Impacts of 2.4-GHz ISM Band Interference on IEEE 802.15.4 Wireless Sensor Network Reliability in Buildings

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***Abstract*—With the recent emergence of standards, wireless solutions are ready to be deployed in building automation networks. IEEE 802.15.4 is a standard for short-range wireless networks. Its major application fields are home and building automation, as well as industrial sensor and actuator networks. It operates primarily in the license-free 2.4-GHz industrial, scientific, and medical band. This feature makes the technology not only easily applicable but also potentially vulnerable to interference by other technologies in this band, e.g., Bluetooth and microwave ovens. There are many possible coexistence scenarios with different network sizes, configurations, interference sources (ISs), and environmental conditions. To investigate the impacts of ISs on the performance of IEEE 802.15.4 wireless sensor networks, this paper performs several experiments with commercially available equipment. The results give a rough indication of the mutual interference of the different systems when any two of the networks operate simultaneously and in range. This work collects important communication parameters to evaluate the impacts of other ISs on IEEE 802.15.4 networks. These results should help designers better understand the challenges of building wireless applications.**

***Index Terms*—Bluetooth, building automation, control systems, interference, microwave oven, reliability, sensor networks, wireless communication.**

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I. Introduction

In the past decade, several short-range wireless technologies were developed as an answer to the increasing demand for portable and flexible connectivity. In particular, wireless technologies are gaining a foothold in home and building automation. Many articles have documented the use of wireless technology in buildings [1]–[6]. Guo *et al.* [7] give a brief review and predicts the possibility of applying IEEE 802.15.4/ZigBee technology in building automation, networking, sensing and control for retrofit or new construction. The IEEE 802.15.4 standard [8] along with the ZigBee specification [9] enables wireless communications for field devices such as room or zone controllers and associated room temperature sensors, variable frequency drives, electrical meters, and point modules at prominent commercial and industrial facilities. These devices are moving from the research stage to commercial deployment by building automation companies.

Concerns still exist, however, among building operators and designers regarding the use of wireless sensors in buildings [10]. Among them is that miscellaneous radio frequency (RF) signals within a building will interfere with the communication signals between sensors and data collection points. With the prevalence of wireless devices in buildings, concerns about interference are bound to continue despite the best efforts of engineers to design wireless systems to avoid interference issues.

IEEE 802.15.4 operates in the license-free industrial, scientific, and medical (ISM) frequency band. Among those bands, the 2.4-GHz band provides the most bandwidth per channel (250-kb/s gross data rate) and the largest number of nonoverlapping channels (16). For these reasons and the fact that the 2.4-GHz band is accepted worldwide, this band is the most prevalent one used by IEEE 802.15.4-compliant RF chips. An obstacle that is faced in this frequency band, however, is that neither resource planning nor bandwidth allocation can be guaranteed. Additionally, other nonnetworking systems may emit electromagnetic waves (e.g., microwave ovens) in the 2.4-GHz band that will affect the communication within the wireless personal area aetwork (WPAN).

Interference among major applications working on 2.4 GHz becomes a serious concern in applying ZigBee in real building automation and control systems. Extensive studies have been carried out regarding the utilization of the 2.4-GHz band [11] and the performance of IEEE 802.15.4 [12], [13]. Since the release of the IEEE 802.15.4 standard in 2003 and the emergence of the first products on the market, there have been several analytical and simulation-based studies presented in the literature that attempt to characterize the performance of IEEE 802.15.4 [12], [14], [15]. Unfortunately, reported results on the practical insights gained from measurement efforts are limited. Pure measurement studies [16], [17] investigate the coexistence impact of an IEEE 802.15.4 network on IEEE 802.11b devices. Betta *et al.* [18] find that even if ZigBee is designed to generate a low interference, sensitive measurement instruments (such as modern spectrum analyzers) or the ones with bandwidth-containing ZigBee-operating frequencies can be susceptible to interference from this technology. Other existing work [19]–[24] that systematically considers interference effects falls in the analytical domain [25], [26]. These studies make several assumptions about topology, workload, or interference characteristics and operate their experiments at the worst case scenarios; therefore, the results cannot be straightforwardly used in a practical system. In the context of wireless sensor networks, several empirical studies have given an understanding of the complex nonideal behavior of low-power wireless links. Major studies [19], [23], [28] focus 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 paper aim to do.

As more companies produce products that use the 2.4-GHz portion of the radio spectrum, designers have to deal with increased signals from other unexpected sources. Sikora [29] carries out an early evaluation of the performance of IEEE 802.15.4 when others coexist. For IEEE 802.11b interference, it can be seen that a channel offset of 10 MHz dramatically reduces the ZigBee packet error rate (PER) from 92% to 30%. A key point to note here is that the separation of the IEEE 802.11b transmitter (Tx) from the ZigBee Tx is only 2 m throughout the test. The characteristics of a Bluetooth interference are also obtained at the worst case scenario when two parallel FTP links are set up in close proximity to one another. Petrova *et al.* [12] briefly address coexistence issues with IEEE 802.11b/g. In their work, they measure the offsets between the central frequencies of the IEEE 802.15.4 and IEEE 802.11b/g channels. With the separation between the IEEE 802.15.4 radios and wireless local area network (WLAN) sources fixed at 3.5 m, they find that the effects of the interference depend upon the size of the transmitted data packets. The small packets of 20 B exhibit significantly less rejection than packets having the maximum size of 127 B. A more recent study is carried out by Shuaib *et al.* [30]. This study examines separation distances less than 6 m, and channel offsets are not considered. An interesting finding is that Bluetooth reduces WLAN throughput by up to 12%, while IEEE 802.15.4 has negligible impact on the throughput despite being placed close to the WLAN radios. Conversely, the WLAN Tx decreases the IEEE 802.15.4 throughput by 10%–22%. Shin *et al.* [31], [32] focus on the effect of interference from IEEE 802.11b on the performance of IEEE 802.15.4. They find that if the distance between ZigBee and WLAN nodes is longer than 8 m, the interference of the IEEE 802.11b radio does not affect the performance of a ZigBee node.

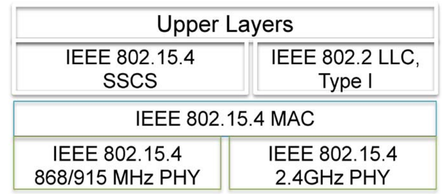

Fig. 1. 802.15.4 architecture [8].

Despite the studies previously carried out to assess the effects of interference, very few standard methods are available to building practitioners to help them determine the effect of various interference sources (ISs) on the performance of the nodes making up a wireless sensor network. To help in the development of such a test method, this paper presents the tests that help to characterize the key factors that should be considered when assessing the performance of wireless sensor networks in the midst of potential ISs. The ISs that are considered are Bluetooth, wireless fidelity (Wi-Fi), and a microwave oven. The metrics of interest are selected as the received signal strength indication (RSSI), link quality indicator (LQI), and the PER.

