Interference Effect on IEEE 802.15.4 Performance

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Abstract* – IEEE 802.15.4 shares its frequency band with many existing technologies such as Bluetooth, IEEE 802.11, microwave ovens and other devices that use the same ISM bandwidth. The interference caused by these technologies can degrade the performance of an IEEE 802.15.4 based wireless network. In this paper we study such degrading effects on a network installed in an industrial environment. The performance measure in this paper is the link Packet Error Rate (PER). To measure the performance degradation we have simulated the physical layer of the IEEE 802.15.4 and used our channel measurements from different industrial sites to choose a reasonable channel model. We have simulated the IEEE 802.11 and Bluetooth transmitters to generate interfering signals and measured the performance degradation of the IEEE 802.15.4. To generate the microwave oven interfering signal in our simulations, we used our measurements of the in-band instantaneous signal power using a spectrum analyzer.

Index Terms— Communication channels, Communication system reliability, Interference, Wireless Telemetry

I. INTRODUCTION

In 2004 GE began work on a project sponsored by the US Department of Energy[1] for the development of wireless sensor network technology suitable for use in industrial environments. This work was also being sponsored by several GE businesses interested in utilizing this technology for equipment condition based maintenance applications as well as a variety of other applications. All of these applications share similar requirements; 1) Sensor readings are infrequent with only small amounts of data. 2) Network devices must be self-powered with very long service intervals. 3) No sophisticated installation process should be required as these applications must be installed quickly by those not trained in RF systems. 4) Devices should be inexpensive and be usable in most countries.

These requirements lead us to select the emerging IEEE 802.15.4 technology operating in the 2.4GHz ISM band but with some minimal customizations. Device battery life became a major driving force for reliability. Many factors effect battery life and one of these include network reliability. As we studied network reliability we focused on individual link reliability and how to best characterize it [4]; we chose packet error rate (PER) as our measure. By understanding packet error rate we can predict device battery life.

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Link quality is a major factor in determining PER. To better understand the factors in link quality we undertook an extensive measurement campaign. At the end of this campaign an exhaustive analysis was performed by David Brady of Northeastern University and will be the subject of a future publication. This analysis allowed us to develop both a large-scale propagation loss model as well as small scale fading models and temporal models for channel performance. Interference was also characterized and is the subject of this report.

To better understand the industrial environment we conducted an extensive measurement campaign in true industrial settings such as the one shown in

Figure 1. Although each site had unique qualities we were able to develop an overall picture of the propagation and interference characteristics of these environments. We used these measurements to characterize the channel models for our analysis of fixed wireless communications.

Figure 1: Industrial Environment

One interference source we found in many industrial environments in locations in and around where sensor networks would be deployed is the residential microwave oven, used to prepare meals by plant personnel. Although not used on a perpetual basis, these devices should be considered in an overall estimation of link quality and are a driver in determining device battery life. Microwave interference was studied exhaustively in an early NTIA report [1]. We consider this interference source in the industrial RF channel when an IEEE 802.15.4 network is utilized. Typically interference and channel effects are studied independently, however in this paper we study them together. Other sources of interference included IEEE 802.11b and proprietary frequency hopping networks.

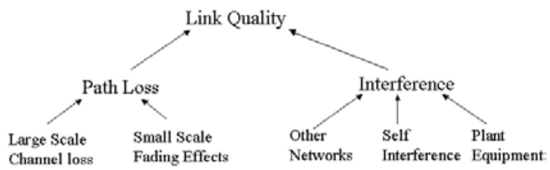


Figure 2: Link Quality Effects

The rest of this paper is organized as follows: In Sections II and III we present the basis of our physical layer simulations and we lay out our channel model. In Section IV we compare the PER found by the simulation and the measured PER using a Chipcon CC2420. In Section V we study the performance of IEEE 802.15.4 when an IEEE 802.11 interferer is present. We compare the simulation results with the lab measurement. In Section VI the performance of the system in presence of a Bluetooth interferer is studied. In section VII we study the effect of microwave ovens on the performance of the system. We conclude this paper in Section VIII.

