Performance Evaluation of IEEE 802.15.4: Experimental and Simulation Results

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Abstract - **Wireless Local Area Networking standard (Wi-Fi) and the WPAN standard (Bluetooth and Zigbee) products utilize the same unlicensed 2.4 GHz ISM band. Co-existence between such wireless technologies within the same frequency spectrum is crucial to ensure that each wireless technology maintains and provides its desired performance requirements. This paper provides a brief description of the newly introduced Zigbee standards including the Physical (PHY) and media access control (MAC) layer. It focuses on developing MatLab/Simulink models for the Zigbee protocol and the performance evaluation of these models. Several simulations were run and the results were analyzed for the different scenarios. The results showed how the relationship between the signal Bit Error Rate (BER) and Signal to Noise Ratio (SNR) was affected when varying the data rate and power. Furthermore, this paper investigated the co-existence of WLAN (IEEE 802.11g) with Zigbee (IEEE 802.15.4 by quantifying potential interferences and examining the impact on the throughput performance of IEEE 802.11g and Zigbee devices when co-existing within a particular environment. The effect of Zigbee on IEEE 802.11g was compared with the effect of Bluetooth under the same operating conditions.**

Index Terms---**WLAN, Bluetooth, Zigbee, Performance Analysis, IEEE 802.15.4.**

1. INTRODUCTION.

Wireless Personal Area Network (WPAN) and Wireless Local Area Network (WLAN) [1] technologies are growing fast with new emerging standards being developed. WLAN technologies have been leading the indoor Internet distribution in education, business and home environments. They are usually deployed as wireless extension of a broadband access to the network. These technologies are based on CSMA/CA medium access with a positive MAC layer acknowledgement and a retransmission mechanism that aids noisy channel propagation condition and eventual undetected collisions. Today, WLAN standard defines high rate data throughputs; such as the IEEE 802.11b with a maximum throughput of 11Mbps and the IEEE 802.11g with maximum throughput of 54Mbps. Both IEEE 802.11b and g operate at the 2.4 GHz band. Typically, WLAN devices operate within 100 meters of distance range depending on the surrounding environment. While, the IEEE 802.11b utilizes direct sequence spread spectrum (DSSS) using complementary code keying (CCK) modulation, IEEE 802.11g is based on the orthogonal frequency division multiplexing (OFDM) modulation technique and the CCK modulation for backward compatibility with 802.11b.

For sometime, Bluetooth [2, 4] was the most widely used for short range communication in the proximity of a person. Recently, Zigbee [3, 5] was introduced as an alternative to Bluetooth for devices with low power consumption requirements and applications of lower bit rates. Although products based on the Bluetooth standard are often capable of operating at greater distances, the targeted operational area is the one around an individual, (e.g. within a 10 meters diameter). Bluetooth utilizes a short range radio link that operates in the 2.4 GHz industrial scientific and medical (ISM) band similar to WLAN. However, the radio link in Bluetooth is based on frequency hop spread spectrum. Although at any point in time, the Bluetooth signal occupies only 1MHz, the signal changes the center frequency (or hops) deterministically at a rate of 1600Hz. Bluetooth hops over 79 center frequencies, so over time the Bluetooth signal actually occupies 79MHz.

The new short range, low power, low rate wireless networking protocol, Zigbee, complements the high data rate technologies such as WLAN and open the door for many new applications. This standard operates at three bands, the 2.4 GHz band with a maximum rate of 250 kbps, the 915 MHz band with a data rate of 40 kbps, and the 868 MHz band with a data rate of 20 kbps. While Bluetooth devices are better suited for fairly high rate sensor and voice applications, Zigbee is better suited for low rate sensors and devices used for control applications that do not require high data rate but must have long battery life, low user interventions and mobile topology. Some of these applications are in the fields of medicine,

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home/office automation, military, and many others [6]. In the medicine field, sensors utilizing Zigbee are used for monitoring the heartbeat, blood pressure and the percentage of the cholesterol in the blood. In the field of home automation, Zigbee capable sensors can be used in turning On/Off the AC if the temperature exceeded a certain value, turning On/Off the lights and locking doors. In the military field, sensors running Zigbee can be used to observe and track the movement of the enemy.

Recently, there have been several investigations related to Zigbee. However; there are not enough simulation-based performance evaluations of the new standard. One of the performance evaluation studies that used simulation was presented in [7]. In this study, authors evaluated the suitability of the Zigbee standard for medical applications. Their main objective was investigating the scalability issue, since patients might need several communicating devices near them. They developed models for low-rate WPAN access protocol and evaluated the performance of these models using OPNET. In the research done in [8], the authors focused on power consumption. They evaluated the energy efficiency of the standard in a dense network. They calculated the expected power consumption in certain scenarios and examined how energy is used during data transmission. On the other hand, there have been investigation studies related to the co-existence of WLAN with WPAN and other technologies [9, 10]. For example, the authors in [9] discussed interferences between Zigbee and the signals of particular medical equipments. In [10], a study was done on the interference between Bluetooth and IEEE 802.11b. In [11] the authors present a brief technical introduction of the IEEE 802.15.4 standard and analyze the coexistence impact of an IEEE 802.15.4 network on the IEEE 802.11b devices.

