Experimental Assessment of Wireless Coexistence for 802.15.4 in the Presence of 802.11g/n

Nickolas J. LaSorte, Samer A. Rajab, Hazem H. Refai

Electrical and Computer Engineering, University of Oklahoma
Tulsa, OK, USA
`nicklasorte@ou.edu`
`samer.rajab@ou.edu`
`hazem@ou.edu`

***Abstract*— Wireless coexistence is a growing concern, given the ubiquity of wireless technology. Although IEEE Standards have started to address this problem in an analytical framework, a standard experimental setup and process to evaluate wireless coexistence is lacking. Literature that reports experimental assessment of wireless coexistence places little emphasis on separation distance of wireless nodes under test or the spectrum occupancy of the interfering network, making comparisons difficult. This paper provides an extensive literature survey of 802.15.4 and 802.11 b/g/n wireless coexistence and demonstrates that in a higher wireless channel occupancy environment, ZigBee to coexist with 802.11n better than 802.11g. A reproducible, versatile, and practical test setup is presented to serve as a starting point toward establishing standard practice for wireless coexistence testing of wireless systems in general and wireless medical devices in particular. Experimental evaluations demonstrated consistency with results reported in the literature.**

I. INTRODUCTION

Wireless coexistence of communication services is a growing concern. The early 802.16.2-2001 standard [1] specified guidelines and deployment practices for minimizing interference among fixed broadband wireless access systems and covered frequencies from 10-66 GHz. The standard was later superseded by IEEE 802.16.2-2004 [2] and then IEEE 802.15.2-2003 [3], which recommended coexistence practices among personal area networks and other selected wireless devices operating in unlicensed frequency bands. IEEE 802.15.4-2003[4] followed and listed suggested factors for ZigBee coexistence that can be found in Annex E. IEEE 1900.2-2008 [5] recommended interference analysis and measurement methods for wireless systems and offered an exhaustive list of coexistence factors in both the physical and medium access control layers. The standard also suggested a structure for a coexistence report.

The IEEE 802.19 Wireless Coexistence Working Group [6] is a technical advisory group created in the wake of 802.15.2 success. Members act as a coexistence advisory committee for all IEEE 802 standards. The primary focus, however, is on IEEE 802 standards operating in unlicensed bands. The group is currently concentrating on practice methods to assess wireless network coexistence. Although each standard [1-6] adequately outlines analytical guidelines for determining coexistence, there is no widely used experimental protocol for evaluating interference among wireless services.

In the literature, a notable problem exists: wireless networks are purported to emulate real-world environments; however, no specific methodology is recognized [24, 30, 32, 33, 34, 45, 46]. Line-of-sight (LOS) is most often used, and wireless transmission characteristics and separation distances among wireless nodes are dissimilar. For these reasons, it is difficult to compare results.

A. *Contribution*

Coexistence among wireless devices is dependent on three main factors: 1) frequency, 2) space, and 3) time. The key to achieving coexistence lies in the ability to control at least one of the three aforementioned factors. Coexistence is possible given one of the three following conditions: 1) Adequate frequency separation between wireless networks; 2) Sufficient distance between wireless networks, effectively decreasing the signal-to-interference ratio (SIR) in each; and/or 3) Relatively low overall occupancy of the wireless channel. Taking these three factors into consideration, we have developed an experimental coexistence test protocol that is practical, versatile, and reproducible.

The main contribution of this paper is the validation of a reproducible non-light-of-sight (NLOS) setup to test coexistence of 802.15.4 alongside 802.11g and 802.11n. We demonstrate that in a higher wireless channel occupancy environment, ZigBee coexistence with 802.11n is superior to 802.11g. A discussion of coexistence factors will be illustrated utilizing IEEE 802.15.4 (ZigBee) and 802.11b/g/n. Relevant literature discussed in this paper is limited to these standards. Experimental results in the NLOS test setup are shown consistent with trends found in the literature. The NLOS test setup provides a practical, versatile, and reproducible test method as a starting point toward determining a coexistence standard.

