Performance Measurement and Analysis of Low Data Rate Wireless Communication under Interference Sources in Buildings

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***Abstract*—Interference from collocated networks operating over the same frequency range becomes an increasingly severe problem as the number of networks overlapping geographically increases within commercial and residential buildings. This paper aims to highlight the issues affecting co-existence of IEEE 802.15.4 (ZigBee) systems in the presence of interference. ZigBee uses the IEEE 802.15.4 PHY and MAC layer standards to handle devices. The practical performance of ZigBee systems are established with reference to supporting empirical and simulated data. Our experiments show that, among different interferers, interference from microwave ovens is indeed a major problem. Guidelines are provided for installing sensors inside buildings.**

***Keywords*—**Zigbee, Wireless Sensors, Interference, Building Automation and Control

I. INTRODUCTION

A Building Automation System (BAS) is a distributed control system that is designed to monitor and control the mechanical and lighting systems in a building. The main advantage of a BAS is that it reduces building energy and maintenance costs when compared to a non-controlled building [1]. To enable better control and monitoring of the building environment as part of BAS's, the IEEE 802.15.4 [2] and ZigBee [3] standards for short range wireless communication are being used as a tool to place low data rate transducers in a building with less cost. The IEEE 802.15.4 standard documents a low data rate physical layer for short range wireless systems. ZigBee uses the IEEE 802.15.4 PHY and MAC layer standards and adds specifications for higher layers that lead to interoperable wireless nodes for building automation [4]. These standards utilize the license-free industrial scientific medical (ISM) frequency band. IEEE 802.15.4 makes provisions for communications for both the 900 MHz ISM band and the 2.4 GHz ISM band. 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). For these reasons and the fact that the 2.4 GHz band is uniform world-wide, it is the most prevalent band used by IEEE 802.15.4 RF-chips. A challenge occurs, however, because of the fact that many devices that emit RF pulses in this frequency range are utilized in modern buildings. In particular, many wireless devices based on protocols such as WiFi [5], Bluetooth [6], Zigbee, and wireless USB utilize this part of the electromagnetic spectrum. These devices and others that emit radiation in this range include cordless phones, wireless mice, wireless keyboards, and the humble microwave oven. As a new paradigm for building automation and control based on wireless sensors and actuators conforming to the ZigBee standard [7], the increasing number of devices and systems interfering with those wireless nodes becomes a concern. In the 2.4 GHz frequency band, neither resource planning nor bandwidth allocation can be guaranteed. Additionally, other non-communication systems may emit electromagnetic waves (e.g., microwave ovens) in the 2.4 GHz-band, which will also affect ZigBee communication.

Testing of the interference patterns of Zigbee wireless sensor communication has not been fully documented. In this paper, we perform a full characterization of commercially available wireless radios (motes). A testbed has been set up to measure the Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI), and Packet Error Rate (PER) of the ZigBee communications. These results are obtained as a function of distance, channel, and transmit power. By analyzing the metrics with respect to distance and channel, we present a clear picture of the actual capabilities of Zigbee communication in the presence of different interference sources. The eventual aim of the work is to offer a set of guidelines for setting up wireless sensor networks that will enable them to achieve the desired Quality of Services (QoS) and maximum lifetime.

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The remainder of the paper is organized as follows. We begin by presenting related work in Section 2. The experimental approach is presented in Section 3, and observations from those experiments are presented in Section 4. Finally, conclusions are drawn in Section 5.

II. RELATED WORK

There is a growing interest in understanding and modeling interference in wireless communication. The traditional approach to avoiding interference problems has been to license frequency bands to primary network users who are the only ones allowed to transmit in that frequency [8]. Although this approach removes the problem of interference, it results in low utilization when the primary owner does not use the allocated spectrum frequently. 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 [9-14]. Major studies [9, 15,16]) have focused on wireless link quality in the absence of concurrent transmissions. These studies evaluate the impact 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.