The rest of the paper is organized as follows. Section 2 provides a brief summary of the Zigbee/IEEE 802.15.4 standard which includes the physical and MAC layer specifications. Section 3 discusses the developed MatLab/Simulink models. Section 4 shows the obtained results and analysis from the Matlab simulation, section 5 presents experimental results on the co-existence of Zigbee with WiFi and the paper is concluded in section 6.

2. OVERVIEW OF ZIGBEE/IEEE 802.15.4

The Zigbee/IEEE 802.15.4 protocol is considered the newly introduced WPAN standard which was approved and published in 2003 [3]. It defines the characteristics of the physical layer and the MAC layer. In this section, a brief description of the characteristics for these two layers is presented.

A. The IEEE 802.15.4 Physical Layer.

As with any other wireless communication technology, the main functions of the physical layer are spreading, de-spreading, modulation and demodulation of the signal. At the physical layer, Zigbee operates in the ISM band within three different frequency bands. There is a single channel between 868.0 and 868.6MHz, Ch 0, 10 channels between 902.0 and 928.0 MHz, Ch 1-10, and 16 channels between 2.4 and 2.4835 GHz, Ch 11-26. Zigbee uses DSSS as a spreading technique. DSSS is used to increase the frequency of the signal in order to increase its power and reduce the influence of noise from nearby networks. The 2.4 GHz band uses the Orthogonal Quadrature Phase Shift Keying (OQPSK) technique for chip modulation. Each 4-bit symbol is mapped into a 32 chip PN sequence as shown in Fig. 1. In the 915 MHz and 868 MHz bands each one-bit symbol is mapped into a 15 chip PN sequence, and uses the Binary Phase Shift Keying (BPSK) technique for modulation. The Zigbee standard specifies a receiver sensitivity of -92 dbm in the 868/915 MHz bands and -85 dbm in the 2.4 GHz band. The physical layer of the stated frequency bands uses the same common frame structure as shown in Fig. 2. Having several channels in different frequency bands makes it possible to relocate within the available spectrum.

B. The IEEE 802.15.4 MAC Layer.

The MAC layer controls the access to the communication channel. It provides flow control through acknowledgments and retransmissions. It is also responsible for data validation, synchronization and providing services to the upper layers. The Zigbee standard defines two types of devices, a full-function device (FFD) and a reduced function device (RFD). The FFD can operate in three different modes: a personal area network (PAN) coordinator, a coordinator, or a device. The RFD is intended for very simple applications that do not require the transfer of large amounts of data and need minimal resources. A WPAN is formed when at least two devices are communicating with one device acting as an FFD assuming the role of a coordinator. Depending on the application requirements, Zigbee devices might operate either in a star topology or a peer-to-peer topology.

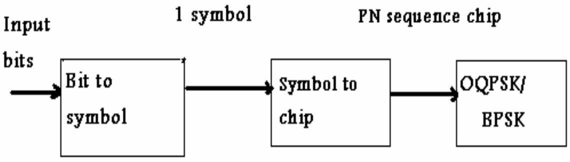

Figure 1. Example of a Zigbee spreading technique at the physical layer

Preamble	Start of Packet	Length Field	Physical layer payload
4 bytes	1 bytes	1 bytes	(2-127 bytes)

Figure 2. The Zigbee physical layer frame structure

There are three types of data transfer mechanisms between Zigbee devices: from a coordinator to a device, from a device to a coordinator and between two peer devices. The data transfer mechanism used depends on whether the network supports the transmission of beacons or not. For example, in a non-beacon-enabled network, a device simply transmits its data frames using un-slotted CSMA-CA to the coordinator. However, in a beacon-enabled network, the device first listens for the network beacon and, at the right time, it transmits its data frames, using slotted CSMA-CA to the coordinator. In a peer-to-peer network, any device can communicate with any other device within its transmission radius using one of two options: by constantly listening to the channel and transmitting its data using un-slotted CSMA-CA or by synchronizing with other nodes in order to save power. In the beacon-enabled network, the super-frame structure must be used. The structure of the super-frame is defined by the coordinator. The super-frame is bounded by two beacons and the time between these two beacons is divided into 16 time slots. It has an active and an inactive portion. In the inactive portion, the coordinator enters a low power mode and doesn't interact with its PAN. The active portion is divided into two periods: a contention access period (CAP), and a contention free period (CFP). In the CAP, the device must compete with other devices using the slotted CSMA-CA mechanism. In the CFP, the PAN coordinator assigns guaranteed time slots (GTS) to a single device, which together forms the CFP. Fig. 3 shows the super-frame structure as used in Zigbee.