B. *Literature Review*

Early efforts to study wireless interference in the 2.4 GHz band commenced in the latter part of the 1990s. In 1997 Kamerman and Erkocevic [7] investigated interference caused by microwave ovens operating in the vicinity of a WLAN network and then presented requirements on the single-to-noise ratio (SNR). In the following two-year period, a handful of papers addressed possible interference between 802.11 and Bluetooth operating in the 2.4 GHz ISM band [8-16]. SIR threshold of an 802.11b receiver decoding a signal was found empirically [11, 13] and this provided a defined interference factor.

In 2001, several papers reported analytical and experimental evaluation of the interference between 802.11 and Bluetooth. Soltanian et al. [17] and Howitt et al. [18] were the first among them to mention that the effect of adjacent channel interference on bit-error rate strongly depends on the frequency offset between useful and interfering carriers. Howitt [19] studied Bluetooth network performance in the presence of an interfering 802.11b network in 2002. His methodology consisted of a three-step process: 1) Characterize 802.11b interference under static condition; 2) Characterize Bluetooth network performance when collocated with a single 802.11b source; and 3) Characterize Bluetooth network performance when operating in an arbitrary 802.11b environment. In 2003, IEEE published a recommended practice [3] reporting the development of simulation and analytical models addressing coexistence problems between 802.15.4 and 802.11b wireless networks. Later that year, Howitt el al. [20] was one of the first papers to report the impact of an 802.15.4 network on an 802.11b network.

In the years that followed, wireless coexistence literature focusing on 802.15.4 can be categorized into two types—those looking at the physical layer and those looking at the medium access control (MAC) layer. Literature pertaining to the physical layer can be further broken down into three sections: frequency [21-31], distance [24-43], and time [21, 22, 32-38, 44-46]. Literature regarding the MAC layer is primarily concerned with the clear channel assessment threshold (CCA) [21, 27, 40, 47, 48] and the size of 802.15.4 packets [33-36].

The remainder of this paper is organized as follows. Section II presents an NLOS test protocol and then describes the equipment used during testing. Section III presents the experimental results.

II. EXPERIMENTAL SETUP

A. Non-Line-of-Sight Test Setup

NLOS testing was performed without an anechoic chamber and could, therefore, be considered real world. During the compliance testing phase for medical devices, it is possible that the transmit power of the wireless medical device might not be adjustable. To simulate changes in transmit power, adjustment should be made to the path loss of the wireless signal. The test setup illustrated in Figure 1 incorporates SIR and was utilized to control the received signal strength (RSS) for a medical device under test.

An ambient scan was first conducted at each point where a wireless medical device under test was placed to identify background noise in the 2.4 GHz ISM band. Previous testing showed that RSS is a poor indicator of link quality in noisy environments, as the receiver cannot distinguish between signal and interference power [49]. Instead, SIR perceived by the receiver is a more robust metric for determining packet decoding success rate.

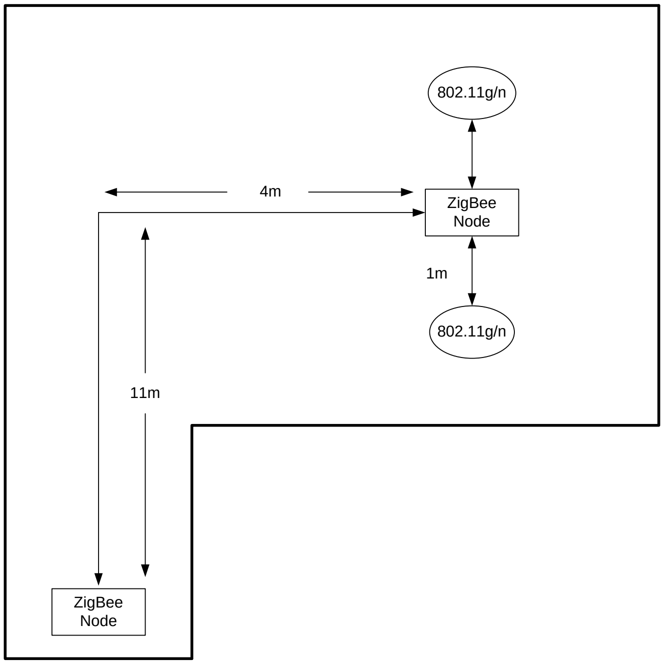

Fig. 1. NLOS Test Setup

TABLE I
INITIAL AND MINIMUM DISTANCES REQUIRED BY ANSI C63-18

Transmit Power	INITIAL DISTANCE	Minimum Distance
<600 mW	1 m	0.25 m
600 mW – 2 W	2 m	0.5 m
2 W – 8 W	3 m	1 m