This paper is organized as follows: Section II gives an overview of the systems considered. Section III presents the experimental design, while Section IV provides results from measurements and a discussion of the results. Finally, conclusions are presented in Section V.

II. Overview of IEEE 802.15.4 (ZigBee)

Wireless sensing applications in buildings are characterized by low data rates (because of large time constants for changes in the parameters of interest) and the need to minimize power draw to reduce maintenance cost. The standards that have received the most interest have been IEEE 802.15.4 and its accompanying ZigBee standard. The IEEE 802.15.4 standard is part of the IEEE family of standards for physical (PHY) and link layers for WPANs. The WPAN working group focuses on short-range wireless links instead of WLANs or wireless metropolitan area networks. The focus of the IEEE 802.15.4 standard is to enable low-data-rate WPANs, with low complexity and stringent power consumption requirements. Both star networks and mesh networks are allowed in the standard, with devices being characterized as either full-function devices or reduced-function devices.

IEEE 802.15.4 specifies the PHY and media access control (MAC) sublayers as shown in Fig. 1. The PHY layer specifies three different frequency bands in which devices can operate: the 868-MHz band (available in Europe), the 915-MHz band (available in the U.S.), and the 2400-MHz band (available worldwide). To allow the coexistence of several IEEE 802.15.4 networks in the same location, a Frequency Division Multiplexing (FDM) approach is adopted. This scheme divides each of the frequency bands into a total of 27 channels. The channels defined in the lower two bands are intended for very low bit rate operations, with the rates of 20 and 40 kb/s per channel for the 868- and 915-MHz bands, respectively. The 2.4-GHz ISM band, however, allows bit rates up to 250 kb/s per channel. Table I provides the channelization scheme. The

TABLE I
FREQUENCY ALLOCATIONS AND PHYSICAL LAYER IN IEEE 802.15.4 [9]

Frequency Band (MHz)		868 (868 – 868.6)	915 (902 – 928)	2450 (2400 – 2483.5)
Spreading Parameters	Chip rate (kchips/s)	300/400	600/1000/ 1600	2000
	Modulation	BPSK/ ASK/ O-QPSK	BPSK/ ASK/ O-QPSK	O-QPSK
Data Parameters	Bit rate (kb/s)	20/100/ 250	40/250	250
	Symbol rate (ksymbol/s)	20/12.5/ 62.5	40/50/62.5	62.5
	Symbols	Binary/ 20-bit DSSS /16-ary Orthogonal	Binary/ 5-bit DSSS /16-ary Orthogonal	16-ary Orthogonal

O-QPSK = Offset Quadrature Phase Shift Keying
BPSK = Binary Phase Shift Keying
DSSS = Direct Sequence Spread Spectrum

2400-MHz band attracts the most focus from the wireless industry because of its higher bandwidth and potential to produce globally accepted products.

Since the focus of this paper is on interference, it is worthwhile to discuss the mechanisms incorporated in the standard to minimize interference. IEEE 802.15.4 devices utilize a direct-sequence spread-spectrum (DSSS) transmission scheme. In DSSS, the signal is spread over a wider frequency band than that required by mapping the signal's bit pattern into a higher data rate sequence using a "chipping" code. Since the signal is spread over a larger bandwidth, narrow-band interferers block a smaller overall percentage of the signal, enhancing the probability that the receiver (Rx) will recover the signal. The data are modulated into a digital form using binary phase-shift keying for the 868- and 915-MHz bands, while offset quadrature phase-shift keying is used for the 2400-MHz band. The access method in IEEE 802.15.4-enabled networks is carrier sense multiple access with collision avoidance (CSMA–CA). The IEEE 802.15.4 PHY includes Rx energy detection that is intended for use by a network layer as a part of the channel selection algorithm, LQI that is a characterization of the strength and/or quality of a received packet, and clear channel assessment. Both contention-based and contention-free channel access methods are supported. The IEEE 802.15.4 standard employs 64-b IEEE and 16-b short addressesable to support 65 000 nodes per network.

Zigbee utilizes the 802.15.4 standard and specifies more aspects of the lower protocol layers to enhance the interoperability of low-data-rate radios intended for sensing applications. It specifies a CA algorithm similar to 802.11b; each device listens to the channel before transmitting in order 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 CA algorithms to minimize data loss caused by collisions. If ZigBee uses a channel that overlaps a heavily used Wi-Fi channel, field tests have shown that up to 20% of all ZigBee packets are retransmitted due to packet collisions [33].

TABLE II
IEEE 802.11 FREQUENCY [34]

Ch.	Lower Frequency (GHz)	Center frequency (GHz)	Upper frequency (GHz)
1	2.401	2.412	2.423
2	2.406	2.417	2.428
3	2.411	2.422	2.433
4	2.416	2.427	2.438
5	2.421	2.432	2.443
6	2.426	2.437	2.448
7	2.431	2.442	2.453
8	2.436	2.447	2.458
9	2.441	2.452	2.463
10	2.446	2.457	2.468
11	2.451	2.462	2.473

III. POTENTIAL ISs IN THE 2.4-GHz ISM BAND

Radios conforming to the IEEE 802.15.4 standard are quickly gaining popularity for sensing applications in the building community, but there are a number of devices that are attempting to utilize the 2.4-GHz ISM band. As part of this effort to develop test methods by which one can assess the effect of interference on the performance of wireless sensors, a number of ISs are selected for testing. In addition to communication schemes that utilize the 2.4-GHz band (IEEE 802.11 and Bluetooth), this paper also considers the effect of microwave ovens.

A. IEEE 802.11g

Wireless Ethernet has become ubiquitous in buildings, with the IEEE 802.11 standard and the accompanying Wi-Fi protocol being the leading methods by which users gain access to the Internet. In this paper, equipment conforming to the IEEE 802.11g standard is used. The 802.11g standard offers high bandwidth (54-Mb/s maximum throughput and 30 Mb/s in practice) on the 2.4-GHz frequency range. It is backward-compatible with the 802.11b standard.

The IEEE 802.11g standard specifies a total of 11 channels available in the 2.4-GHz band, as shown in Table II. Each channel, numbered 1–11, has a bandwidth of 22 MHz and a midfrequency separation of 5 MHz between channels. As a result of this specification, channels overlap as shown in Fig. 2, and it can be seen that a maximum of three nonoverlapping channels can be utilized at one time. Wi-Fi routers are often set to Channel 6 as the default, and the set of Channels 1, 6, and 11 is the most widely used.

The IEEE 802.11g standard defines the MAC sublayer and PHY layer for WLANs. The standard's network access method is based on the CSMA/CA protocol, which involves waiting until the network is free before transmitting data frames [13]. Once the connection is established, a station must be linked to an access point in order to transmit packets. The 802.11g standard allows for a maximum data transfer speed of 54 Mb/s with a range of approximately 33 m. While this range is less than that of 802.11b, which delivers a range of approximately 45 m, most networks are well within this limit. It is important to note that the range can vary depending on many factors, including the building environment and existing interference.