Researchers have done significant empirical work in understanding the interference properties using the Signal-to-Interference-plus-Noise Ratio (SINR) model for low power wireless links using the first generation motes [13]. Of particular relevance to this work is the study by Sikora [17]. This study carries out preliminary interference tests that are then extended in [18]. The researchers give a good early study of the co-existence performance of ZigBee and WiFi networks. They perform their experiments to represent the worst case scenarios and are stated in the report as having "limited real world relevance." However, some reasonable conclusions are drawn. For IEEE 802.11b interference, it can be seen that a channel offset of 10 MHz dramatically reduces the ZigBee PER from 92 % to 30 %. The key point to note here is that the separation of the IEEE 802.11b transmitter from the ZigBee transmitter is only 2 m throughout the test. Characteristics of Bluetooth interference are also obtained at the worst case scenario when two parallel File Transfer Protocol (FTP) links are set up in close proximity to one another. A ZigBee PER of less than 10 % is achieved. Petrova *et al.* [19] also studied the co-existence of ZigBee and IEEE 802.11b networks. Measurements made for different offsets between the central frequencies of ZigBee are also taken into account, although no details of the traffic characteristics of the interferer are provided. Separation between the ZigBee and IEEE 802.11b sources is fixed at 3.5 m. According to [19], there should be at least 7 MHz offset between the operational frequencies for satisfactory performance of ZigBee radios. The use of small packets (on the order of 20 bytes) exhibits significantly better co-channel rejection (i.e., elimination of interfering signals) than using the maximum packet size of 127 bytes.

Shuaib et al. [20] carried out a study in an office environment using an IEEE 802.11g interference source with 9.8 Mbps data throughput. The bi-directional ZigBee data throughput is also set near to the full channel capacity at 115 kbps. The results show that, for ZigBee nodes placed between 3 m and 6 m on either side of a WLAN transmitter, ZigBee throughput is decreased between 10 % and 22 %. It must be noted that this result is for operation at overlapping channels. Separation distances greater than 6 m and channel offsets are not considered. The investigators discovered that Bluetooth interference had considerable effects on the WLAN throughput – up to 12 % at the worst case, compared with the negligible impact on throughput due to ZigBee interference.

The coexistence issues of ZigBee-based devices and other interferers have been examined in the above work, but no quantitative measurements for real building/office environments have yet been documented. Compared to most of the existing simulation based studies, the research effort presented here is guided by extensive field experiments of received signal strength in a real office environment over a long period of time using recent sensor network platforms, which realistically addresses the real-world wireless communication challenges in low-data rate wireless sensor networks. This work makes the following contributions: 1) it reveals the spatiotemporal impacts of interference on wireless communication and 2) it identifies the relationship between interferer-receiver distance and sender-receiver distance. A full factorial experimental design is implemented to explore the effects of key parameters on RSSI, LQI, and PER. Conclusions are drawn from further analysis of collected data.

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. The transmitter and receiver are placed in different positions with respect to each other in a typical indoor office environment to observe good, moderate, and bad links. The experimental testbed consists of two different motes using a radio chip that is compliant with the IEEE 802.15.4 PHY layer standard in the 2.4 GHz ISM band, which are MicaZ [21] and Telosb nodes [22]. In the experiment, a 4-byte data payload is transmitted over the wireless link once every second. The transmit power can be programmed at 8 discrete levels between 0.003 mW and 1 mW (-25 dBm and 0 dBm). In our experiments, we set the transmitting power at the highest level, which is 1 mW (0 dBm).

To estimate reliability, three main metrics have been studied. In particular, RSSI and LQI are computed at the receiving radio to estimate the quality of the connection between a transmitter and receiver. The receiver sampled 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). This value can be read directly from the RSSI register. 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 a certain duration. 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. 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.

