Proceedings of the 2010 IEEE
International Conference on Mechatronics and Automation
August 4-7, 2010, Xi'an, China

An Experimental Study of Interference Impacts on ZigBee-based Wireless Communication Inside Buildings

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***Abstract*—ZigBee is a wireless technology developed as an open global standard to address the unique needs of low-cost, low-power wireless sensor networks. This standard takes full advantages of the IEEE 802.15.4 physical radio specification and operates in unlicensed bands (e.g., 2.4 GHz) worldwide at different frequencies. As more and more companies make products that use the 2.4 GHz portion of the radio spectrum, network designers have had to deal with increased signals from collocated networks operating over the same frequency range. This paper aims to highlight the issues affecting co-existence of ZigBee systems in the presence of different interferences. We present an experimental study of ZigBee-based wireless communication over a period of time with WiFi, BlueTooth and microwave ovens. Results are presented for several different link configurations. Based on observations of the Packet Error Rate, we propose interference prediction algorithms to explore the impacts of WiFi/microwave oven on ZigBee communications.**

I. Introduction

A wireless sensor network can be defined as a network of sensor nodes that covers a wide area and provides environmental information such as temperature and humidity about the monitored area through wireless communication protocols. It can be applied in many fields including healthcare, environmental monitoring, home automation, and the military. Wireless sensors have significant potential to allow for more cost-effective and efficient installation of a widespread sensor network than wired sensors. Many articles have documented the use of wireless technology in buildings [1-6]. A previous paper [7] summarizes how wireless networks can support communications for field devices such as room or zone controllers. The sensors and actuators that are based on wireless interfaces and protocols provide a new paradigm for building automation and control as they have integrated sensing, control, computation and communication capabilities into a single tiny node [8]. To better control and monitor the building environment as well as to reduce the cost of cabling and maintenance, IEEE 802.15.4 [9] and ZigBee [10] standards are being promoted for short range wireless communications for building automation and control. ZigBee uses IEEE 802.15.4 PHY and MAC layer standards to handle devices used for short range wireless networks, especially for network use in building automation and control [7]. The radios operate in the license-free industrial, scientific, and medical (ISM) frequency band. In the U.S., ISM band usage is governed by Federal Communications Commission (FCC) rules. ZigBee in the 2.4 GHz-band provides the widest bandwidth per channel (250 kbits/s gross data rate) and the largest number of channels (16 non-overlapping channels) [10]. With the increasing number of devices and systems operating in the 2.4 GHz band, however, interference between these systems becomes a serious concern. To date, the most widespread systems in the 2.4 GHz ISM band are WiFi, Bluetooth, and cordless telephones. Because of the non-proprietary nature of this band, neither resource planning nor bandwidth allocation can be guaranteed. Additionally, other non-networking systems (e.g., microwave ovens) may emit electromagnetic waves in the 2.4 GHz-band, which will also affect ZigBee communications. We seek to develop a prediction approach for further study of interference effects from different sources. The ultimate goal is to develop guidelines for suitable positioning of nodes in buildings when interference sources are present.

There is a growing interest in understanding and modeling interference in wireless communication. The traditional approach in solving this problem is to license frequency bands to primary network users who are the only ones allowed to transmit in that frequency [11]. Although this approach removes the problem of interference, it results in low utilization of the frequency bands when the primary owner does not make full use of the allocated spectrum.

Analysis of the impacts of interference is challenging because interference introduces complex interdependencies of a variety of factors such as distance, frequency, and angle. Testing of the interference patterns of Zigbee wireless sensor communication has not been fully documented. Most existing work [12-17] that systematically considers interference effects falls in the analytical domain [18-20]. These authors make several assumptions about topology, workload, or interference characteristics and operate their experiments at the worst case scenarios; therefore the results cannot be straightforwardly adapted for use in a practical system. In the context of wireless sensor networks, several empirical studies have given an understanding of the complex non-ideal behavior of low-power wireless links. Major studies [12, 16, 21] focus on wireless link quality in the absence of concurrent transmissions. These studies evaluate the impact

This work was supported in part by the U.S. Department of Commerce under Grant 70NANB9H150.