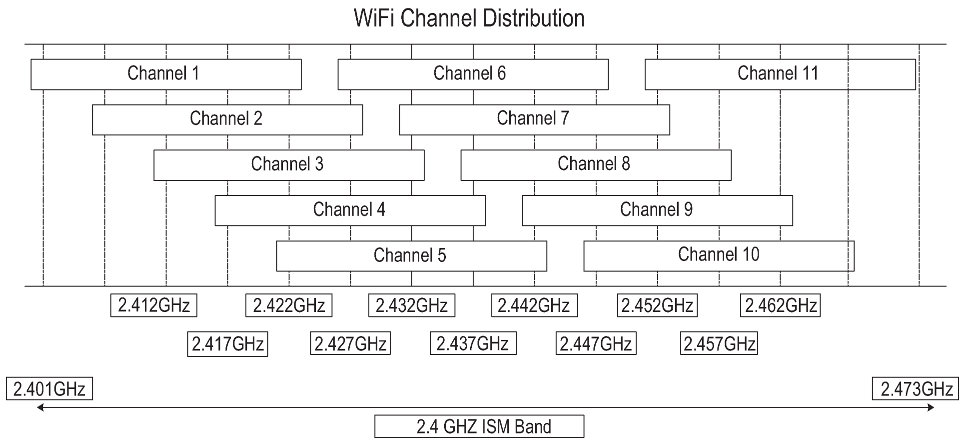

Fig. 2. IEEE 802.11 channel distribution.

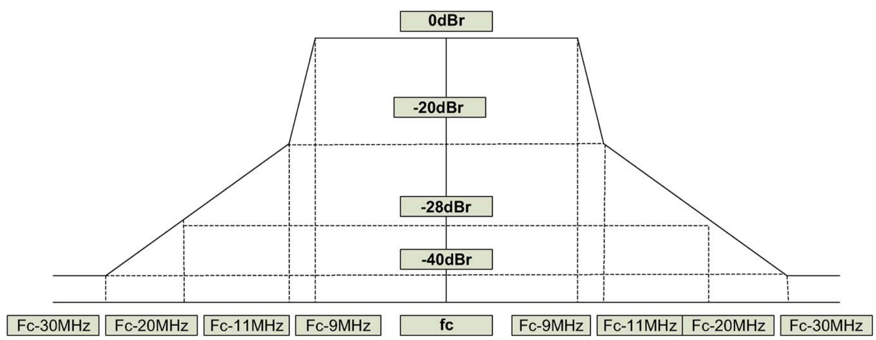

Fig. 3. IEEE 802.11g spectral mask.

The 802.11g standard achieves higher data rates by implementing an additional Orthogonal FDM transmission scheme. This approach leads to fundamentally different spectral masks as seen in Fig. 3. The IEEE 802.11 PHY layer also includes multirate support. If the current data rate cannot be sustained due to interference or low received signal strength, dynamic data rate switching is applied to choose a more appropriate data rate (and modulation technique) [35].

B. Bluetooth

Bluetooth technology is designed to replace proprietary cables that connect multiple devices by using one universal short-range radio link. A Bluetooth transceiver is a frequency-hopping spread-spectrum (FHSS) device that uses the unlicensed (worldwide) 2.4-GHz ISM frequency band. In most countries, there are 79 channels available. To minimize system degradation due to interference, the system employs a frequency-hopping scheme where it searches for the most appropriate frequency band to transmit. In addition, the Bluetooth transceiver employs a Gaussian-filtered binary frequency modulation, Gaussian frequency-shift keying, and a time-division-duplex scheme. To minimize cost and size, a single-chip solution or module is predominantly used. The nominal bandwidth for each channel is 1 MHz, and channel center frequencies are defined by the formula $f = 2402 + k\,(\mathrm{MHz}),\ k = 0{-}78$. Bluetooth has a nominal range of approximately 10 m, although ranges up to 100 m can be achieved with amplifiers. Because the transceiver has an extremely small footprint, it is easily embedded into physical devices, making it a truly ubiquitous radio link.

Bluetooth uses polling-based packet transmission. All communications between devices take place between a master and a slave, using time-division duplex, with no direct slave-to-slave communication. The master polls each active slave to determine if it has data to transmit. The slave may only transmit data when it has been polled. Also, it must send its data in the time slot immediately following the one in which it is polled. When connected to other Bluetooth devices, a Bluetooth device hops (changes frequencies) at the rate of 1600 times/s for typical use, with a residence time of 625 μs for every single time slot, representing the length of a single-slot packet. When in inquiry or page mode, it hops at 3200 hops/s with a residence time of 312.5 μs. The master transmits only in even-numbered time slots, while the slaves transmit only in odd-numbered time slots. In each time slot, a different frequency channel is used (a hop in the hopping sequence).

In the baseband layer, a packet consists of an access code, header, and payload. The access code contains the piconet address (to filter out messages from other piconets) and is usually 72 b in length. The header contains link control data, encoded with a forward error-correcting code (FEC) with a 1/3 rate for high reliability. Such code is a repetition code, and thus, every bit in the header is transmitted three times. The header is usually 18 b in length and includes the active member address for a currently active slave. The payload can contain from 0 to 745 b of data, and it may be protected by FEC. Overall, the transmission scheme used in Bluetooth is

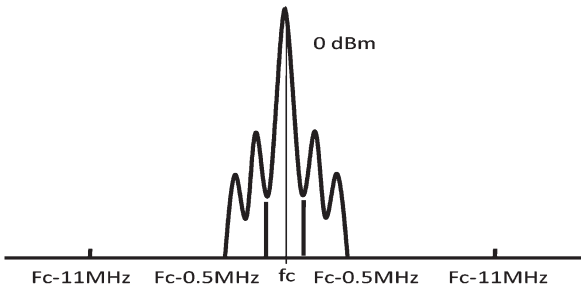

Fig. 4. Bluetooth spectral mask.

fundamentally different from that used in IEEE 802.11 systems. The 802.11 networks use DSSS to spread energy across a relatively wide signal bandwidth, while Bluetooth uses FHSS to transmit a narrow-band signal as shown in Fig. 4.

Interference from Bluetooth should be minimal due to the hopping nature of the Bluetooth transmission. If a Bluetooth device transmits on a frequency that overlaps a Wi-Fi channel while a Wi-Fi device is doing a "listen before transmit," it does a random backoff. During this time, the Bluetooth device hops to a nonoverlapping channel, thereby allowing the Wi-Fi device to begin its transmission.