A pair of nodes is set up in an indoor office environment, one as the sender and the other as the receiver. The experimental site is a room sized approximately 9 m by 6 m. The distance from the sender to the receiver is varied at the following levels: 1 m, 2 m, 4 m, 6 m, and 10 m. At each distance, the transmitter sends 600 data packets in total at a rate of 1 packet per second. A low data rate was chosen to mimic the operation of a real building automation and control situation. At each distance, a set of different interferer to receiver distance parameters are chosen for select channels (ZigBee channel 11, 15, 19, 23 and 26). Each test is carried out for 30 s, and each test is repeated for a total of 20 runs to calculate the average value of RSSI, LQI, and PER.

IV. EXPERIMENTAL OBSERVATIONS

A. *Preliminary tests – indoor/outdoor test comparison*

To better understand the performance of the hardware and obtain background control data of the experimental site, it is valuable to first examine the metrics of interest in an environment in which no interference is expected. All figures in this study are plotted according to the same rules: the X-axis refers to the distance between either sender and receiver or interference source and receiver. In RSSI plots, the Y-axis provides the raw dBm readings provided by the radio chip. In LQI plots, the Y-axis represents the raw LQI value scaled to 1 to 100. In PER plots, the Y-axis presents the percentage of the transmitted messages not received by the receiver.

To determine the characteristics of the indoor test environment, measurements were conducted in two environments: inside an office building and outdoors on a grassy field. In these tests, the transmitter is set with an output power level of 1 mW (0 dBm), and messages of length 25 bytes are sent at rate of 1 s^{-1}. For the initial indoor tests, the receiver is separated from the transmitter at distances of either 1 m or 6 m. It should be mentioned that the indoor measurements are done in a lab without any serious obstacles for the propagating signal. In these experiments, the three metrics of interest are collected and compared. The results, as shown in Fig. 1, indicate that the lab to be used in the subsequent experiments is expected to be similar to the outdoor environment. No more interference can be detected compared to the outdoor test results. The uncertainty estimates of the data presented in all figures are based on a series of tests carried out with these radios. The uncertainty in RSSI is estimated as ± 2 dBm and that of the LQI is $\pm$ 25. Tests also indicate an uncertainty of ± 1 % on measurements of the PER.

B. *Parametric Tests*

The next step in the investigation involved the measurement of the impacts of WiFi, Bluetooth and microwave ovens on ZigBee communication with a variety of sender and receiver distances. Since PER is the metric of interest for building applications, we adopt it as our main evaluation metric. In the following tests, the distance between the interference source and receiver is defined as $D_{IS\text{-}Rx}$ and the distance between the transmitter and receiver is defined as $D_{Tx\text{-}Rx}$.

1) Different Sender and Receiver Distances

The purpose of this group of tests is to assess how different sender and receiver distances impact Zigbee communication in the presence of interference sources. The distance between the sender and receiver are varied at the following levels: 1 m, 2 m, 4 m, 6 m and 10 m. Different interference sources are set up and maintained at a constant distance from the receiver. The WiFi interference source was an 802.11 router streaming data to a client. The Bluetooth source was a computer streaming music to a wireless headset. The microwave oven was a commercially available unit with a maximum rated power of 1200 W. In this group of experiments, $D_{IS\text{-}Rx}$ is set equal to 0.5 m and the test results are shown in Fig. 2. The observation from Fig. 2 is that the microwave oven interferes with Zigbee communication most severely and leads to the highest PER. It is also evident that WiFi, when $D_{Tx\text{-}Rx}$ reaches 6 m, causes a significant change in PER. Bluetooth interference does not appear to affect Zigbee communication. It can be clearly seen that high PER values occur with large sender to receiver distance.

To investigate the impacts of different interference sources on different ZigBee channels, the same experimental approach as previously described is carried out with ZigBee transmissions set on both channels 15 and 26. Channel 26 uses the outermost frequency band, which does not overlap with frequencies utilized by WiFi. Channel 15 is designed to use a frequency band between those used by WiFi. Fig. 3 shows results from tests carried out when channel 26 is used; note that Fig. 2 shows these same results when channel 15 is used. These figures show that less impact on Zigbee communication is noticed when using channel 26.