II. SIMULATIONS OF THE PHYSICAL LAYER

The IEEE 802.15.4 physical layer uses two frequency bands in the 868/915 MHz and 2.4 GHz bands. In this paper we only consider the 2.4 GHz band. The physical layer is based on the direct sequence spread spectrum (DSSS) method, and the transmission rate is 250 kb/s. The 2.4 GHz band supports 16 channels between 2.4 GHz and 2.4835 GHz with a channel spacing of 5 MHz [2]. All signal transmissions in this IEEE standard are packet based. Each packet, or PHY protocol data unit (PPDU), contains a synchronization header (a preamble of 4 bytes plus one byte which is the start of packet delimiter), a one byte PHY header to indicate the packet length, and the payload with a length between 0 and 127 bytes, or PHY service data unit (PSDU).

The 32-bit preamble is designed for the acquisition of symbol and chip timing, and in some cases may be used for coarse frequency adjustment. Channel equalization is not required due to the combination of a small coverage area and the relatively low chip rates.

Each group of four bits in the packet data is spread using 32 chips. The spreading sequence is quasi orthogonal. The spread signal is then modulated using offset quadrature phase shift keying (O-QPSK) with half sine wave shaping.

The equivalent baseband complex envelope of the O-QPSK signal can be represented by [3]

$$s_l(t) = \sum_{n=-\infty}^{+\infty} I_{2n} g(t-2nT) + j\sum_{n=-\infty}^{+\infty} I_{2n+1} g(t-2nT-T) \qquad (1)$$

where I_n and J_n are the transmitted pair of bits, T denotes a symbol period (in O-QPSK every two bits are modulated as one symbol with an offset of a half a symbol period), and $g(t)$ is the half sine pulse shape.

For an Additive White Gaussian noise (AWGN) channel the complex envelope of the received signal is

$$\begin{aligned} r_l(t) = e^{-j\varphi}\Big(&\sum_n I_n g(t-nT+\tau) + \\ j&\sum_n J_n g(t-nT-T/2+\tau)\Big) + n(t) \end{aligned} \qquad (2)$$

where φ is the random phase of the received signal, and τ is the random delay of the received signal.

To estimate the phase and the delay of the received signal we use the maximum likelihood estimation (MLE) method for our carrier recovery and synchronization module. The log likelihood function for the phase and the delay is

$$\begin{aligned} \Lambda(\varphi,\tau) &= \mathrm{Re}\Big[1/N_0 \int_T r_l(t) s_l^*(t,\varphi,\tau)dt\Big] \\ &= \frac{1}{N_0}\cos(\varphi)\sum_n \Big(I_n \int_T (r_I g(t-nT-\tau)dt + \\ &\quad J_n \int_{T_0} r_Q g(t-nT-T/2-\tau)dt\Big) \\ &\quad -\frac{1}{N_0}\sin(\varphi)\sum_n \Big(I_n \int_T (r_Q g(t-nT-\tau)dt - \\ &\quad J_n \int_T r_I g(t-nT-T/2-\tau)dt\Big) \end{aligned} \qquad (3)$$

To find the solution of the MLE problem, we set the derivative of the above equation to zero. Therefore, we have

$$\begin{aligned} \frac{\partial\Lambda}{\partial\varphi} = &-\sin(\varphi)\Big(\sum_n I_n \int_T (r_I g(t-nT-\tau)dt + \\ &J_n \int_T r_I g(t-nT-T/2-\tau)dt\Big) \\ &-\cos(\varphi)\Big(\sum_n I_n \int_T (r_Q g(t-nT-\tau)dt - \\ &J_n \int_T r_I g(t-nT-T/2-\tau)dt\Big) \\ &= 0, \end{aligned} \qquad (4)$$

and

$$\begin{aligned} \frac{\partial\Lambda}{\partial\tau} = &\cos(\varphi)\Big(\sum_n I_n \int_T (r_I \dot{g}(t-nT-\tau)dt + \\ &J_n \int_T r_Q \dot{g}(t-nT-T/2-\tau)dt)\Big) \\ &-\sin(\varphi)\Big(\sum_n I_n \int_T (r_Q \dot{g}(t-nT-\tau)dt - \\ &J_n \int_T r_I \dot{g}(t-nT-T/2-\tau)dt\Big) \\ &= 0. \end{aligned} \qquad (5)$$

An analytical solution for equations (4) and (5) does not exist, therefore, we use these two equations to derive a feedback loop so that the received signal follows the received phase and delay continuously. In the implemented carrier recovery and synchronization module we simplified the module one step further and we used correlation to estimate the delay.