C. Microwave Ovens

Microwave ovens pose a potential interference threat to IEEE 802.15.4 systems. Microwaves are a form of electromagnetic radiation with frequencies ranging from several hundred megahertz to several hundred gigahertz and wavelengths ranging from approximately 1 to 20 cm. The technology has been extensively used by the broadcast and cable television industries, as well as in other telecommunication applications, since the early 1950s. Because of their high frequencies, microwaves have the advantage of being able to carry more information than ordinary radio waves and are capable of being beamed directly from one point to another. In addition to their telecommunication applications (which include telephony and computer networking, as well as television), microwaves are used in cooking, police radar, and certain military applications.

Microwave ovens operate at approximately 2.45 GHz. Although they should be covered by a Faraday cage, it is still possible for some leakage to occur around the doors. This leakage is increased when mechanical abuse or simple "wear and tear" causes door seals to become less effective. For these reasons, microwave ovens are a potential source of interference for IEEE 802.15.4 communication.

IV. Experimental Platform and Methodologies

A series of experiments is carried out to develop potential approaches for implementing performance tests to assess the communication reliability of wireless sensors in the presence of ISs. The objective of the tests is to evaluate the impact of the ISs specifically on the communication between radios conforming to the IEEE 802.15.4 communication standard. As a first step, the three sources of interference previously discussed (Wi-Fi, Bluetooth, and microwave ovens) are used.

A. Experimental Setup

The experimental setup is designed for continuous monitoring of a wireless link between a Tx and Rx for a period of time while varying Tx–Rx distance, interferer–Rx distance, and channel setting. 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. The nodes are powered by two AA batteries and include microprocessors to convert analog sensor signals to their digital form and to convert data to a signal that can be transmitted over the airwaves. The test specimens consist of two different commercially available motes 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-B data payload is transmitted over the wireless link once every second. The key difference between the two models is their antenna. The first set of nodes has a one-inch 1/2 dipole antenna that is connected to the board, while the second set has an antenna that is integral to the circuit board. The maximum reported transmission range for the directional antennas tested is approximately 350 m. Tests showed no difference in performance between the two sets of nodes, so subsequent results do not differentiate the wireless radios used. The same hardware that is used to transmit data can also serve as an Rx of the data. The receiving nodes are attached to a board that is connected to a computer via a serial cable. A software program is written to receive the data transmitted over the cable and archive them in a text file for later analysis.

Wireless sensor hardware is programmed using the open-source TinyOS operating system. Since the focus of this paper is on the reliability of the wireless link in building applications, the sensors that can be attached to the nodes are not used. Instead, a short data message is created by the onboard microprocessor. A test is carried out for 30 s, and each test is carried out 20 times. This scenario results in a total of 600 data transmissions that are used to assess the reliability of the data transmissions through measures such as RSSI, LQIs, and PER. By carrying out each test 20 times, it is anticipated that random errors due to fluctuating environmental conditions and equipment factors are largely reduced. All the measurements use two networks: a primary network and a competing network. The former is always a Zigbee network using the motes indicated earlier. The second network is within the 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 and Rx node are situated according to different test requirements. The different ISs sit next to the Rx at different distances. The distance from the Tx to the Rx ($D_{\text{Tx-Rx}}$) is varied at the following levels: 1, 2, 4, 6, and 10 m. At each distance, a set of different interferer–Rx distances ($D_{\text{IS-Rx}}$) is chosen for each selected channel (ZigBee Channels 11, 15, 19, 23, and 26). In each experiment, the Tx sends 600 data packets in total at a rate of 1 pkt/s.

The Wi-Fi source that is used consists of a laptop computer connected to a wireless 802.11g router by an Ethernet cable.

This computer serves as a client to a desktop server that delivers data through its wireless access port. The client requests data continuously at a rate of 54 Mb/s on Wi-Fi Channel 6. The Bluetooth source is a wireless headset that communicates with a laptop computer having built-in Bluetooth transmission capabilities. The output power of the Bluetooth headset is less than 4 dBm. The headset is maintained at a distance of 1 m from the laptop, and a stream of music is sent to it at a rate of 1 Mb/s. The microwave oven is a commercial household version with a maximum rated power of 1100 W. During the tests of interference, the microwave is operated at a maximum power for the duration of the 30-s test.

B. Reliability Metrics

The key issue that is investigated is the reliability of the 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 PER value, which can be calculated as the ratio of the number of packets unsuccessfully received to the total number of packets transmitted over a certain period of time. This reliability metric cannot be determined in most situations, however, because the Rx or Tx does not necessarily know whether each data transmission is successfully received. To estimate reliability, other metrics have become popular. In particular, RSSI and LQI are computed on board to estimate the quality of the connection between Tx and Rx. RSSI provides a measure of the strength of the received signal in mW or dB. RSSI is calculated at the radio chip on the Rx and provides a useful surrogate for network link quality. LQI is a metric on a scale from approximately 0 to 108 that provides an estimate of the signal strength in the light of interference and multipath errors. As mentioned previously, most wireless sensor hardware has the capability to measure these values for each transmitted message received. CC2420, the radio chip used in these tests, provides RSSI and LQI values, and those values are collected in a spreadsheet to facilitate further analysis. Thus, they can potentially be useful to determine the reliability of a link. These three metrics have been considered in this paper, 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 be used to estimate the reliability.

V. Experimental Observations and Prediction

A. Preliminary Tests: RSSI, LQI, and PER as Functions of Distance

To better understand the performance of the hardware that is used, it is valuable to first examine the metrics of interest in an environment in which no interference is expected [36]. Fig. 5 shows the plots of each metric as a function of distance in an outdoor situation on grass. In these tests, Tx is set with an output power level of 1 mW (0 dBm), and the messages of length 25 B are sent at a rate of 10 Hz. Rx is moved away from Tx in 1-m increments until the signal is no longer received. These results show RSSI dropping off progressively with distance, while PER remains rather low until reaching a distance at which most packets are dropped in error. The estimated uncertainty in RSSI is 1 dBm based on the standard deviations of multiple tests, while the uncertainty of LQI is approximately 1 unit. PER uncertainties are under 1% up until the signal starts being dropped; uncertainties are very high after this point, approaching a level of 50%. At these distances, however, the key conclusion is that the signal is not reliable.

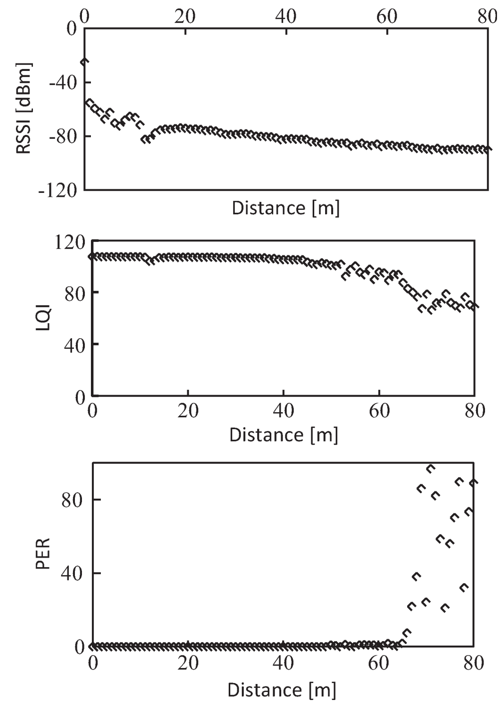

Fig. 5. Wireless signal metrics as functions of distance for Tx–Rx pair on grass.