Results in Figs. 2 and 3 show that, even though average RSSI values might not decrease considerably, the associated PER can still vary significantly and can reach high levels (more than 14%). To further analyze the performance of Zigbee communication in the presence of WiFi and a microwave oven, another set of screening tests were carried out. Since negligible impacts are observed for Bluetooth, the Bluetooth interference source will not be considered in further tests.

2) Channel Selection test results

a) WiFi interference on ZigBee communication

The previous tests suggest that different results are observed for different channels. To further explore effects of channel selection on reliability, tests were carried out using channels 11, 19, and 23.

To test the validity of these expectations, experiments are designed to adjust the channel of the Zigbee link while the WiFi communication channel is kept constant at Channel 6. When WiFi is used as the interference source, all ZigBee channels except channel 26 showed decreases in reliability, most notably channel 15. Channel 15 is located within the frequency band of WiFi channel 6. Fig. 4 indicates that RSSI drops from -40 dBm to -80 dBm, and the PER increases up to 25 %. It appears that channel 26 is likely to have the lowest level of interference fluctuation and is therefore a good candidate for reliable transmission.

b) Effect of Microwave Oven Interference on ZigBee Communication

The interference source was then changed to a microwave oven. The purpose of these tests is to evaluate the effect of the microwave oven on different ZigBee channels. $D_{Is\text{-}Rx}$ is set as 0.5 m. Results are demonstrated in Fig. 5. Dramatic changes are noticed when the microwave oven is 0.5 m away from the receiver and the sender is 2 m away from the receiver.

3) Interference location impacts on Zigbee communication

Finally, to further assess the impacts of the location of WiFi sources and microwave ovens on Zigbee communication, a series of tests was performed. Intuitively, it is expected that a smaller $D_{Is\text{-}Rx}$ would result in higher interference and larger PER's. From the previous test results, $D_{Tx\text{-}Rx} = 2$ m served as a threshold for the microwave oven to interrupt communications while 4 m was the threshold for WiFi interference. Fig. 6 shows results when $D_{Tx\text{-}Rx}$ is maintained at 2 m and $D_{Is\text{-}Rx}$ varies from 0.5 m to 7 m. The observation from Fig. 6 is that when $D_{Tx\text{-}Rx}$ is kept at 2 m, WiFi interference is negligible. All PER values are around 2.5 %. Fig. 7 reveals that the ZigBee link is affected by microwave oven interference if $D_{Tx\text{-}Rx}$ is fixed at 2 m when $D_{Is\text{-}Rx}$ is less than 2 m. The maximum PER is detected when the microwave oven is placed 0.5 m away from the receiver.

V. Discussion and Conclusion

In this study, we perform a set of measurements on later generation motes and report our findings. WiFi, Bluetooth and microwave oven interference sources are deployed in the same office environment as Zigbee radios. Given a variety of test conditions, interference from collocated networks can cause different PER's in low-power, battery-operated Zigbee communication.

The type of interference source has the most significant impact on the results. Bluetooth has negligible impact on the Zigbee link compared with the other two. Therefore, Bluetooth interference is likely not an issue for IEEE 802.15.4 communication. To minimize the effect of interference from WiFi sources, a non overlapping channel between Zigbee and WiFi is recommended with at least 4 m separation distance between the ZigBee receiver and the WiFi interference source. A microwave oven, compared with others, has the most significant impacts on PER if $D_{Tx\text{-}Rx}$ is over 2 m.

The sender to receiver distance has the next greatest effect. When WiFi sources are present, a $D_{Tx\text{-}Rx}$ under 6 m resulted in reliable transmission, while a $D_{Tx\text{-}Rx}$ under 2 m was required to ensure reliable transmission in the presence of a microwave oven. Additionally, high PER values are not only related to sender-receiver distance but also associated with the interference source-receiver distance. Furthermore, a channel effect was observed in which the highest ZigBee channel (channel 26) yielded the most reliable communications.