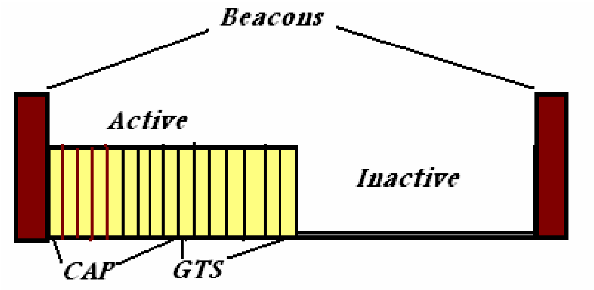

Figure 3. The Zigbee super frame structure

3. SIMULATION USING MATLAB/SIMULINK.

We used MatLab/Simulink to design three models for the three physical layer Zigbee bands. The generic model is shown in Fig. 4. This model includes the following major building blocks: a spreader, a de-spreader, a modulator, a demodulator, and an Additive White Gaussian Noise (AWGN) channel. For the 2.4 GHZ model, a random integer generator block generates a number randomly between 1 and 16. Then, this integer is taken as input to the spreader block, which spreads it into 32 bits according to Table 1 as defined by the Zigbee standard. Following that, the 32-bit-stream is taken as an input to the OQPSK modulation block. After modulation, noise is added to the modulated stream using the AWGN block. The latter is then passed through the OQPSK demodulation block before being de-spread.

The BER of the received data is calculated as follow: The received 32 bits are sent to the de-spreader which converts them back to an integer. Then, the integer-to-bit-converter converts the received integer to a 4-bit-stream. Finally, the 4-bit-stream is compared with the original one and the BER is calculated.

The second Simulink model is similar to the first one introduced above. It is generated by modifying the code in the embedded MatLab spreader/de-spreader function according to the mapping function of Table 2. This is done as defined by the Zigbee standard for the enhanced OQPSK 868/915 bands with a spreading sequence of 16 instead of 32 bits as specified in the Zigbee standards.

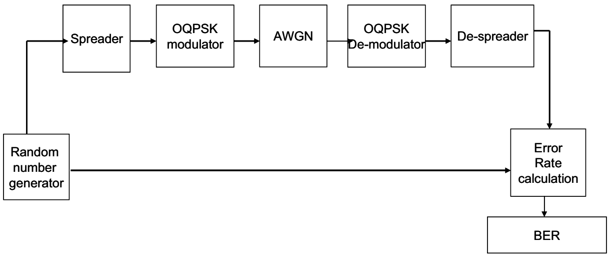

Figure 4. Generic MatLab/Simulink model

In the third Simulink model, the OQPSK modulator and demodulator is replaced by the BPSK modulator and demodulator. The code in the embedded MATLAB spreader/de-spreader function is changed to have only two values of 15 bits sequence according to the symbol to chip mapping of Table 3 as defined by the Zigbee standards.

TABLE 1. SYMBOL TO CHIP MAPPING FOR THE 2.4 GHZ BAND

Data symbol (dec.)	Data symbol (bin.)	Chip values (c0 c1…c30 c31)
0	0000	11011001110000110101001000101110
1	1000	11101101100111000011010100100010
2	0100	00101110110110011100001101010010
3	1100	00100010111011011001110000110101
4	0010	01010010001011101101100111000011
5	1010	00110101001000101110110110011100
6	0110	11000011010100100010111011011001
7	1110	10011100001101010010001011101101
8	0001	10001100100101100000011101111011
9	1001	10111000110010010110000001110111
10	0101	01111011100011001001011000000111
11	1101	01110111101110001100100101100000
12	0011	00000111011110111000110010010110
13	1011	01100000011101111011100011001001
14	0111	10010110000001110111101110001100
15	1111	11001001011000000111011110111000

4. RESULT AND ANALYSIS.

Simulations were performed to study the bit error rate (BER) versus signal to noise ratio (SNR) of the designed models. The results show the effects of various communication parameters on the BER for Zigbee operating in the different frequency bands. The first simulation case was run using the 2.4 GHZ signal frequency. The noise power in the AWGN channel was fixed at 0.168 watts per symbol, while the data rate was varied between 64, 128 and 250 Kbps. The results are shown in Fig. 5. Looking at the results where the SNR was 5 db the value of the BER is 10^{-4} for a data rate (DR)

=64 Kbps. While for both DR=128 and 250 Kbps the BER value is approximately $10^{-3.6}$. This shows that the higher the data rate, the higher the probability of error for a desired SNR.