B. Parametric Tests

To initially assess the important parameters that should be considered in setting up a test method for wireless sensor transmissions, a test plan is developed to assess the effect of various parameters on PER, RSSI, and LQI. The issues that are investigated in this paper include the following:

1) IS;
2) distance between a Tx and Rx ($D_{\text{Tx-Rx}}$);
3) distance between an IS and Rx ($D_{\text{IS-Rx}}$);
4) position of an IS in relation to the line of sight between Tx and Rx as represented by the angle between Rx and IS (θ); and
5) transmitting channels.

Fig. 6 shows a schematic of the test that displays the factors of interest. The purpose of these tests is to investigate which factor has the most effect on the reliability. The IS has four levels for the test, while the other factors are limited to two factors as shown in Table III. The high and low levels for each distance are selected to accommodate testing in a typical laboratory. While sensors may be designed to be placed up to 20 m away, the maximum distance between Tx and Rx for a potential test

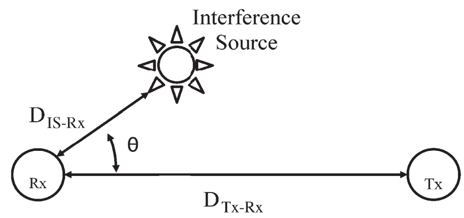

Fig. 6. Schematic of test setup.

TABLE III
FACTORS AND THEIR LEVELS INVESTIGATED IN INITIAL SCOPING EXPERIMENTS

Factor	Values
Interference Source (IS)	None, WiFi, Bluetooth, Microwave
Transmitter to Receiver Distance (D_{Tx-Rx})	1 m, 6 m
Interference Source to Receiver Distance (D_{IS-Rx})	0.5 m, 4 m
Position of IS in relation to Tx-Rx line-of-sight (θ)	0°, 180°
Channel	15, 26

method is limited by a typical space available in a laboratory. A full factorial test plan is carried out, with every potential combination of factors being tested for a total of 64 tests.

The analysis of the variance of results from the tests carried out at differing levels of each factor helps to identify the key factors affecting the reliability of the data transmission. Fig. 7 shows PERs for all tests by a factor along with the average for each level of the factor. The lines connecting the averages give a quick visual indication of the magnitude of the change in PER when the factors are changed. For example, Fig. 7(a) shows PER determined for each test by the IS used. Note that the points involve different sets of the other factors as specified in the full factorial design. These figures show which factors have the greatest effect on PER.

Fig. 7 shows that the type of IS has the most significant impact on the results, while the Bluetooth device has negligible impact compared with the situation where no IS is present. These results comply with the conclusion presented in [35]. Wi-Fi and the microwave oven increase the average PER from 2.0% to 3.0% and 4.5%, respectively. Other factors have less effect. Additionally, the combinations of factors are also considered, but no particular combinations appear to have an inordinate effect compared to the primary effects of each factor. Fig. 8 shows the difference between the high average value and the low average value for each factor. It can be seen that the IS can have a marked effect on PER. The channel is the only other factor that provides a difference greater than 0.5%. All other factors do not appear to have a significant effect on PER in these tests.

As noted previously, it is also valuable to examine those quantities that can be measured in real time (i.e., RSSI and LQI) to determine how they can be used to assess reliability when ISs are present. Fig. 8(a) shows the maximum differences in average RSSI for the different levels, while Fig. 8(b) shows the maximum differences in average LQI for the different levels of each parameter. The change in RSSI for the IS is the greatest, a finding consistent with the large differences in PER with IS. It should be noted, however, that the factor with the second greatest impact on PER, namely, channel, has the smallest effect on RSSI. The results that show the changes in LQI show little correlation to the results of PER. In fact, the differences in the LQI values are miniscule for all factors considering that the LQI scale is composed of integers ranging from 0 to 108. Even the greatest effect shows only a difference in results between the two levels of each factor of less than 0.5. The interesting finding is that the LQI changes little even though the PERs are significantly different. These results lead one to question the appropriateness of the LQI metric in predicting the reliability of packet transfer.

C. *Effect of Tx-to-Rx Distance*

The results discussed in the previous section motivate the further study of several parameters. Studies are carried out at more discrete levels of the channel, Tx-to-Rx distance, and the IS-to-Rx distance. First, the distance between Tx and Rx is varied from 1 to 10 m with the ISs fixed at either 0.5 or 4 m from Rx. These tests are carried out with the ZigBee channel set to either Channel 15 or 26. Control tests are carried out with no IS to assist in isolating the effect of the IS. Fig. 9 shows the PERs as a function of Tx–Rx distance with communications occurring on Channel 15. Fig. 9(a) shows the data when the IS is located 0.5 m from Rx, while Fig. 9(b) shows the data with the IS located 4 m from Rx. These data show some interesting trends. First, as is seen previously, a Bluetooth device has a little effect on the results compared with the control case. At both distances between the IS and Rx, Wi-Fi has a negligible effect until Tx is positioned at a distance of 10 m from Rx. As the distance between ZigBee and Bluetooth increases, the PER of ZigBee decreases as expected. This result is in line with the theoretical research results presented in [32]. However, the OPNET simulation results of PER based on [32] cannot match our experimental results. The simulation results show that the PER of ZigBee under Bluetooth interference with the ZigBee sender–Rx distance of 1 m changes from 10^{-1} to approximately 10^{-7} if the Bluetooth interferer is placed from 1 to 4 m away from the ZigBee Rx. In our experiments, when Bluetooth is 1 m away from the ZigBee Rx, PER for ZigBee is 2.3%, while it changes to 2.1% when the Bluetooth interferer is located 4 m away from the ZigBee Rx. Therefore, the change is still significant compared to the simulation results. The microwave oven increases the PER at all distances, with a steady rise in PER being observed as the distance between Tx and Rx is increased.