The correlation between PER and RSSI/LQI is not totally clear. Even though average RSSI/LQI values may not increase considerably, the corresponding PER values could change significantly. This uncertainty will motivate the development of interference metrics that may use RSSI/LQI measurements to predict interference and subsequently choose the optimal channel for future data transfers.

In performing co-existence studies, difficulties can arise in determining the typical characteristics of an interferer and the expected traffic rates in the network. In establishing the characteristics of an interference source, transmitter payload size, inter-packet delay and output power are important factors. In these tests, we set all parameter values to simulate real office sensor communication configurations. It is expected that the effort of this project can form the basis of experimental methods of test to assess the ZigBee-based wireless sensor networks for building applications.

References

[1] J. Braun, "Intelligent Building Systems – Past, Present, and Future," *in Proc. of the 2007 American Control Conference*, NYC, pp. 4374 - 4381, New York City, USA, July, 2007.

[2] IEEE 802.15 WPAN Task Group 4, http://www.ieee802.org/15/pub/TG4.html, 2010.

[3] ZigBee, http://www. ZigBee.org, 2010.

[4] W. Guo, W. Healy and M. Zhou, "ZigBee-Wireless Mesh Networks for Building Automation and Control," To be published in Proc. Of IEEE International Conference on Networking, Sensing and Control, 2010.

[5] WiFi, http://www.wi-fi.org/, 2010.

[6] Bluetooth, http://www.bluetooth.com/bluetooth/, 2009.

[7] W. Guo and M. Zhou, "An emerging technology for improved building automation control," *in Proc. of IEEE International Conference on Systems, Man, and Cybernetics,* pp. 337-342, San Antonio, TX, Oct. 2009.

[8] P. Mitran, "Interference reduction in cognitive networks via scheduling," *IEEE Trans. on Wireless Comm.*, pp. 3430-3434, Aug. 2009.

[9] D. Ganesan, D. Estrin, A. Woo, D. Culler, B. Krishnamachari, and S. Wicker, "Complex behavior at scale: An experimental study of low-power wireless sensor networks," Technical Report CS TR 02-0013, UCLA, 2002.

[10] D. Lal, A. Manjeshwar, F. Herrmann, E. Uysal-Biyikoglu, and A. Keshavarzian, "Measurement and characterization of link quality metrics in energy constrained wireless sensor networks," *in Proc. Of IEEE Global Telecommunications Conference,* vol.1, pp. 446-452, San Fransico, USA, Dec. 2003.

[11] J. Zhao, R. Govindan, and D. Estrin, "Computing aggregates for monitoring wireless sensor networks," *in Proc. of the First IEEE International Workshop on Sensor Network Protocols and Applications*, pp. 139- 148, 2003.

[12] A. Woo, T. Tong, and D. Culler, "Taming the underlying challenges of reliable multihop routing in sensor networks," *In Proc. of the First ACM Sensys Conference*, pp. 14–27, Los Angeles, CA, USA, 2003.

[13] D. Son, B. Krishnamachari, and J. Heidemann, "Experimental study of concurrent transmission in wireless sensor networks," *In Proc. of the Fourth ACM Conference on Embedded Networked Sensor Systems (SenSys),* pp. 237 – 250, Boulder, Colorado, USA, 2006.

[14] A. Cerpa, J. Wong, L. Kuang, M. Potkonjak, D. Estrin, "Statistical model of lossy links in wireless sensor networks," *in Proc. of the Fourth International Symposium on Information Processing in Sensor Networks,* pp. 81- 88, Los Angeles, California, 2005.