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of increased interference and traffic load on higher layer protocols, but they do not explain the fundamental behavior of wireless links under interference as the experiments in this work aim to do.

In this paper, we perform a full characterization of commercially available nodes. A testbed is set up to measure the RSSI (Received Signal Strength Indicator), LQI (Link Quality Indictor), and PER (packet error rate) of the ZigBee communications. These three results are obtained via measurement as a function of distance, channel, and transmit power. By analyzing them with respect to distance and channels, we present an estimation result of Zigbee communication in the presence of different interference sources. We aim to offer a set of prediction methods for setting up wireless sensor networks that will enable them to achieve their QoS (Quality of Service) goals and maximum lifetime.

The remainder of the paper is organized as follows. We begin by presenting major applications of the 2.4 GHz ISM band in Section 2. In Section 3, we present the experimental setup. Performance evaluation and simulation results are presented in Section 4. Finally, conclusions are drawn in Section 5.

II. Major applications on 2.4GHz ISM band

Buildings contain many devices that emit RF pulses in ISM bands. Although the risk of interference is minimized by various engineering methods of signal generation, the potential for interference from these devices still exists considering the large number of devices emitting at similar frequencies.

A. ZigBee

ZigBee has been designed as a standardized solution for sensor and control networks. Most Zigbee devices are extremely power-sensitive (e.g., thermostats and security sensors), with target battery life being measured in years. Zigbee uses a Direct Sequence Spread Spectrum (DSSS) radio signal in the 868 MHz band (Europe), 915 MHz band (North America), or the 2.4 GHz ISM band (available worldwide). In the 2.4 GHz ISM band, as shown in Fig. 1, 16 channels are defined. Each channel occupies 3 MHz and is centered 5 MHz from its adjacent channel, giving a 2 MHz gap between pairs of channels. ZigBee uses an 11-chip PN code, with four information bits encoded into each symbol, giving it a maximum data rate of 128 kbps. The physical and MAC layers are defined by the IEEE 802.15.4 Working Group and share many of the same design characteristics as the IEEE 802.11b standard.

Zigbee specifies a collision avoidance algorithm similar to 802.11b. Each device listens to the channel before transmitting to minimize the frequency of collisions between Zigbee devices. Zigbee does not change channels during heavy interference; instead, it relies upon its low duty cycle and collision avoidance algorithms to minimize data loss caused by collisions.

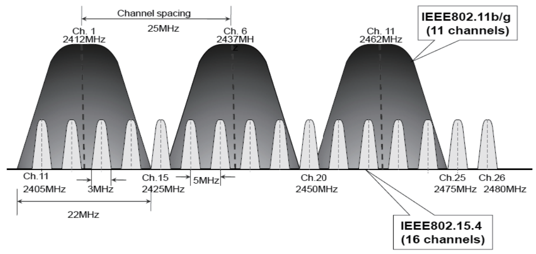


Fig. 1 IEEE 802.11g and IEEE 802.15.4 Channel Distribution

B. WiFi

WiFi is one of the most popular methods for providing Internet access without wired connections. WiFi employs DSSS technology to reduce crosstalk with other communications at the same frequency. However, DSSS systems may suffer from transmission losses when overlapping with another DSSS system. There are things that designers of DSSS systems can do to obtain the frequency agility of Frequency-Hopping Spread Spectrum (FHSS) systems. One approach involves network monitoring. If the DSSS system uses a polled protocol (where packets are expected at specified intervals), then the master radio can switch channels after a number of failed transmission attempts or poorly received packets.

C. Bluetooth

The smallest-scale network is a personal area network (PAN), which allows devices to communicate with each other over short distances. Bluetooth networks are the best example of a PAN. Bluetooth is an open standard specification for an RF-based, short-range technology that enables short-range communications. It operates over the 2.4 GHz ISM band and is designed to be an inexpensive, wireless networking system for all classes of portable devices, such as laptops, PDAs, and mobile phones. It also enables wireless connections for desktop computers, making connections between monitors, printers, keyboards, and the CPU cable-free.