We use the estimate of the received carrier phase and the delay to demodulate the received signal and to apply the matched filter. Then we use the output of the matched filter to despread the received signal. We should point out that we use the soft decision variables for despreading.

III. MULI-PATH FADING CHANNEL

If an extremely short pulse is transmitted over a time-varying multipath fading channel, the received signal appears as a train of pulses. This train of pulses can be viewed as the channel impulse response. The delay spread of the channel is directly related to the length of the channel impulse response. In a wideband communication system the receiver can take advantage of this channel characteristic by using a RAKE receiver and estimating the channel impulse response. The IEEE 802.15.4 standard emphasizes on low power and inexpensive receivers that do not need RAKE receivers or channel equalization [5]. In this case the delay spread indeed degrades the performance of the radio link, i.e. a high root mean square (RMS)-delay spread of the channel will degrade the performance of the communication system to the extent that is inoperable. One of the goals of our study is to quantify the effect of delay spread on the performance of the radio link.

For a multipath fading channel, we represent the received bandpass signal as follows

$$\begin{aligned} r(t) &= \sum_m \alpha_m(t) x(t-\tau_m(t)) \\ &= \mathrm{real}\Big(\big(\sum_m \alpha_m(t) e^{-j2\pi f_c \tau_m(t)} x_l(t-\tau_m(t)\big) e^{j2\pi f_c t}\Big) \end{aligned} \tag{6}$$

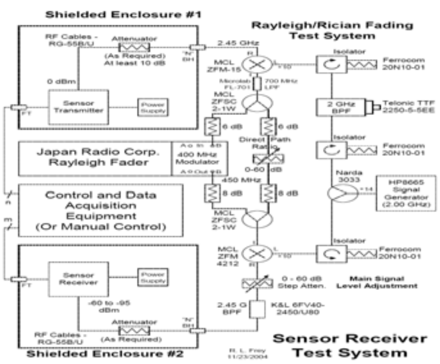
and the complex envelope of the received signal is

$$r_l(t) = \sum_m \alpha_m(t) e^{-j2\pi f_c \tau_m(t)} x_l(t-\tau_m(t)) \tag{7}$$

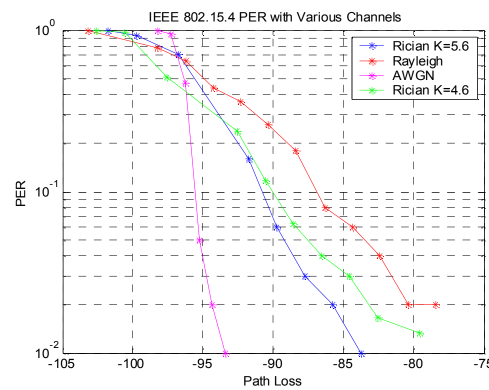
Therefore, the equivalent low pass channel is described by the time varying channel impulse response

$$c(\tau,t) = \sum_n \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} \delta[\tau-\tau_n(t)]. \tag{8}$$

The dependency on t is because of the variation of the channel in time. For a wide band communication system or for a system with multi-channels over a relatively wide frequency band, the dependency on τ exhibits itself in the channel frequency response that is not flat. For a band limited signal many of the paths (terms of the summation in (6)) with similar path delays (time difference less than 1/BW where BW is the bandwidth of the transmitted signal) are grouped in a single path. They are added either constructively or destructively.



(a)



(b)

Figure 3: PER measurement for C2420 for AWGN, Rayleigh, and Rician channel. (a) Block diagram of the measurement apparatus. (b) Measured PER.

IV. TRANSMISSION OVER A FADED CHANNEL

To be able to evaluate the performance degradation caused by an interfering signal we simulated transmission of IEEE 802.15.4 signals over typical wireless channels in an industrial environment without presence of interference. The PER recorded from these simulations later was used as the benchmark for the performance degradation caused by interfering signals. We used Rayleigh fading channels with different RMS-delays to model the industrial wireless channels[2]. The high RMS-delays are associated with the interior of large buildings with a lot of open spaces cluttered by equipment, and the low RMS-delays are associated with smaller buildings. An AWGN channel is simulated for comparison purposes. To validate our simulation data we have also measured the PER of the Chipcon 2420 radio for several wireless channels. CC2420 is a single chip IEEE 802.15.4 transceiver with typical receiver sensitivity equal to –94 dBm [6]. Figure 3a shows the block diagram of our fading simulator used for the CC2420 PER measurement. Figure 3b

[2] We have done extensive measurements of the wireless channel in industrial environments. The PER performance of of Rayleigh fading channel is a conservative approximation of these wireless channels.

shows the CC2420 PER for the AWGN, the Rician, and the Rayleigh channels.