These plots, however, only tell a part of the story. There is also a dependence upon the channel used by the wireless nodes for transmission of the data. Fig. 10(a) shows PER as a function of Tx-to-Rx distance with the Wi-Fi source located 0.5 m from Rx for five different channels, and Fig. 10(b) shows PER with the microwave located 0.5 m from Rx for the same five channels. In the case of the Wi-Fi IS, all channels are relatively immune to interference except at a Tx–Rx distance

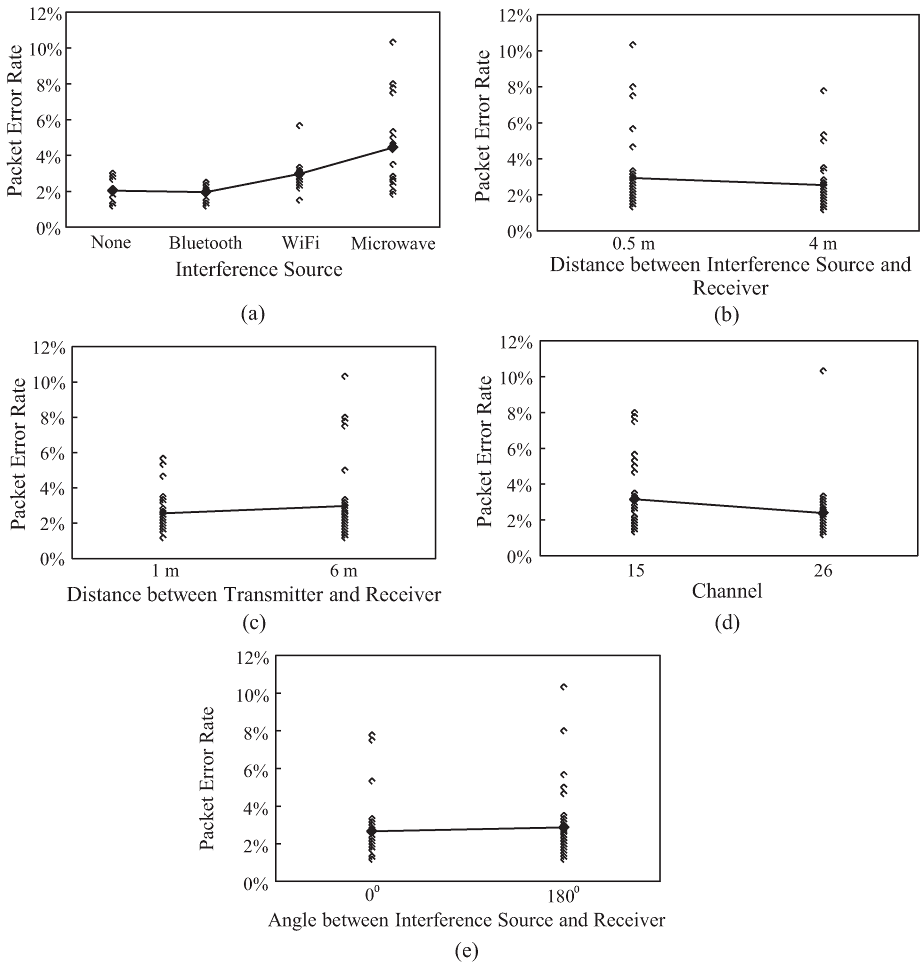

Fig. 7. PER results for experiments. (a) PER versus different ISs. (b) PER versus distances between IS and Rx. (c) PER versus distances between Tx and Rx. (d) PER versus IEEE 802.15.4 channels. (e) PER versus θ.

of 10 m. At this distance, it can be seen that there are some channel effects. Channel 15 shows the greatest increase in PER, while Channel 26 shows the least. Channel 26 lies outside the communication spectrum for Wi-Fi, and thus this finding is expected. Channel 15 supposedly lies between two adjacent Wi-Fi bands, but Wi-Fi still has some effects on the transmission on this channel. For the case when the microwave oven serves as the IS, a channel dependence can also be seen. Once again, Channel 26 suffers from the least amount of interference, while other channels see PERs above 10% when the Tx–Rx distance is 10 m.

The final tests are carried out to determine the effect of the distance between the IS and Rx on PER. The proposed experiment methods extend the one in [31] by choosing different interferer-to-ZigBee-Rx distances. Fig. 11 shows PER data when Tx is maintained at a distance of 2 m from Rx and the IS is moved from 0.5 to 10 m away from Rx. Fig. 11(a) shows that within this range, the distance between the Wi-Fi source and Rx does not have a significant effect on PER. The examination of the previous plots of Tx–Rx distance confirms this finding. Fig. 11(b) shows that the microwave oven has a significant effect when it is brought within 2 m of Rx. Beyond that distance with the Tx–Rx distance maintained at 2 m, it can be seen that the microwave has less effect.

VI. Discussion and the Coexistence Model of ZigBee and Wi-Fi/Microwave Oven

The data presented here show the care that must be taken when placing wireless sensors in buildings to avoid adverse effects from ISs. The key parameters that must be considered are the ISs that are present in the space and the distance from each of those sources to Rx of the sensor signals. In the tests carried out here, Wi-Fi emitters and microwave ovens show significant effect on the reliability of the wireless links as demonstrated by the increase in PER. It is interesting to note, however, that RSSI and LQI, which are metrics that are commonly used to predict reliability, do not always coincide with the rate of missing data packets. For these reasons, it is suggested that alternative metrics should be developed to better indicate the reliability of wireless links in the presence of ISs.

For the tests carried out here, it appears that the use of Channel 26 in the IEEE 802.15.4 spectrum mitigates interference problems because it does not overlap with transmission bands for IEEE 802.11. As expected, the closer the sensor nodes are placed to each other, the less effect that ISs will have on their reliability. It is not always feasible, however, to shorten the distance between wireless nodes in buildings, and it is believed that a typical distance between the nodes of 10 m is a realistic target to which systems should be designed.