A comparison of these three protocols that operate in the 2.4 GHz band is shown in Table 1. WiFi and Bluetooth technologies have limitations that suggest that they are inappropriate for sensor networks [7]. ZigBee is focused on control and automation, while Bluetooth is focused on connectivity between personal electronic devices and WiFi is meant for high-bandwidth communications. The data rate of ZigBee is low, hence it consumes lower power and can only send packets of small size; Bluetooth and WiFi use a higher data rate, consume higher power, and work with larger size packets. ZigBee networks can support a large number of devices. Because of these differences, the technologies are geared toward different applications. As an example, Bluetooth requires frequent battery recharging, while a major goal of ZigBee is to eliminate the need to change batteries for months or years. In timing-critical applications, ZigBee is designed to respond quickly, while Bluetooth takes much longer.

Table 1 Comparison of WiFi, Bluetooth and ZigBee [22]

	WiFi	BlueTooth	ZigBee
Bandwidth	Up to 54 Mbps	1 Mbps	250 kbps
Current Draw at 1.5 V (Transmission)	400 mA	40 mA	30 mA
Current Draw (standby)	20 mA	0.2 mA	<0.1 µA
Protocol stack Size (KB)	100	100	4-32
Stronghold	High data rate	Interoperability Cable replacement	Long battery life, low cost
Transmission Range (meters)	1-100	1-10	1-100
Battery Life (days)	0.5 – 5	1-7	100-1000
Network Size (# of nodes)	32	7	>64 000
Application	Web, Email, Video	Cable replacement	Monitoring & Control
Throughput (kb/s)	11 000	720	20 - 250

III. EXPERIMENTAL PLATFORM AND METHODOLOGY

The experimental setup is designed for continuous monitoring of a wireless link between a transmitter and receiver for a period of time with respect to Transmitter-Receiver distance, Interferer-Receiver distance, and channel variations. The experimental site is sized approximately 9 m by 6 m. The test specimens in these experiments are commercially available sensor nodes that transmit data according to the IEEE 802.15.4 specification. Each node is powered by two AA batteries and includes microprocessors to convert analog sensor signals to digital ones and to convert data to a signal that can be transmitted over the airwaves. The test specimens consist of two different commercially available nodes that use the same radio chipset that conforms to the IEEE 802.15.4 PHY layer standard in the 2.4 GHz ISM band. In the experiment, a 4-byte data payload is transmitted over the wireless link once every second. The key difference between the two models is their antenna. The former has a one inch ½ dipole antenna that is connected to the board, while the latter has an embedded antenna that is integral to the circuit board. The maximum rated transmission range for the directional antennas tested is about 350 m (1150 ft). Tests show no difference in performance between the two sets of nodes, thus results presented here do not differentiate the wireless radios used. The same hardware that is used to transmit data can also serve as a receiver of the data. The receiving nodes are attached to a board that is connected to a computer via a serial cable. All the measurements are performed using two networks: a primary network and a competing network. The former is always a Zigbee network using the nodes indicated above. The second network is within reception range of the former. The primary network consists of two nodes communicating with each other. Single hop networks are used to directly measure packet loss caused solely by interference rather than artifacts caused by network protocols associated with multihop network paths. Both the sender node (Telosb [23]) and receiver node (MicaZ [24]) are situated according to different test requirements. The different interference sources sit next to the receiver at different distances. The distance from the transmitter to receiver ($D_{Tx\text{-}Rx}$) is varied at the following levels: 1 m, 2 m, 4 m, 6 m, and 10 m. At each distance, a set of different interferer-receiver distances ($D_{IS\text{-}Rx}$) are chosen based on select channels (ZigBee channel 11, 15, 19, 23 and 26). In each experiment, the transmitter sends 600 data packets in total at a rate of 1 s^{-1}. Low data rates are utilized in these experiments to mimic real building automation and control situations. Every test is carried out for 30 s, and each test is repeated 20 times to calculate the average value of RSSI, LQI and PER.