IEEE 802.15.4 [50] specifies that a compliant device shall be capable of achieving a sensitivity of -85 dBm or better. For the test reported in this paper, wireless medical devices were separated so that RSS at the receiver was at a minimum and packet error rate (PER) was maintained at 0%. The receiver was placed on the outer edge of the transmitter's cell area, creating a worst-case scenario. To achieve a symbol error rate of $10e^{-5}$ for quadrature phase shift keying (QPSK) modulation, a 13.5 dB SNR must be maintained [51]. Taking these requirements into account and compensating for the transmitter's power amplifier variation, the RSS measured at the medical device receiver is suggested to be -70 dBm. Coding gains are ignored for the ZigBee wireless devices in the development boards that were used (see Section IIB). However, it should be noted that different coding gains in wireless transceivers will alter PER. RSS standard deviation was 0.4493, and median absolute deviation was 0.2640. Toscano [49] showed that RSS for IEEE 802.15.4 is directly related to distance and is also stable, e.g., variation coefficient was below 2% for nearly all measurements. ZigBee wireless network performance was tested to validate 0% PER.

Once parameters were established, ZigBee nodes were subjected to an interfering network (802.11g). Although the interfering network was limited to only two terminals, the configuration is considered general. Because the 802.11g network utilizes a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, only one wireless node can transmit at any given time for a given channel. The (Zigbee) wireless medical device receiver and transmitter were evaluated separately—each exposed to one or multiple interfering wireless networks. Various interference phenomena occurred, depending on whether or not the interfering wireless network was in proximity to the transmitter or the receiver of the wireless network under test. A receiver surrounded by one or more interfering networks experienced increased packet collision at the receiver, i.e., the hidden terminal effect. In contrast, when a transmitter was surrounded by one or more interfering networks, channel utilization decreased, i.e., the exposed terminal effect.

All wireless nodes were positioned on wooden tables at a height of 1m from the ground. The separation distance between the interfering wireless network and the wireless medical device under test was also 1m—a distance suggested by ANSI C63-18 [52]. Initial and minimum distances, shown in Table 1, are based on the transmitting power of the interfering wireless network. The measured power was -60 dBm of the interfering network (802.11g) at the point of the wireless medical device under test. It should be noted that the initial distance between the wireless medical device under test and the interfering network remained at 1m; experiments testing different separation distances were not conducted. Power-auto-leveling algorithms were disabled in all wireless networks during testing, and the interfering wireless networks were set to their maximum transmission powers, creating a worst-case scenario.

Testing NLOS configurations outside an anechoic chamber raises the possibility of collateral phenomena, including reflections from nearby structures that cause multipath. To account for this, multiple test arrangements of the transmitter and receiver terminals can be considered. It is suggested that the wireless device under test be placed in the middle of the room to allow for extra separation distance between the device and the interfering network.

For wireless communication in a multipath environment, excessive time delay spread is known to cause bit error as inter-symbol interference. Because a considerable time delay spread cannot be neglected, transmitted signals will suffer from frequency selective fading. Inter-symbol interference is, therefore, the dominant factor causing irreducible bit error rate [53]. However, if the transmitter symbol rate is lower than the coherent bandwidth, the adverse effect of channel time delay spread on the received signal can be neglected. In this case, multipath propagation causes only transmitted signal fading, and Gaussian noise becomes the dominant factor causing bit error [54]. Literature has been published to quantitatively determine the ratio at which time delay spread can be neglected [53-55].

For ZigBee transmissions, the wireless network is capable of working in a reverberation chamber and is only seriously limited for a value of Q-factor above 5000—a figure greater than one typically found outside a reverberation chamber [57]. ZigBee PER is below 1% with a Q factor of 1000. Johnson et al. [58] measured Q in harsh military-related environments and found no Q factor greater than 1000. Theoretically, a 1000 Q-factor should not be present in any practical environment wherein a wireless medical device operates. Thus, in the NLOS ZigBee network test setup the delay spread of the ZigBee wireless network will not cause inter-symbol interference and can be neglected as a contributor to bit error. To increase reproducibility, wireless channel delay spread can be measured with a vector network analyzer at each lab performing wireless coexistence testing. Future work aims at normalizing test results between different test setup configurations.