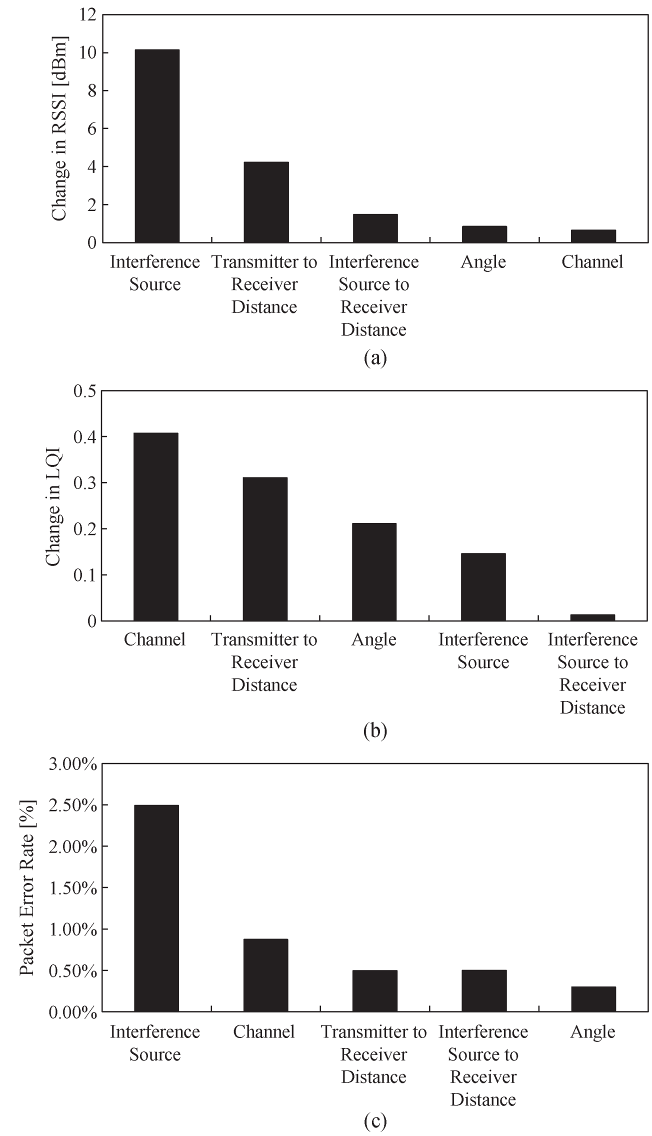

Fig. 8. Difference in RSSI, LQI, and PER between the highest and lowest levels for each factor. (a) Difference in average RSSI between the highest and lowest levels for each factor. (b) Difference in average LQI between the highest and lowest levels for each factor. (c) Difference in average PER between the highest and lowest levels for each factor.

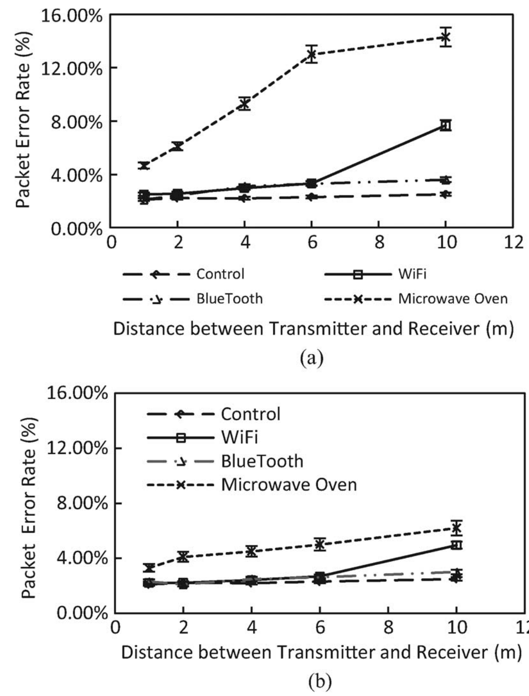

Fig. 9. PER as a function of distance between Tx and Rx. (a) $D_{\text{IS-Rx}} = 0.5$ m. (b) $D_{\text{IS-Rx}} = 4$ m.

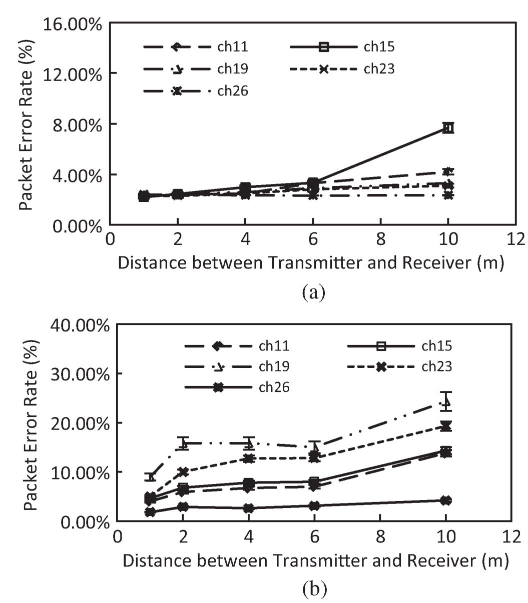

Fig. 10. PER as a function of distance between Tx and Rx and IEEE 802.15.4 channel. (a) PER distribution under Wi-Fi interference impact with $D_{\text{IS-Rx}} = 0.5$ m. (b) PER distribution under microwave oven interference with $D_{\text{IS-Rx}} = 0.5$ m.

Microwaves affect the reliability even when Txs and Rxs are placed much closer together. It should simply be recommended that the position of receiving nodes in reference to microwaves should be considered, preferably increasing the spacing beyond 2 m. Considering the popularity of mesh networks in which all nodes serve as Rxs of data as well as Txs, this consideration is critical in positioning sensor nodes to avoid sporadic outages.

As mentioned earlier, one of the goals of this paper is to develop systematic test methods for assessing the reliability of sensor nodes in the presence of interference. From the data, the following suggestions are made for the development of test methods.

1) The key parameters to note are the expected ISs (IEEE 802.11 radiators and microwave ovens) and the distance between the IS and Rx.
2) An appropriate test may examine an Rx-to-Tx distance of 10 m, as this value would be a typical value for spacing in a building application, and data suggest that this point is one where ISs start to play a more significant role.
3) A method should be developed to merge data from experiments on Tx-to-Rx distance, IS, channel, and IS-to-Rx distance to a simple metric for the determination of the resistance of wireless nodes to ISs.

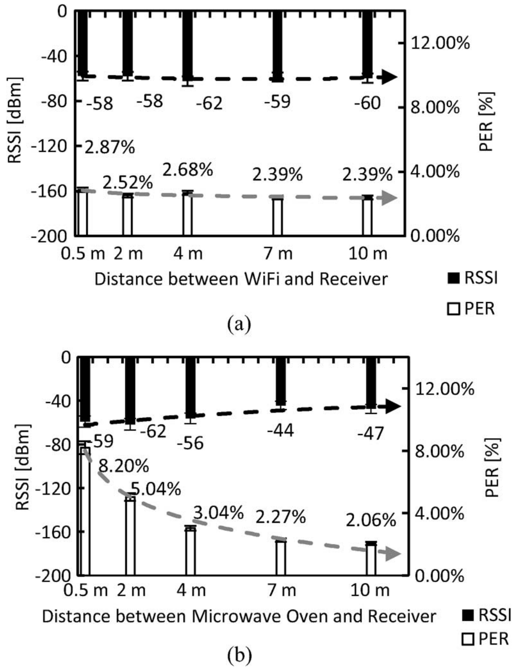

Fig. 11. PER as a function of distance between IS and Rx and IEEE 802.15.4 channel. (a) Wi-Fi as IS. (b) Microwave as IS.

A. Coexistence Model

From these experiments, a significant amount of data is collected that can form the basis of a model of interference effects. A curve-fitting technique is chosen for this modeling. The models to which data are fitted depend on adjustable parameters $D_{\text{Tx-Rx}}$ and $D_{\text{Is-Rx}}$. Through this model, the predictions of reliability can be generated to minimize the effects of interference.

To perform fitting, we define a function that measures the closeness between the data and the model. This function is then minimized to the smallest possible value with respect to the parameters. The parameter values that minimize the function are the best fitting parameters. Based on a signal attenuation model, a new coexistence model is developed and presented in this section.