To estimate reliability, three main metrics have been studied. In particular, RSSI and LQI are computed on board at the receiving radio to estimate the quality of the connection between a transmitter and receiver. The receiver samples the RSSI and LQI through its microprocessor. The radio chip provides a measure of the RSSI (in mW or dBm), which is an estimate of signal strength, averaged over 32 bit periods (128 µs) and is continuously updated. This value can be read directly from the RSSI register. The radio can be set at 8 discrete levels between -25 and 0 dBm. In these experiments, the transmitting power is set at the highest level, which is 0 dBm (1 mW). LQI is a metric on a scale from approximately 0 to 108 that provides an estimate of the signal strength in light of interference and multipath errors. PER is the ratio of the number of failed packets to the total number of packets transmitted over certain durations. The key issue to be investigated is the reliability of data transmissions. In building applications, reliability is usually the most important factor in assessing the performance of a wireless sensor network as opposed to other performance factors such as bandwidth and latency. Fundamentally, the reliability can be measured by determining the ratio of the packets not received successfully to all that are transmitted by a sensor node. This number is termed the PER. Unlike RSSI and LQI, PER cannot be measured in real time because the receiver does not necessarily know if the transmitter has sent a message. For this reason, RSSI and LQI are often used as surrogate metrics for the PER. These three metrics have been considered in this study, with PER serving as the most straightforward metric of reliability while LQI and RSSI have the potential for providing a real-time measurement that can estimate the reliability.

IV. EXPERIMENT OBSERVATIONS AND PREDICTION

A. *Initial Test*

To gain more insight into the effects of interference on ZigBee communication, RSSI, LQI, and PER data are obtained and analyzed. We begin our investigations by measuring the impacts of WiFi, Bluetooth, and microwave ovens on ZigBee communication with different $D_{Tx\text{-}Rx}$. Since an increase in PER is the consequence of interference visible to applications, that measure is adopted as the main evaluation metric. To determine the impact of different interference sources and different $D_{Tx\text{-}Rx}$ on ZigBee communication, tests are carried out with the transmitter and receiver spaced at the following distances: 1 m, 2 m, 4 m, 6 m and 10 m. In this group of tests, each interference source is placed 0.5 m away from the receiver. The WiFi source is a router that streams data on channel 6. The Bluetooth source is a laptop streaming music to a headset. The microwave oven is a commercially available model operated at its nominal maximum power of 1200 W. ZigBee channel 15 is first selected and the resulting plots obtained are shown in Fig 2(a). These tests are then immediately repeated using channel 26 and the results are shown in Fig. 2 (b). Based on standard deviations of the data, the uncertainty for all RSSI data reported is estimated as ±1 dBm. The uncertainty in the PER data is estimated as 1 % based on multiple tests. Fig. 2(a) shows that the microwave oven has the most severe interference with ZigBee communication and leads to the highest PER. Bluetooth interference, as expected, is less of an issue as indicated in Fig. 2. Bluetooth may interfere with a transmission attempt, but will usually have hopped to a different part of the spectrum when it senses other communications on that frequency band. According to Fig. 2(a), the WiFi router has little impact on ZigBee communication if ZigBee is set up on channel 26. This result is consistent with a theoretical analysis that indicates that ZigBee channels 25 and 26 are out of WiFi's spectrum usage. Hence less impact occurs for these two channels.