Dimensions of the test setup are arbitrary. Emphasis is placed on the average RSS at the wireless medical device under test and also on isolating the effects of the interfering wireless network on the transmitter and receiver. To do this, LOS between the interfering wireless network and the wireless medical device under test is required. NLOS is required between wireless medical devices, as well as between the interfering wireless network and the wireless medical device furthest away.

B. Wireless Network Equipment

1) 802.15.4 Wireless Network

Wireless medical devices were simulated using 802.15.4 (ZigBee) development test boards (CC2530) manufactured by Texas Instruments. To generate ZigBee packets, TI SmartRF Studio 7 for ZigBee development boards were used. ZigBee wireless devices were set to channel 22 (2.460 GHz) for all tests, and clear channel assessment (CCA) threshold was set to a maximum of -77 dBm. The literature shows that as the CCA threshold increases, PER decreases [21, 27, 40, 47, 48]. Packet size was set to the development board minimum—a 15-byte length. The literature notes that as the packet size of the wireless network under test decreases, the probability of interference also decreases [33-36]. ZigBee transmission parameters were set to create the best-case scenario and avoid interference exaggeration caused between 802.15.4 and 802.11g. The 802.15.4 channels and center frequencies are listed in Tables II.

2) 802.11g/n Wireless Network

An interfering network was implemented using 802.11g network developmental boards from ADI Pronghorn Metro SBC and 802.11g cards from Ubiquiti SR2. The 802.11n cards were Ubiquiti SR71. The spectrum profiles of the 802.11g and 802.11n transmitters operating on channel 11 are shown in Figures 2 and 3. Wireless nodes were fully programmable in transmission power, radio channel, and modulation, among other factors. Nodes were also able to execute programming scripts, allowing complete control of the testing procedure. In addition to transmitter/receiver pairs, traffic probes, and spectrum analyzers, packet sniffers were used to monitor wireless communication. Power-auto-leveling algorithms were disabled in the wireless nodes, and the maximum transmission power was set to produce a worst-case scenario.

Iperf software was used to generate traffic on the 802.11g wireless network and to test the network data rate. Iperf ensures that a constant data stream is broadcast over the wireless network. Given a server on one node and clients on either one or multiple nodes, Iperf configuration allows users to exchange various traffic rates between terminals in a single network. The software supports both transmission control protocol (TCP) and user datagram protocol (UDP) traffic exchange and gives periodic reports relative to bandwidth and data sent/received on both server and client. A number of connection options can be set on the server/client, including buffer length, window and segment size for TCP, and buffer and packet sizes for UDP. The 802.11g network utilized all 11 channels during testing, as shown in Table III. During coexistence testing, a National Instruments USRP-2921 was used to measure the duty cycle of the interfering network.

III. EXPERIMENTAL RESULTS

Frequency separation between two wireless devices is a major factor in wireless coexistence. Research in this area is separated into two groups: adjacent channel interference and co-channel interference. For co-channel interference analysis, SIR and channel occupancy parameters have been studied. Experimental tests were carried out using NLOS and LOS test setups in these areas, and results were compared.

A. Adjacent Channel Interference

Adjacent channel interference is caused by extraneous power from an adjacent channel and due to either inadequate filtering or improper frequency tuning. The work in [27, 49] shows that interference is a result of spurious emissions caused by surrounding ZigBee nodes employing O-QPSK. Adjacent channel interference has also been studied for 802.15.4 and 802.11b/g [21-31].

In the NLOS test setup, the 802.11g/n nodes transferred data at a maximum, sustainable rate. The 802.11g/n nodes operated on channels 1-11 to test for interference to ZigBee nodes operating on channel 22 (2.460 GHz). The 802.11g/n channels and frequencies are listed in Tables III.