[15] D. Son; B. Krishnamachari, and J. Heidemann, "Experimental study of the effects of transmission power control and blacklisting in wireless sensor networks," *In Proc. of the First Annual IEEE Communications Society Conf. of Sensor and Ad Hoc Communications and Networks,* pp. 289- 298, Santa Clara, CA, USA, Oct. 2004

[16] B. Hull, K. Jamieson, and H. Balakrishnan, "Mitigating congestion in wireless sensor networks," *In Proc. of the 2nd international conference on Embedded networked sensor systems*, pp. 134-147, Baltimore, MD, USA, 2004.

[17] A. Sikora, "Compatibility of IEEE802.15.4 (ZigBee) with IEEE802.11 (WLAN), Bluetooth, and Microwave Ovens in 2.4 GHz ISM-Band, Test Report", Steinbeis Transfer Centre for Embedded Design and Networking, University of Cooperative Education Loerrach, 2004.

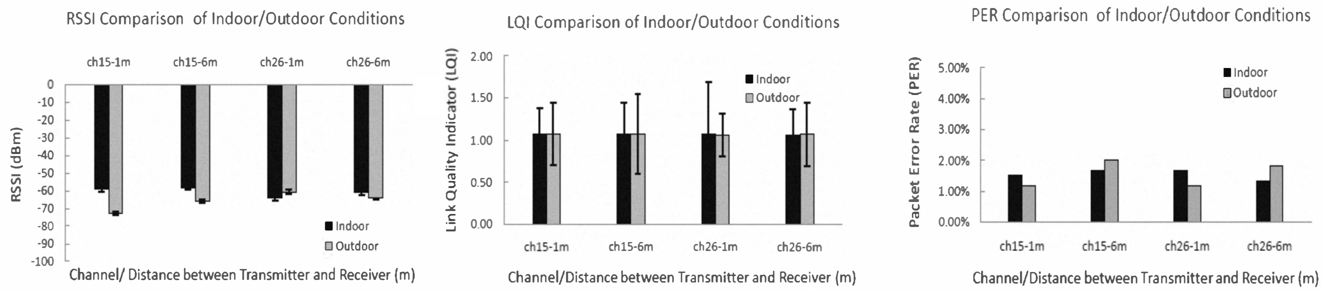
[18] A. Sikora and V. Groza, "Coexistence of IEEE 802.15.4 with other Systems in the 2.4 GHz-ISM-Band," *in Proc. of IEEE Instrumentation and Measurement Technology Conference IMTC 2005,* pp. 1786-1791, OTTAWA, ONTARIO, CANADA, 2005.

[19] M. Petrova, J. Riihijarvi, P. Mahonen, S. Labella, "Performance study of IEEE 802.15.4 using measurements and simulations," *in Proc. of Wireless Communications and Networking Conference,* pp.487-492, *Las Vegas, NV, USA*, 2006.

[20] K. Shuaib, M. Boulmal, F. Sallabi and A. Lakas, "Co-existence of ZigBee and WLAN - a performance study," *in Proc. of IEEE IFIP international Conference on Wireless and Optical Communications Networks,* pp.1-6, Pomana, CA, USA, 2006.

[21] MicaZ, http://www.xbow.com/Products/productdetails.aspx?sid=164, 2010.

[22] TelosB, http://www.xbow.com/Products/productdetails.aspx?sid=252, 2010.



a) Indoor/Outdoor RSSI test result b) Indoor/Outdoor LQI test results c) Indoor/Outdoor PER test results