The second simulation case was run also on the 2.4 GHZ model band to investigate the effect of varying the noise power in the AWGN channel. The DR was fixed at 250 Kbps, while the noise power was varied as 0.158, 0.168 and 0.178 Watts per symbol. The results are shown in Fig. 6. Considering the case where SNR=5 db, the following results can be seen. BER=$10^{-3.8}$ for E=0.158 watts, BER= $10^{-3.7}$ for E=0.168 watts, and BER=$10^{-3.6}$ for E=0.178 watts.

TABLE 2. SYMBOL TO CHIP MAPPING FOR THE ENHANCED OQPSK IN THE 868/915 MHZ BAND

Data Symbol (dec.)	Data Symbol (bin.)	Chip Values (c0 c1…c15)
1	0000	0011111000100101
2	1000	0100111110001001
3	0100	0101001111100010
4	1100	1001010011111000
5	0010	0010010100111110
6	1010	1000100101001111
7	1110	1111100010010100
8	0001	0110101101110000
9	1001	0001101011011100
10	0101	0000011010110111
11	1101	1100000110101101
12	0011	0111000001101011
13	1011	1101110000011010
14	0111	1011011100000110
15	1111	1010110111000001

TABLE 3. SYMBOL TO CHIP MAPPING FOR THE BPSK 868/915 MHZ BAND

Input bits	Chip values (c0….c14)
0	111101011001000
1	000010100110111

The third simulation case was run for different M values (number of bits per symbol). Fig. 7 shows the results for M=2, 4 and 8. As we can see from the figure, M=8 has the lowest BER value compared with the others. For example, if we look at SNR = 0, the value of BER for M=2 is between 10^{-1} and 10^{-2}, for M=4 it is between 10^{-2} and 10^{-3}, and for M=8 it is between 10^{-4} and 10^{-5}. Consequently, it can be seen that the higher the number of bits per symbol, the smaller the encountered BER value for the desired SNR.

The fourth simulation case was run on the second model which uses enhanced OQPSK for the 868/915 bands. The noise power was fixed at 0.168 watts per symbol, while the data rate was varied as 20, 30 and 40 Kbps. As seen from Fig. 8, the BER for the DR of 20 Kbps has the lowest value compared to the other two DRs for the same desired SNR.

The last simulation case was run for the third model which uses BPSK for the 868/915 bands. The noise power was fixed at 0.042 watts per bit, while the data rate was varied as 20, 30 and 40 Kbps. The results are shown in Fig. 9. Again, The BER for a DR of 20 Kbps has the lowest value compared to the other two DR values. However, the difference in performance for the different DRs is much less than that experienced when using enhanced OQPSK which was shown in Fig. 8. Therefore, it can be concluded that for the BPSK modulation, varying the data rate has little impact on the performance with respect to the BER as related to the SNR.

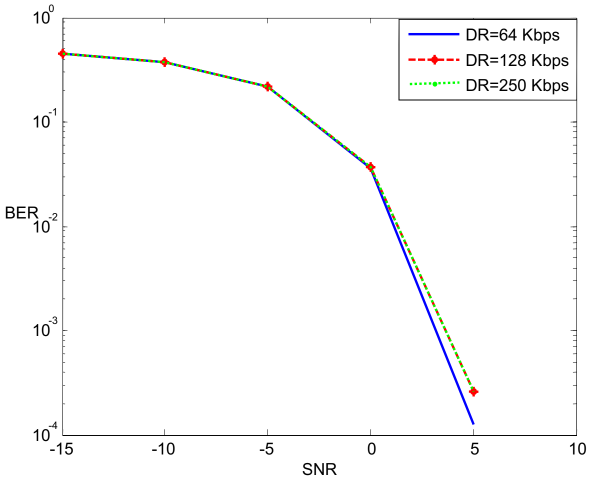

Figure 5. BER versus the SNR for different data rate values

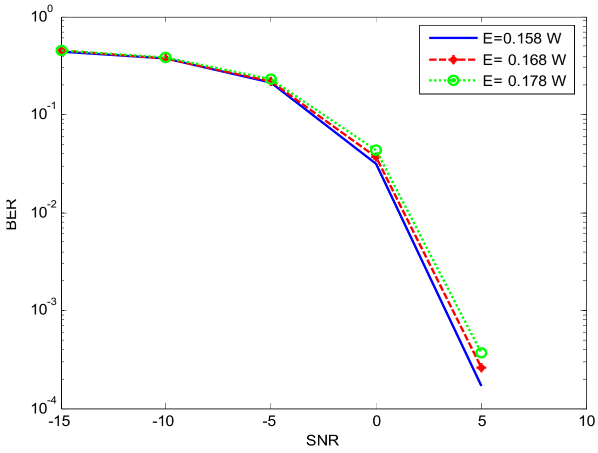

Figure 6. BER versus SNR for different noise power values (E)