Figure 4 shows that the ZigBee packet error rate increases as the frequency separation between the 802.15.4 and the 802.11g network decreases. PER was the highest when the interfering network converged to the same frequency as the ZigBee network (Channel 11). The figure also illustrates the PER when the ZigBee receiver and transmitter were subjected to the 802.11g interfering network. The ZigBee transmitter is affected less by the side-lobes of the interfering network. In this case, the ZigBee transmitter sensed when the wireless channel was free and subsequently sent packets. This was not the case when the transmitter was further away from the interfering network. Instead, the transmitter sensed the

TABLE II
802.15.4 CHANNELS AND CENTER FREQUENCIES

Channel	Center Frequency
11	2.405 GHz
12	2.410 GHz
13	2.415 GHz
14	2.420 GHz
15	2.425 GHz
16	2.430 GHz
17	2.435 GHz
18	2.440 GHz
19	2.445 GHz
20	2.450 GHz
21	2.455 GHz
22	2.460 GHz
23	2.465 GHz
24	2.470 GHz
25	2.475 GHz
26	2.480 GHz

TABLE III
802.11G/N CHANNELS AND CENTER FREQUENCIES

Channel	Center Frequency
1	2.412 GHz
2	2.417 GHz
3	2.422 GHz
4	2.427 GHz
5	2.432 GHz
6	2.437 GHz
7	2.442 GHz
8	2.447 GHz
9	2.452 GHz
10	2.457 GHz
11	2.462 GHz

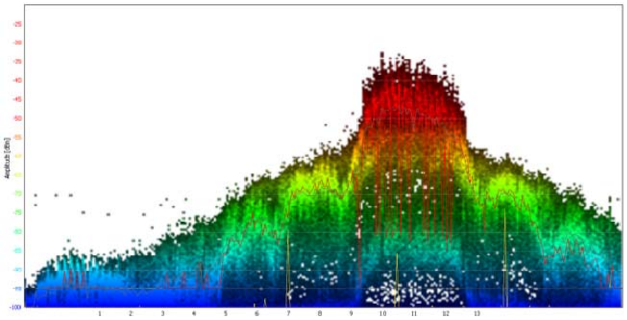

Fig. 2. Spectrum profile of the 802.11g transmitter on channel 11.

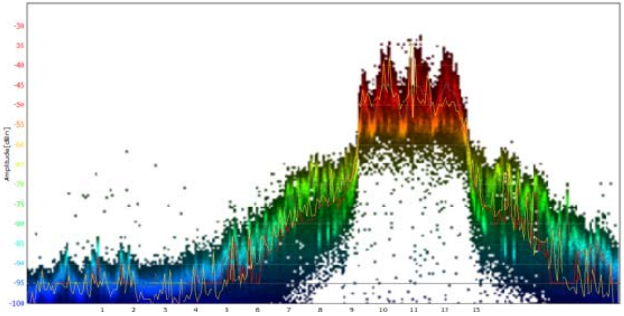

Fig. 3. Spectrum profile of the 802.11n transmitter on channel 11.

channel was free when it might have actually been busy.

Figure 4 also demonstrates that when CSMA in the ZigBee transmitter was disabled, maximum PER improved to 58%. This is in contrast to a 97% improvement with CSMA enabled. When CSMA-enabled ZigBee sensed a busy channel and yet was unable to transmit, the ZigBee buffer overflowed, resulting in additional packet loss. With CSMA disabled, the ZigBee transmitter sent the packets regardless, causing an increase in packet collisions at the ZigBee receiver located furthest away. However, some packets were demodulated due to the QPSK modulation used. This could suggest novel modifications to the CSMA protocol for improving coexistence. Our results suggest that careful analysis of the CSMA configuration is needed to optimize network coexistence.

Figure 5 shows that ZigBee packet error rate for the receiver and transmitter increases as the frequency separation between the 802.15.4 and the 802.11n network decreases. However, it appears that adjacent channel interference to the ZigBee receiver is not as severe when the interfering network is an 802.11n as when it is 802.11g. One factor is that the side lobes of the 802.11n spectrum are lower in power than the spurious side lobes of 802.11g. The CSMA was again disabled in the ZigBee transmitter when subjected to the 802.11n interfering network. It should be noted that when CSMA was disabled, the PER is around 70%, which was higher than the PER when subjected to 802.11g. This is partially due to the fact that 802.11n has a 68% duty cycle, compared to the 48% duty cycle of 802.11g.