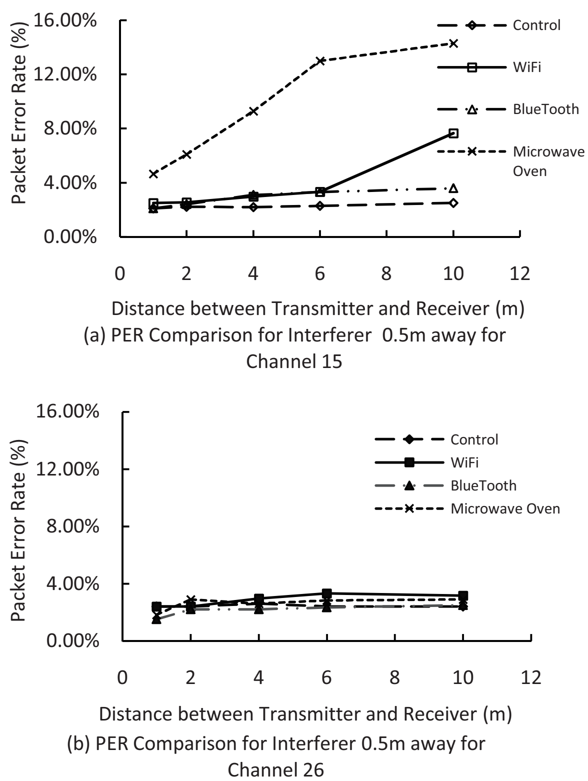


Fig. 2 Effect of $D_{Tx\text{-}Rx}$ on Packet Error Rates

B. *Effect of transmitter-receiver distance on reliability*

Since Bluetooth has only a minor impact on ZigBee communication, the following experiments focus on interference from WiFi and the microwave oven. The experiments are expanded to examine channels 11, 19, and 23. Data presented in the following section are obtained by averaging across channels.

Results in Fig 3(a) show that, under WiFi interference, the overall RSSI value decreases as $D_{Tx\text{-}Rx}$ increases. Commonly accepted theory suggests that further drops would be expected as $D_{Tx\text{-}Rx}$ increases. Figure 3(a) also indicates that the WiFi router causes a jump in ZigBee PER (from 2.5 % to 3.0 %) at a $D_{Tx\text{-}Rx}$ of 6 m. Furthermore, when $D_{Tx\text{-}Rx}$ is 10 m, the PER reaches 3.6 %.

When the interference source is changed to the microwave oven, similar results are obtained as shown in Fig. 3(b). The RSSI value drops when $D_{Tx\text{-}Rx}$ changes from 1 m to 10 m. In consistent with the RSSI changes, the PER value increases from 3.4 % to 7.3 %. These results are encouraging in that they are consistent with previous experimental results, and we are then able to apply a similar approach to further study the impact of interferer location on ZigBee communication.

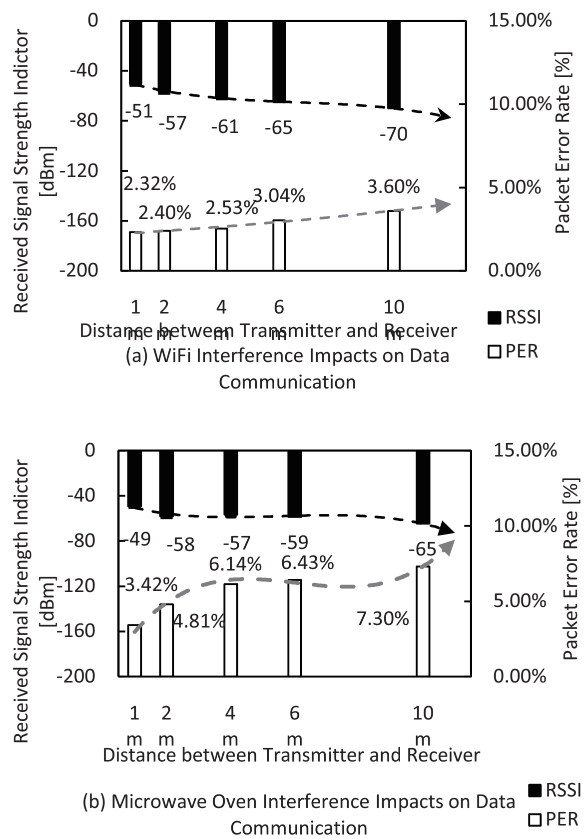
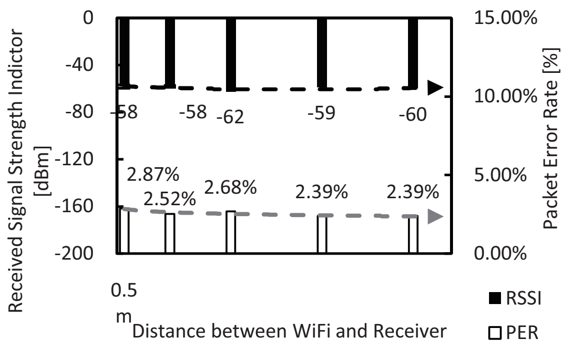