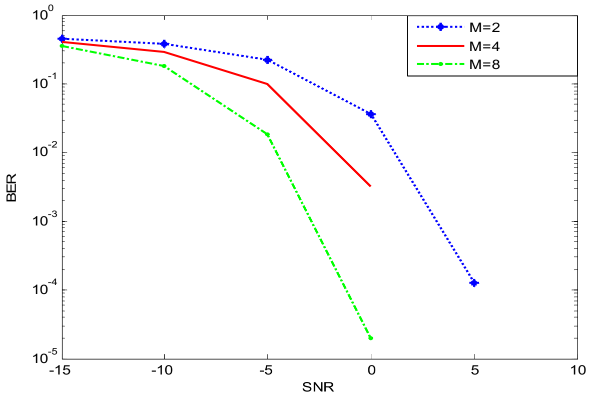

Figure 7. BER versus the SNR for different number of bits per symbol.

5. CO-EXISTENCE OF ZIGBEE WITH 802.11G.

With the increased use of devices operating at the 2.4 GHz band the WLAN and Zigbee devices are likely to be in close proximity to one another with possible interference. To understand the aspects of this problem the RF spectrum at 2.4 GHz and available channels for WiFi (IEEE 802.11 b, g) and Zigbee is shown in Fig. 10. As seen in Fig. 10, the RF channels in ZigBee and WiFi overlap and that generates a concern when such devices are within close proximity. In this paper several tests were conducted to look at the effect of WiFi on Zigbee and vice versa as shown in the subsections below.

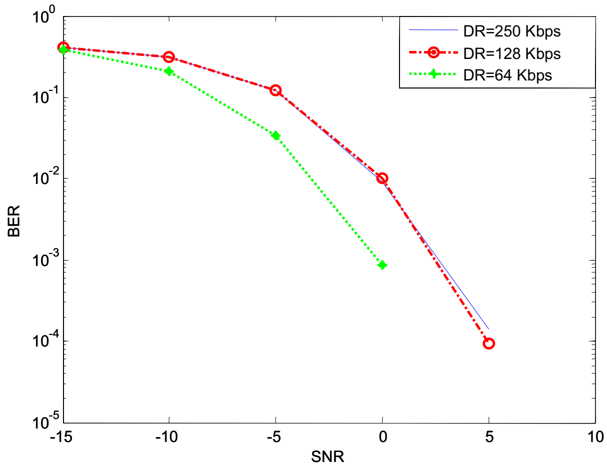

Figure 8. BER versus SNR for the enhanced OQPSK model with different data rates

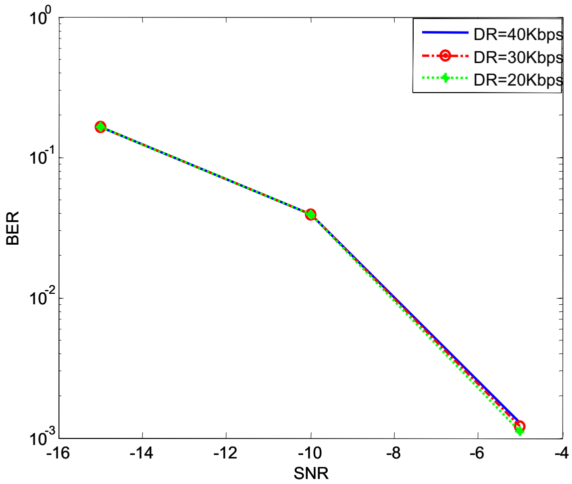

Figure 9. BER versus SNR for the BPSK model.

A. *Test Scenarios.*

A test-bed was created to investigate the potential interference effect of Zigbee on IEEE 802.11g and vice versa. Tests conducted are intended to obtain empirical throughput data corresponding with certain realistic scenarios in which IEEE 802.11g and Zigbee connections may coexist. It is important to realize that many other different coexistence scenarios are probable in realistic usage, each with its own unique set-up characterized by different relative distances, applications, and performance measures.

Test-bed Description: Several tests were conducted to see the effect of Zigbee on the performance of IEEE 802.11g and vice versa. These tests were performed in an open indoor cubical office environment area, with no interferences from any other radio frequency devices except for the ones used in the test-bed. We used a Linksys IEEE 802.11g access point (AP), two Dell Latidude D600 laptops with USB Zigbee or Bluetooth interface cards and one similar laptop with an IEEE 802.11g interface card. As seen from Fig. 11, the AP and a PC server were connected to the Fast Ethernet switch, while the laptop with an IEEE 802.11g interface card was placed on an 80 cm high desk a distance 10.5 meters from the base of the AP which was placed on a 2.5 meters wood post. TCP traffic was generated from a single source on the IEEE 802.11g client and received at the PC Server. The traffic was generated using the “LanTrafficV2” software with packet payload size of 1460 bytes and a fixed inter-packet delay of 1 ms. For all tests, 60,000 packets where transferred between the IEEE 802.11g client and the PC server.