B. Co-Channel Interference

Literature for co-channel interference categories are based on SIR and channel occupancy. Literature discussing SIR [24-43] mentions several factors, including the distance between the interfering network and the wireless node under test; clear channel assessment threshold of the network under test; and receiver sensitivity. Literature focusing on channel occupancy [21, 22, 32-38, 44-46] also notes that as packet size of the wireless network under test increases, the probability of interference increases [33-36].

In the NLOS test setup, the 802.11g/n nodes occupied channel 11 (2.462 GHz) and the ZigBee nodes occupied channel 22 (2.460 GHz). The 802.11g/n nodes exchanged data at various rates, creating different channel occupancy rates.

Figure 6 shows that ZigBee PER increased as the channel occupancy increased due to increasing throughput of the 802.11g wireless network. Throughput was increased until PER was greater than 90%. Figure 6 also illustrates PER when the ZigBee receiver and transmitter were subjected to the 802.11g interfering network. To cause a PER greater than 90%, the transmitter needed to be exposed to a higher throughput. This is due to the fact that the ZigBee transmitter senses when the channel is clear when it is placed near the interfering network (as opposed to when furthest away). CSMA was then disabled in the ZigBee transmitter. The 802.11g wireless network throughput was tested from 0 to 19 MB/s and found unreliable to transmit beyond 19 MB/s; thus, limiting throughput testing. At 16 MB/s, ZigBee PER without CSMA is 23%; ZigBee PER with CSMA was 96%.

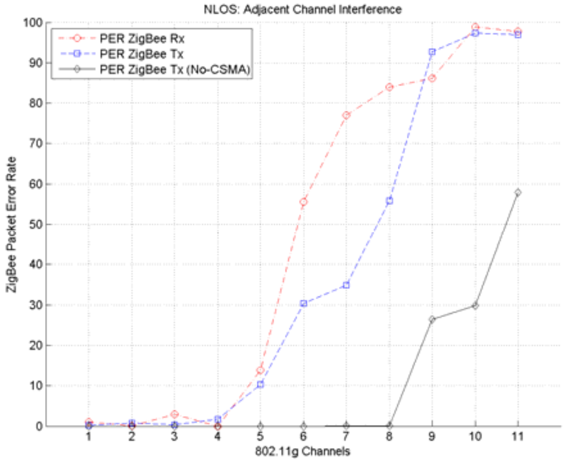

Fig. 4. ZigBee receiver and transmitter subjected to 802.11g channels 1-11.

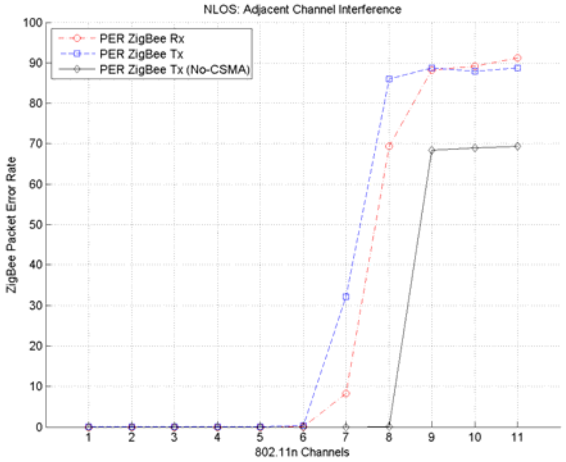

Fig. 5: ZigBee receiver and transmitter subjected to 802.11n channels 1-11.

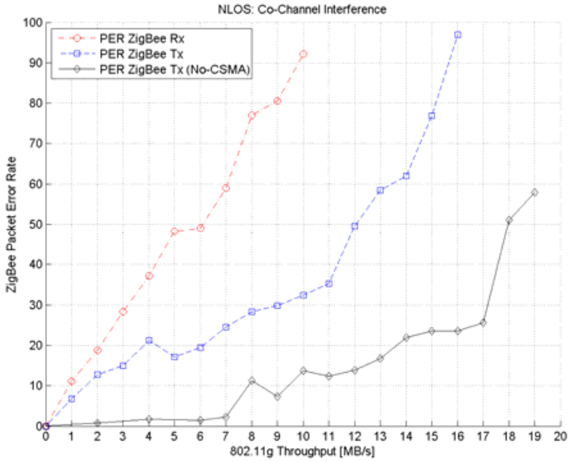

Fig. 6: ZigBee receiver subjected to an increasing throughput of the 802.11g that operates on the same channel.