Fig. 1 Indoor/Outdoor test comparison results

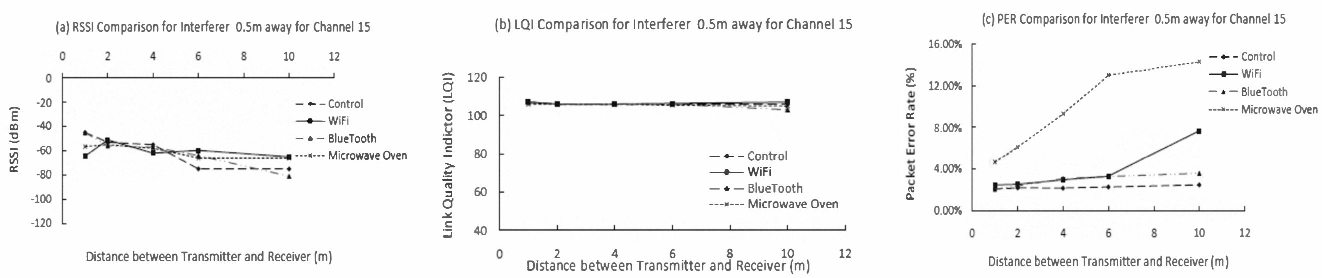


Fig. 2 ZigBee performance results vs. $D_{Tx\text{-}Rx}$ at channel 15

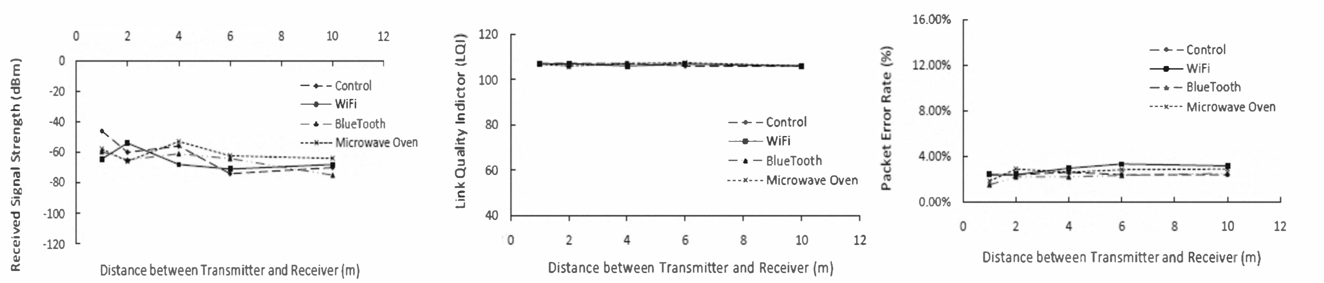


Fig.3 ZigBee performance results vs. $D_{Tx\text{-}Rx}$ at channel 26

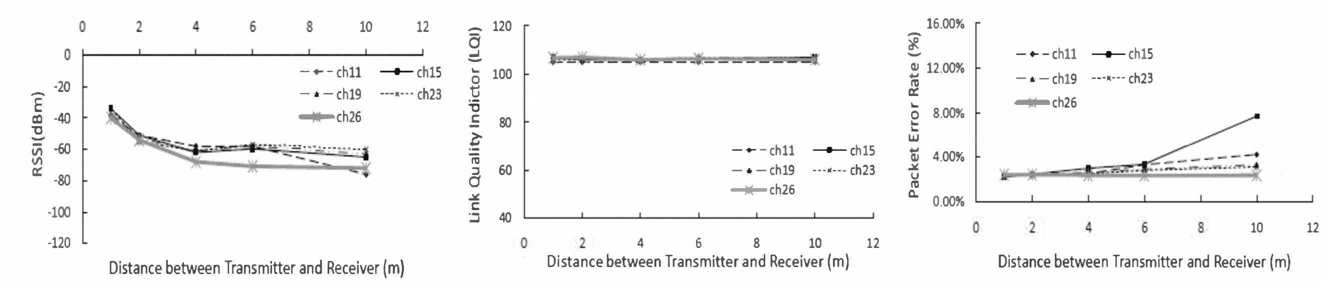


Fig. 4 WiFi's impacts on ZigBee performance results vs. $D_{Tx\text{-}Rx}$ for different channels.