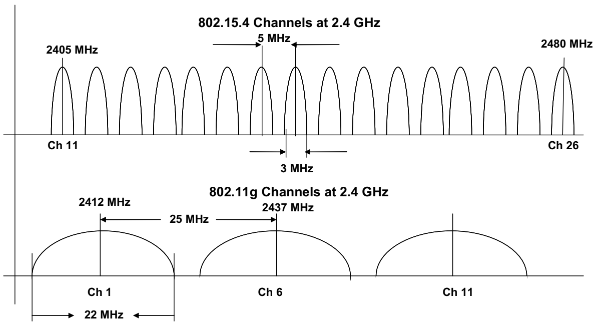

Figure 10: RF Spectrum for Zigbee and WiFi

For all testing scenarios, the RTS/CTS protection mode was on at the IEEE 802.11g Linksys AP. In this mode, when a device wants to communicate it sends a Request To Send (RTS) to the destination node, and waits for a Clear To Send (CTS) message before it transmits any data. This is done to avoid collisions, but it brings the maximum data throughput performance down [12]. The RTS/CTS handshaking provides positive control over the use of the shared medium. The primary reason for implementing RTS/CTS is to minimize collisions among hidden stations. This occurs when users and access points are spread out throughout the facility and a relatively high number of retransmissions occurring on the wireless LAN

After a baseline testing of the throughput performance of IEEE 802.11g, the Zigbee devices were introduced at different positions with respect to each other, the WLAN AP and the IEEE 802.11g client. Fig. 12 shows the general layout of the testing area. Fig. 13 shows the baseline throughput performance of the IEEE 802.11g client operating when placed in the reference cubical with respect to the AP using Ch6 and then Ch11, with no interference from any other devices. In this case, the average received throughput for the IEEE 802.11g client was 9.8 Mbps for both channels. The reported throughput for all test cases as measured by the "LanTrafficV2" was for the transport layer payload after the removal of all underlying headers.

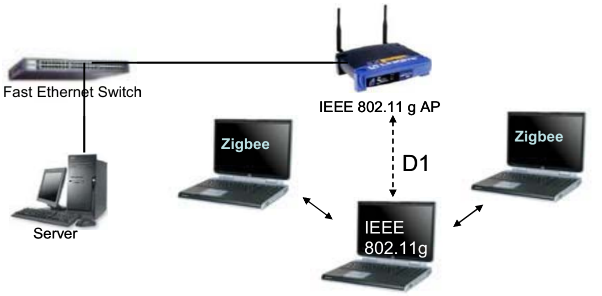

Figure 11: Basic test-bed for IEEE 802.11g throughput

B. Performance Results and Analysis.

To look at the effect of Zigbee devices on the performance of WLAN, two laptops were equipped with USB Zigbee interface cards were introduced into the test-bed area and placed at different positions with respect to both the IEEE 802.11g AP and laptop. All tests ran to investigate the effect of Zigbee on the WLAN while data was being transferred between the two laptops with Zigbee interface cards. The Zigbee interface cards were Maxstream XBee-PRO USB RF modems [13] using an omni-directional 15 cm antenna. The two Zigbee modems were used in a unicast peer-to-peer communication where data was sent bi-directionally at the rate of 115 Kbps with an inter packet delay of 200 ms. The channels on the Zigbee modems and IEEE 802.11g AP were chosen depending on the test to be run. Several tests were conducted not just to examine the effect of Zigbee on IEEE 802.11g and vice versa, but also to compare Zigbee with Bluetooth as per its interference effect on the performance of the IEEE 802.11g.

Experiment 1, IEEE 802.11g using Channel 11 and Zigbee using Channel 12: In this experiment, the maximum frequency separation between the central carrier frequencies of the interfering devices was chosen where the IEEE 802.11g channel was set to be Ch11 operating at a central carrier frequency of 2462 MHz, while the channel on the Zigbee modems was set to be Ch 11 operating at a central carrier frequency of 2405 MHz. The IEEE 802.11g client and the two Zigbee devices were placed within the reference cubical as seen in Fig. 12. The distance between the IEEE 802.11g AP and the IEEE 802.11g client placed in the reference cubical was 10.5 meters, with the two Zigbee devices being 1 meter a part near the IEEE 802.11g client. For this test case, no interference effect was reported neither on the performance of the IEEE 802.11g client nor on the throughput of the Zigbee devices. Using the same test-bed and under the same conditions, but replacing Zigbee with Bluetooth, there was a great effect on the throughput performance of the IEEE 802.11g client operating at Ch11. The average throughput of the IEEE 802.11g client dropped by 19% and was measured to be 7.9 Mbps.