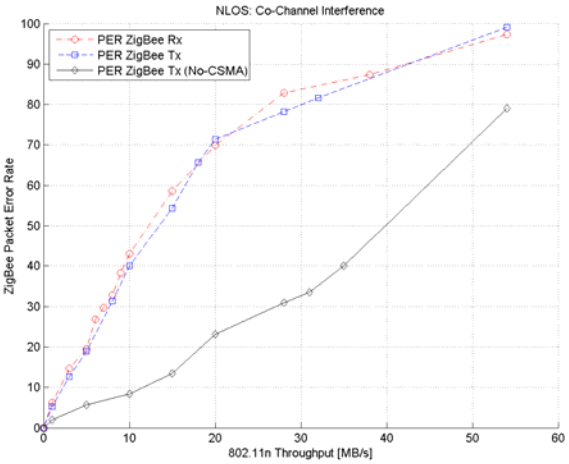

Fig. 7: ZigBee receiver subjected to an increasing throughput of the 802.11n that operates on the same channel.

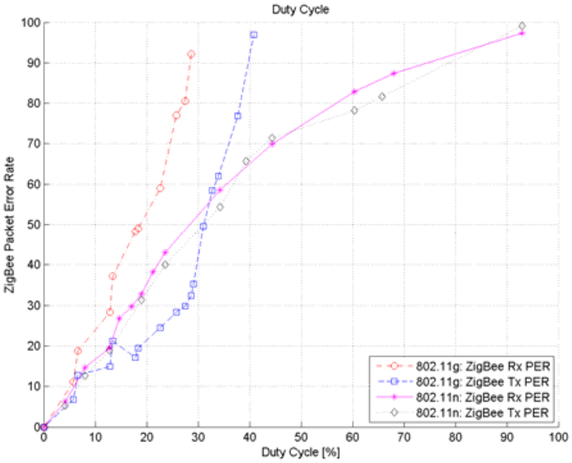

Fig. 8: Packet error rate of ZigBee when exposed to an 802.11g and 802.11n interfering network compared with duty cycle.

Figure 7 shows the PER of the ZigBee receiver and transmitter exposed to the 802.11n interfering network transmitting data from 1-54 MB/s. PER is similar in each case when the receiver and transmitter are exposed to the interfering network. The ZigBee receiver and transmitter have similar PER when exposed to the 802.11n interfering network, as opposed to when they are exposed to the 802.11g interfering network. Again, CSMA is disabled in the ZigBee transmitter and it is exposed to the 802.11n interfering network. The trend that a disabled CSMA ZigBee transmitter will produce a lower PER was confirmed again. Of note is that an 802.11n with 93% duty cycle will produce a 79% PER when CSMA is disabled in the ZigBee transmitter.

Figure 8 compares the PER of the ZigBee receiver and transmitter when subjected to the 802.11g and 802.11n interfering networks and where the x-axis is the measured duty cycle of each interfering network at different throughputs. For duty cycles less than 30%, the PER is similar. However, when the PER of the ZigBee network is >60%, there is divergent behaviour between the 802.11g and 802.11n interfering networks. Of note is that at higher duty cycles for 802.11n, the ZigBee network is able to send packets with a 70% duty cycle as opposed to when it is exposed to the 40% duty cycle of the 802.11g interfering network. In a higher wireless channel occupancy environment, ZigBee coexistence with 802.11n is better than with 802.11g.

IV. CONCLUSION

Reproducible NLOS test parameters were determined for testing the wireless coexistence of 802.15.4 with 802.11g and 802.11n networks. The purpose of the test protocol was to gain helpful information to efficiently tackle coexistence problems between heterogeneous networks while optimizing their deployment in real-life conditions.

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