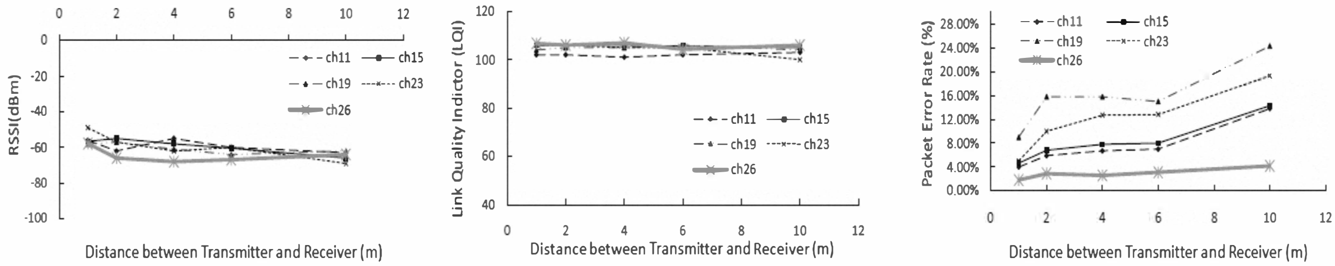


Fig. 5 Microwave oven's impacts on ZigBee performance results vs. $D_{Tx\text{-}Rx}$ for different channels

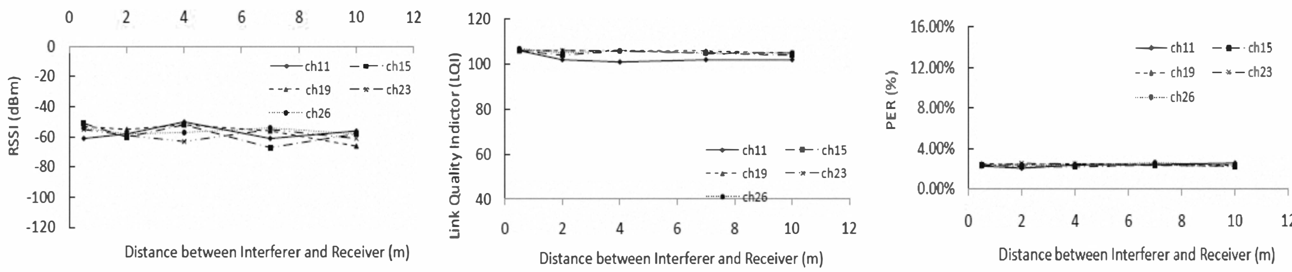


Fig. 6 WiFi's interference impacts on ZigBee performance results vs. $D_{IS\text{-}Rx}$ for different channels

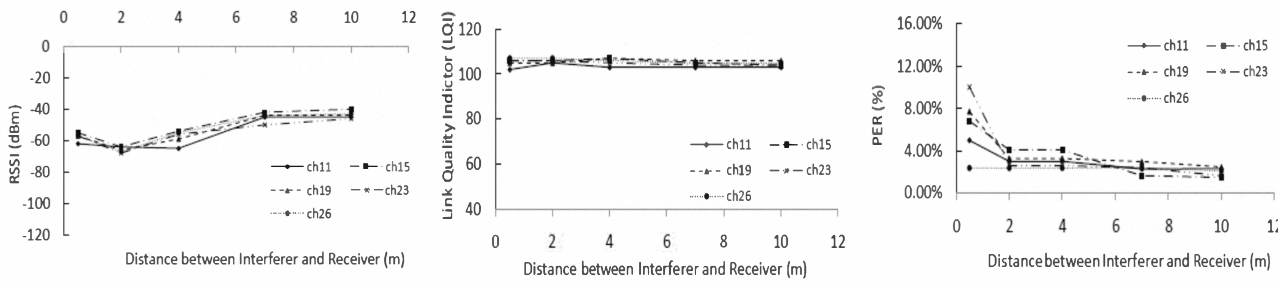


Fig. 7 Microwave oven's impacts on ZigBee performance results vs. $D_{IS\text{-}Rx}$ for different channels