Experiment 2, IEEE 802.11g using Channel 6 and Zigbee using Channel 17: In this experiment, the channels on the interfering devices were chosen so that their spectrum co-inside with each other. Ch6 operating at a central carrier frequency of 2437 MHz was chosen on the IEEE 802.11g AP, and Ch17 operating at a central carrier frequency of 2435 MHz was chosen on the Zigbee devices. Three test cases were conducted: the first test case was run with the IEEE 802.11g and Zigbee devices within the same reference cubical as in Experiment 1. The second test case was run with the Zigbee devices placed one in cubical R1 and the other in cubical L1 (approximately 6 meters apart) while the IEEE 802.11g client was in the reference cubical. The third test case was as the second one, with the Zigbee devices placed in R2 and L2 being approximately 12 meters apart. The results for these experiments are summarized in Table 4. The same three experiments were conducted with Bluetooth replacing Zigbee and the results are summarized in Table 5. As can be seen by looking at the results in Table 4, there was no significant effect on the performance of the IEEE 802.11g due to interference from Zigbee for all conducted test cases. However, that was not true for the Zigbee devices since the throughput was affected in all test cases with case three being the worst. Table 5 shows how Bluetooth greatly affected the performance of the IEEE 802.11g client and vice versa the performance of Bluetooth was also greatly affected by the presence of an IEEE 802.11g network in close proximity.

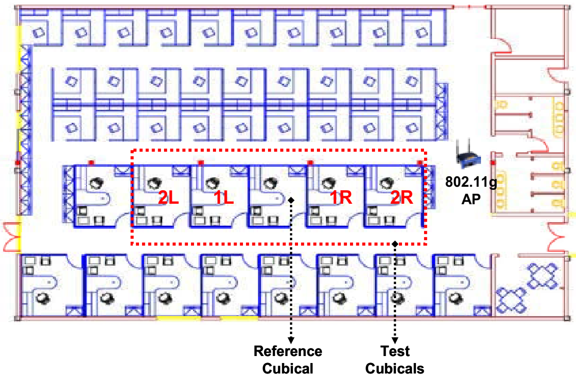

Figure 12: Test-bed layout setup area

Experiment 3, Effect on the uplink from the IEEE 802.11g AP to the IEEE 802.11g client: The first set of experiments was done to study the interference effect when Zigbee or Bluetooth devices are placed within a close proximity from an IEEE 802.11g client. These tests basically looked at the impact on the IEEE 802.11g down link channel from the IEEE 802.11g AP to the IEEE 802.11g client. In this experiment we looked at how such devices might affect the performance of IEEE 802.11g when placed near the AP rather than the WLAN client, i.e. affecting the uplink between the WLAN AP and its client. With the IEEE 802.11g client residing in the reference cubical, the Zigbee or Bluetooth devices were placed D2 meters apart at several positions on the same horizontal line as the IEEE 802.11g AP but on a 50 cm high table. Table 6 summarizes the results for these test cases.

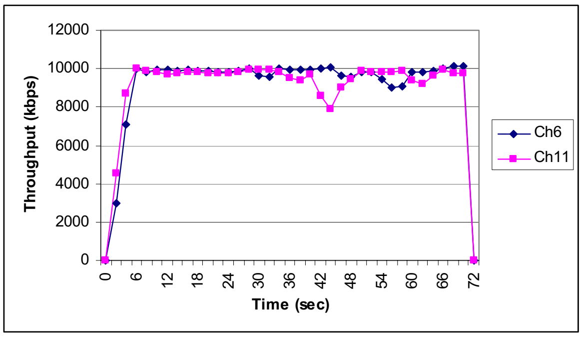

Figure 13: Baseline throughput results of IEEE 802.11g when operating at Ch6 and Ch11

TABLE 4. RESULTS FOR THE THREE TEST CASES IN EXPERIMENT 2

Test Case	*Percentage drop in IEEE 802.11g throughput*	*Percentage drop in Zigbee throughput*
1	Insignificant	10% (from 100% to 90%)
2	Insignificant	10% (from 100% to 90%)
3	Insignificant	22% (from 83% to 65%)

Experiment 4, IEEE 802.11g weak signal:To see the effect of Zigbee and Bluetooth on WLAN, in an environment where the IEEE 802.11g signal strength is weak, we emulated positioning the IEEE 802.11g client at a distance considered far from the AP. This was done by placing the AP behind an obstacle that brought down the signal strength indicator on the IEEE 802.11g card software fluctuating around -80 dbm. At this signal strength level, a test was performed with all interfering devices placed within the reference cubical with the AP operating on Ch6 and the Zigbee devices operating on Ch17. The baseline performance of the IEEE 802.11g client, without any source of interference, and at this signal strength level was measured at 6.7 Mbps. Table 7 summarizes the obtained results for this test case. As seen in Table 7, there was a slight effect on the performance of the 802.11g client for this test case due to interference from Zigbee; however, the effect of Bluetooth was drastic with a 53% drop in the throughput compared to 21% drop when the IEEE 802.11g signal strength was at full strength around -40 dbm as was shown in Table 5.