Fig. 3 RSSI and PER Results of WiFi and Microwave Interference Impacts on ZigBee Communication at different $D_{Tx\text{-}Rx}$

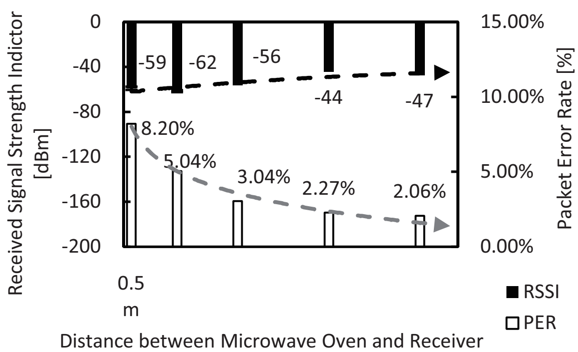
C. *Interference at different interferer-receiver distances*

Finally, to further assess the impact of the location of the WiFi and microwave ovens on Zigbee communication, a series of tests were performed in which $D_{IS\text{-}Rx}$ is varied. Results are illustrated in Fig. 4. Intuitively, one would expect that a shorter $D_{Is\text{-}Rx}$ would result in a larger PER. In this set of tests, $D_{Tx\text{-}Rx}$ is maintained at 2 m and $D_{Is\text{-}Rx}$ is varied from

0.5 m to 7 m. The observation from Fig. 4(a) indicates that when $D_{Tx\text{-}Rx}$ is kept as a constant at 2 m, the WiFi interference effects on the Zigbee link are steady over the distances studied. All PER values are in a range from 2.4 % to 2.9 %. Under microwave oven interference, however, the maximum PER (8.2 %) is detected when the microwave oven is placed 0.5 m away from the receiver, and results are heavily dependent upon D_{IsRx}.



(a) WiFi Interference Impacts on Data Communication



(b) Microwave Oven Interference Impacts on Data Communication

Fig. 4 RSSI and PER Results of WiFi and Microwave Interference Impacts on ZigBee Communication at different $D_{Is\text{-}Rx}$

D. *Coexistence model of ZigBee and WiFi/microwave oven*

To better understand the implication of the measurements, PER is modeled mathematically. The ZigBee and WiFi/microwave oven coexistence model for ZigBee communication channels 11 to 24 uses a combination of analytical and empirical methods. In this work, the PER results for ZigBee communication vary based on distance between transmitter-receiver, distance between interferer-receiver, and interference source. The PER in the presence of a WiFi router can be expressed in (1), where x = $D_{Tx\text{-}Rx}$ (transmitter-receiver distance) and y = $D_{Is\text{-}Rx}$ (interferer-receiver distance) for mathematical conciseness. C is a constant value calculated as $1/10\sqrt{2\pi}$.

$$PER(x,y)=\begin{cases}\left|y\cdot\ln(1-\frac{x}{y})\cdot10^{-3}\right|+C\cdot x\cdot e^{-\frac{x}{2}}, & y-x\geq5m\\ \left|x\cdot\ln(\frac{x}{y})\cdot10^{-3}\right|+C\cdot y\cdot e^{-\frac{y}{2}}, & Others\end{cases}\tag{1}$$

When the interference source changes to microwave oven, the PER can be estimated through (2):

$$PER(x,y)=\begin{cases}\left|\alpha\cdot y\cdot\ln(\frac{x}{y})\right|+C\cdot e^{-\frac{y}{2}}, & y\leq0.5m\\ \left|\beta\cdot y\cdot\ln(\frac{x}{y})\cdot10^{-4}\right|+\frac{C}{2}\cdot e^{-\frac{x}{2}}, & y\leq0.5m\ \ and\\ & y-x\geq5m\\ \left|x\cdot\ln(\frac{x}{y})\cdot10^{-3}\right|+\frac{C}{2}\cdot e^{-\frac{x}{2}}, & Others\end{cases}\tag{2}$$

where α = 0.6 and β=5.