To better understand the implication of the measurements, the ZigBee and Wi-Fi/Microwave Oven coexistence model for ZigBee communication Channels 11–24 uses a combination of analytical and empirical methods. Signal attenuation is an important parameter in telecommunication applications because of its importance in determining signal strength as a function of distance. The PER prediction model follows this rule. In this paper, the PER results for ZigBee communication vary with distance between Tx–Rx, distance between interferer–Rx, and IS. PER, in the presence of a Wi-Fi router, can be expressed as

$$\text{PER}(x,y) = \begin{cases} \left|\ln\left(\frac{y}{2}\right)\cdot 10^{-2}\right| + D_N, & y = x \\ \left|x\cdot\ln\left(\frac{x}{y}\right)\cdot 10^{-2}\right| + D_N, & \text{Others} \end{cases} \tag{1}$$

where $x = D_{\text{Tx-Rx}}$ (Tx–Rx distance) and $y = D_{\text{IS-Rx}}$ (interferer–Rx distance) for mathematical conciseness. D_N is an added quantity that can be obtained by evaluating an integral given later and is a function of x. The PER prediction model for Wi-Fi interference is calculated in (1). When the IS changes to microwave oven, the PER can be estimated through

TABLE IV
COMPARISON EXPERIMENT TABLE

$D_{\text{Tx-Rx}}$ (m)	1m/10m
Channel	11/15/23
$D_{\text{IS-Rx}}$ (m)	2m/10m

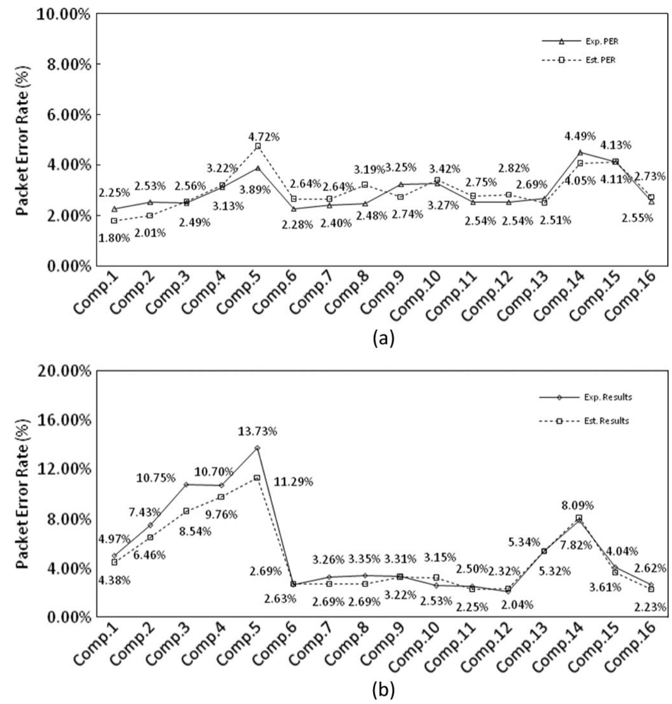

Fig. 12. Comparison results of experimental results and estimated results under Wi-Fi interference. (a) PER comparison result under Wi-Fi Interference. (b) PER comparison result under microwave oven interference.

$$\text{PER}(x,y) = \begin{cases} \left|\alpha\cdot\ln\left(\frac{x}{2}\right)\right| + \beta\cdot D_N, & x = y \\ \left|\gamma\cdot\ln\left(\frac{x}{y}\right)\right| + \gamma\cdot D_N, & y \le 2m \\ \left|\varepsilon\cdot\ln\left(\frac{x}{y}\right)\right| + \beta\cdot D_N, & \text{Others} \end{cases} \tag{2}$$

where $D_N = 1/\sqrt{2\pi}\int_{-\infty}^{x}\exp(-(x^2/2))dx$, $\alpha = 0.01$, $\beta = 0.02$, $\gamma = 0.03$, and $\varepsilon = 0.05$.

B. Performance Evaluation

The model is evaluated by comparing PER from a new group of experiments with calculated results. The experiments follow a similar setup and methodology as previously reported. Two different ISs, Wi-Fi and microwave oven, are applied in the tests. For each interferer, a test plan is deployed as shown in Table IV. For both interferers, various $D_{\text{Tx-Rx}}$ (from 1 to 10 m) with corresponding $D_{\text{IS-Rx}}$ (from 2 to 10 m) are tested for Channels 11, 15, 19, 23, and 26.

Fig. 12 shows PER comparison results for Wi-Fi and microwave oven interference. The figures show that the coexistence models for Wi-Fi and microwave oven give a similar PER value compared to the data from real experiments. Subject to

Wi-Fi interference, the PERs are predicted within a 0.8% error, while the PERs are predicted within a 2.5% error subject to interference from microwave ovens.

Compared to the aforementioned related work, the experimental work presented here is straightforward. These results can serve as a good reference in designing a practical sensor network. Compared to the work mentioned in [16] and [17], the current work involves a full factorial experiment to evaluate different scenarios that may occur in real building applications. The focus has not been purely on the higher level protocols, but rather, the fundamental behavior of wireless links under interference is explored. Based on this, a mathematical model has been derived in this paper that can be used to predict the interference impacts on the ZigBee communication and to identify the bottleneck in terms of distance, IS, and communication channels. Once these bottlenecks are identified, either additional nodes can be used or best sensor locations can be figured out to obtain better network connectivity. In more general applications, network delay is also an important parameter [37], but it has not been a focus of this paper as most applications in buildings have large time constants that make slight latency inconsequential. The experimental validation of interference models for ZigBee communication is a very important topic. To our knowledge, no models have been generated to predict the interference impacts on ZigBee communication prior to this paper, yet it is acknowledged that further improvements to such models are needed.

VII. Conclusion

Tests have been carried out to assess the effects of interference from IEEE 802.11 Txs, Bluetooth Txs, and microwave ovens on the reliability of wireless sensor links conforming to the IEEE 802.15.4 standard. Results show that IEEE 802.11 and microwave ovens cause significant increases in the PERs, raising those error rates from a typical value of approximately 2% with no ISs present to an upward of 25% depending upon the distances among Rx, Tx, and IS. The channel on which the sensor signals are transmitted also has an effect on the PER, particularly when considering 802.11 as the IS. In these tests, RSSI and LQI values that are computed at Rx do not always correlate with the PERs, suggesting that alternative means should be pursued to gauge the reliability of wireless nodes in the presence of interference. It is anticipated that the results of this paper can lead to improved test methods to predict the communication reliability of wireless sensor nodes that will be used in building applications. Another area is related to data security [38]–[42].

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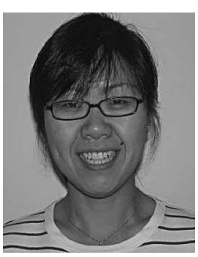

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