6. CONCLUSIONS.

Several MATLAB/Simulink simulations were done to evaluate the performance of Zigbee/IEEE 802.15.4 physical layer. The simulation results show how the BER versus the SNR values were affected when varying communication parameters such the input data rate, the level of the AWGN power and number of bits per symbol. In addition to the Matlab simulations, an extensive campaign of experiments and measurements was done to quantify the interference effect of Zigbee devices on the throughput performance of the IEEE 802.11g and vice versa. The results show that the Zigbee interference has more effect on the IEEE 802.11g uplink rather than the downlink. Furthermore, the results show how IEEE 802.11g is greatly more affected by Bluetooth than Zigbee and how IEEE 802.11g affects the performance of Zigebee when the spectrum of the chosen channels of operation co-inside.

TABLE 5. RESULTS FOR THE THREE TEST CASES IN EXPERIMENT 2, WITH BLUETOOTH REPLACING ZIGBEE.

Test Case	*Percentage drop in IEEE 802.11g throughput due to Bluetooth*	*Percentage drop in Bluetooth throughput due to IEEE 802.11g*
1	12% (from 9.8 Mbps to 8.6 Mbps)	21% (from 554 kbps to 440 kbps)
2	6% (from 9.8 Mbps to 9.2 Mbps)	36% (from 512 kbps to 328 kbps)
3	4.6% (from 9.8 Mbps to 9.35 Mbps)	17% (from 365 kbps to 303 kbps)

TABLE 6. RESULTS FOR EXPERIMENT 3

D2 (meters)	*Percentage drop in 802.11g throughput due to Zigbee*	*Percentage drop in IEEE 802.11g throughput due to Bluetooth*
4	11% (from 9.8 to 8.7 Mbps)	19% (from 9.8 to 7.9 Mbps)
6	6% (from 8.8 to 9.2)	17% (from 9.8 to 8.1 Mbps)
8	Insignificant	20% (from 9.8 to 7.8 Mbps)

TABLE 7. RESULTS FOR EXPERIMENT 4

Percentage drop in IEEE 802.11g throughput when using Zigbee	*Percentage drop in IEEE 802.11g throughput when using Bluetooth*
6% (from 6.7 to 6.3 Mbps)	52% (from 6.7 to 3.2 Mbps)

REFERENCES

[1] *IEEE standard 802.11 Wireless Medium Access Control and Physical Layer Specifications 1999.*

[2] *Bluetooth SIG, "Specifications of the Bluetooth System – Version 1.2," Nov. 2003*

[3] *IEEE P802.15.4/ D18, "Low Rate Wireless Personal Area Networks" draft std, February 2003*

[4] *Bluetooth Special Interest Group, "Specifications of the Bluetooth System, vol. 1, v.1.0B 'Core' and vol.2.oB 'Profiles'," Dec. 1999.*

[5] *J. A. Gutierrez, M. Naeve, E. Callaway, M. Bourgeois, V. Mitter and B. Heile, "IEEE 802.115.4; A Developing Standard for Low Power, Low Cost Wireless Personal Area Networks," IEEE Network, vol. 15, no. 5, Sept/Oct 2001, pp 12-19.*

[6] *P. Baronti, P. Pillai, V. Chook, S. Chessa, A. Gotta and F. FunHu, Wilreless Sensor Networks: a Survey on the State of the Art and the 802.15.4 and ZigBee Standards, Mobile and Satellite Communication Research Centre, UK, May 12, 2006.*

[7] *N. Golmie, D. Cypher and O. Rebala. "Performance evaluation of low rate WPANs for sensors and medical*

applications", Military Communications Conference (MILCOM), 2004.

[8] *B. Bougard, F. Catthoor, C. Daly, A. Chandrakasan, and W. Dehaene, Energy efficiency of IEEE 802.15.4 Standard in dense wireless microsensor network: Modeling and improvement perspectives, Design, Automation and Test in Europe (DATE),2005*

[9] *N. Golmie, D. Cypher, O. Rebala, "Performance Evaluation of Low Rate WPANs for Sensors and Medical Applications," Proceeding of MILCOM 2004, Monterey, CA, USA October 31-November 3, 2004.*

[10] *Matthew B. Shoemake, "Wi-Fi (IEEE 802.11b) and Bluetooth Coexistence Issues and Solutions for the 2.4 GHz ISM Band", Texas Instrument white paper, 2001.*

[11] *Howitt, I. and Gutierrez, J.A. "IEEE 802.15.4 low rate - wireless personal area network coexistence issues", Wireless Communications and Networking, 2003. WCNC 2003. IEEE, Volume: 3, 16-20 March 2003.*

[12] *Broadcom white paper, "IEEE 802.11g: The New Mainstream Wireless LAN Standard", 2003.*

[13] *www.maxstream.net.*

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