interference to a network manager/fusion center. Upon some criteria provided by the application, the network manager may direct the network to leave the current operating channel and move to another vacant channel with no interference from other devices(e.g., channel 26). If the unlicensed ISM band is very crowded, the fusion center may direct the WSN to switch to a licensed frequency band.

## VII. Conclusion

The problem of coexistence between Wi-Fi networks and ZigBee based WSNs in indoor environments is studied using experimental measurements and OPNET simulations. The performance degradation of ZigBee networks is tested through different performance metrics such as the received signal strength, link quality indicator, end to end delay, media access delay and packet loss ratio. It is shown that ZigBee channels with center frequency closer to the WLAN operating center frequency will experience more degradation. The degradation due to increasing distance between the ZigBee coordinator and ZigBee nodes of the same network in presence of fixed WLAN-coordinator interference has been quantified. The negative impact of decreasing the distance between interfering WLANs and the Zigbee coordinator or increasing the number of interfering nodes has also been quantified. It is shown that increasing the packet sizes of WLAN interfering networks has a negative effect on the performance of target Zigbee networks. It is also shown that intra-technology (ZigBee to ZigBee) interference is less severe than inter-technology interference.

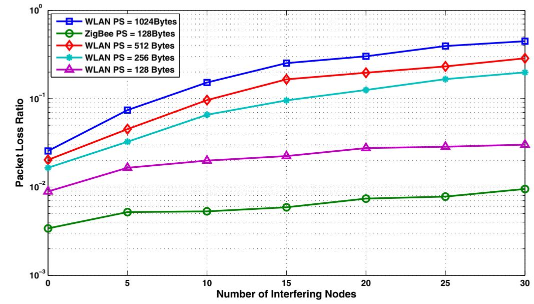


Fig. 13: Variation of packet loss ratio with the number of nodes in the interfering WLAN/ZigBee networks

We conclude that for robust operation of ZigBee networks in ISM band, the ZigBee nodes should be equipped with cognitive radio capability for quick sensing of interference while in operation and frequency agility to channels free from interference.

## References


[1] Hsinchu ”A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi” , The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON), Taipei, Taiwan, March. 2008, pp. 46-51.

[2] IEEE 802.15.4: IEEE standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), 2003.

[3] S.Shin, S.Choi, H.S.Park, and W.H. Kwon, ”Packet error rate analysis of IEEE 802.15.4 under IEEE 802.11b interference,” in proceedings of WWIC 2005, LNCS, Springer, May, pp. 279-288.

[4] M. Petrova, J. Riihijarvi, P.MAhonen, S. Labella, performance study of IEEE 802.15.4 Using Measurements and Simulations, WCNC 2006.

[5] K. J. Muoung, S. Y. Shin, H. S. Park, W. H. Kwon, ”802.11b performance analysis in the presence of IEEE 802.15.4 Interference, IEICE Trans. Commun., Vol. E90-B, No.1 Jan. 2007.

[6] A. Sikora. ”Coexistence of IEEE 802.15.4 with Other Systems in the 2.4 GHz-ISM-Band.”, In the IEEE Instrumentation and Measurement Technology Conference, vol. 3, pp. 17861791. Ottawa, Canada, 2005.

[7] ”Datasheet for chipcon True System-on-Chip solution for 2.4 GHz IEEE 802.15.4 / ZigBee,” http://www.ti.com/product/cc2430 [referenced Jan 1,2012].

[8] On line Documentation, ”OPNET Modeler,” http://www.opnet.com/, Date visited: Jan 2012.

[9] ZigBee Alliance, ZigBee specification, 2008.

[10] S. Pollin, M. Ergen, S. C. Ergen, B. Bougard, L. Van der Perre, I. Moerman, F. Catthoor, A. Bahai, P. Varaiya, ”performance Analysis of slotted Carrier Sense IEEE 802.15.4 Medium Access Layer”, IEEE Globecom 2006.

[11] IEEE standard for information technology-telecommunications and information exchange between systems local and metropolitan area networks-specific requirements - part 11: ”Wireless LAN medium access control (MAC) and physical layer(PHY) specifications”, IEEE Std 802.11, 2007.

[12] G. Bianchi, ”Performance Analysis of the IEEE 802.11 Distributed Coordination Function,”. IEEE Journal on Selected Areas in Communications, Vol.18, March 2000.

[13] ”Datasheet for TP-LINK TL-WA500G access point,” http://www.tp-link.com/en/products/details/?model=TL-WA500G [ referenced Jan 2, 2012].

[14] http://sourceforge.net/projects/iperf/, Date visited: Jan 2012.

[15] http://supp.iar.com/Download/SW/?item=EW8051-EVAL, Date visited: Jan 2012.

[16] http://www.ti.com/tool/packetsniffer, Date visited: Jan 2012.

[17] J. Mitola III and G.Q. Maguire Jr, ”Cognitive radio: making software radios more personal,” IEEE Personal Communications, vol. 6, no. 4, pp. 13–18, 1999.