E. *Performance Evaluation*

The model is evaluated by comparing PER from the experiments with calculated PER values. The experiments follow a similar setup and methodology as previously reported. Two different interference sources, WiFi and microwave oven are applied in the tests. For each interferer, a test plan is deployed as shown in Table 2. For both interferers, various $D_{Tx\text{-}Rx}$ (from 1 m to 10 m) with corresponding $D_{Is\text{-}Rx}$ (from 0.5 m to 10 m) are tested.

Table 2 Comparison Experiment Table

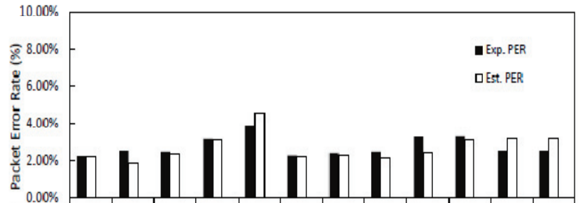
$D_{Tx\text{-}Rx}$ (m)	**1m**	**2m**	**4m**	**6m**	**10m**
$D_{IS\text{-}Rx}$ (m)			0.5m/4m		

$D_{Tx\text{-}Rx}$ (m)			**2m**		
$D_{IS\text{-}Rx}$ (m)	0.5m	2m	4m	7m	10m

Fig. 5 shows PER comparison results for WiFi and microwave oven interference. These results are obtained using a pair of ZigBee nodes and their corresponding interferer. The distances between the transmitter and receiver and the interferer and receiver are set according to the tables. The figures show that the coexistence models for WiFi and microwave oven give a similar PER value compared to the data from real experiments. We observe some differences between estimation results and experimental results. We hypothesize that these differences are due to measurement errors.

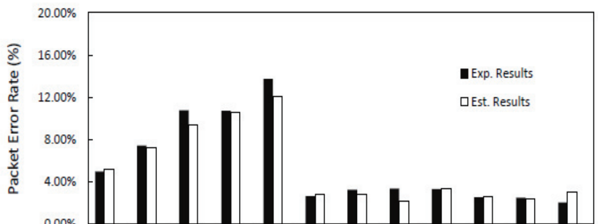
V. Conclusion

Results of an experimental study of ZigBee communication in the presence of different interferers operating in the 2.4 GHz license-free band are presented. We have explored a variety of interference sources and their effect on ZigBee communications. Based on experimental measurements and mathematical analysis, coexistence models are proposed to predict interference impacts on ZigBee communication based on interference source, transmitter-receiver distance, and interferer-receiver distance. In each of these situations, ZigBee and WiFi/microwave oven exhibit different interactive behavior and hence different performance, which are quantified by the analysis and verified by the experiment. The estimation can be improved as more measurements are taken during the normal operation of the ZigBee communication. As a first step, we focus on one interferer at one time. The WiFi and microwave oven coexistence situation will be studied as future work.



■ Exp. PER	2.25%	2.53%	2.49%	3.13%	3.89%	2.28%	2.40%	2.48%	3.25%	3.27%	2.54%	2.54%
□ Est. PER	2.25%	1.83%	2.39%	3.04%	4.55%	2.19%	2.30%	2.16%	2.40%	3.08%	3.17%	3.16%
Error(%)	0.13%	38.17%	4.27%	2.63%	16.96%	3.78%	4.22%	12.90%	25.99%	5.99%	19.91%	19.60%

(a) PER Comparison Results under WiFi Interference



■ Exp. Results	4.97%	7.43%	10.75%	10.70%	13.73%	2.63%	3.26%	3.35%	3.31%	2.53%	2.50%	2.04%
□ Est. Results	5.19%	7.27%	9.35%	10.56%	12.09%	2.85%	2.85%	2.16%	3.38%	2.62%	2.34%	3.08%
Error(%)	4.37%	2.13%	13.06%	1.29%	11.88%	8.70%	12.54%	35.52%	2.01%	3.70%	6.72%	33.63%

(b) PER Comparison Results under Microwave Oven Interference

Fig. 5 Comparison Results of Experimental Results and Estimated Results

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