The comparison of the experimental data and the simulation data is shown in Figure 4. From the figure we see that for the AWGN and the Rayleigh fading channel with 0 ns RMS-delay, the simulation data and the experimental data agree quite nicely (We did not have any experimental data for RMS-delays greater than zero.). This confirms that the simulation data is valid and can be trusted for analysis of the CC2420. In Figure 4 the curves with solid lines are fitted to the simulation data.

The target average PER for our sensor network for monitoring industrial machinery is set to 5%. For this target average PER the required signal to noise ratios for RMS delay up to 250 ns are almost the same. Therefore, for the rest of this paper we assume that the wireless channel is flat fading.

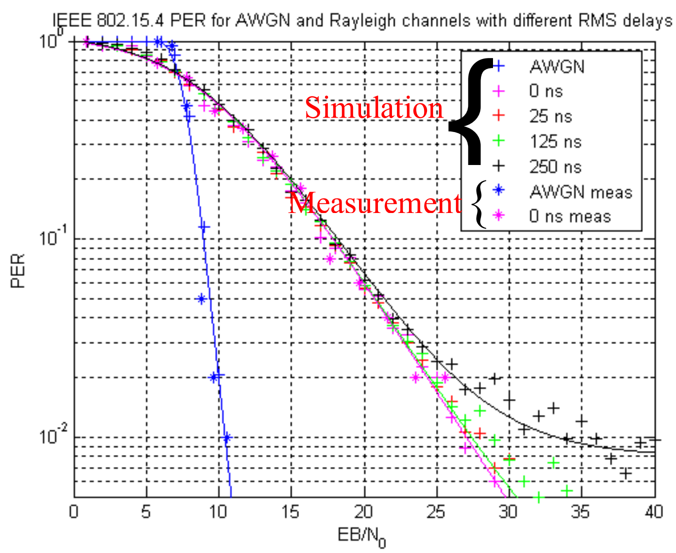


Figure 4: PER for IEEE 802.15.4 radio link experimental and simulation data. For an AWGN channel and Rayleigh fading channels with an exponential delay profile and different RMS-delays.

V. INTERFERENCE CAUSED BY IEEE 802.11B(G)

The bandwidth of an IEEE 802.11 signal is 22 MHz so its interference is considered wideband and can be modeled by equivalent filtered AWGN. To confirm this assumption we simulated the IEEE 802.11 signal in 11 Mb/s mode using Complementary Code Keying (CCK) which is a kind of DSSS [7]. We used the simulated IEEE 802.11 signal and measured its impact on the IEEE 802.15.4 signal and compared it with equivalent filtered AWGN. The differences between these two approaches were very small. Therefore, we used the equivalent filtered AWGN model for the rest of our simulations. This model is especially convenient, since the interference is treated similarly to noise and this simplifies the simulations. Another simplification that we have in our simulation is that whenever an IEEE 802.15.4 packet and an IEEE 802.11 packet collide we assume that the IEEE 802.11 packet is present during the entire transmission of the IEEE 802.15.4. This is a conservative approximation and the real PER should be slightly lower.

As a first step we validated our simulation with the PER data measured using CC2420 in the presence of an IEEE 802.11 interferer. The details of the measurement are as follows:

- IEEE 802.15.4 transmitting at Channel 14, 2420 MHz, -82.9 dBm mean RSSI
- IEEE 802.11b transmitting at Channel 3, 2422 MHz, peer-to-peer mode
- Coaxial cable channels used for both IEEE 802.11b and IEEE 802.15.4 links
- IEEE 802.15.4 packets were 1.6 ms long, transmitted every 250 ms. Approximately 1000 - 2000 packets were used for each measurement.
- IEEE 802.11b signal generated using "fping" application, 1024 data bytes transmitted continuously every 10 mS. The IEEE 802.11b signal power was varied in 5 dB steps, from approximately -40 dBm to -100 dBm applied at the IEEE 802.15.4 mote antenna port.

Figure 5 shows the comparison of the measured data and the simulation data. Again we see that the simulation data provides a good approximation for measured data.

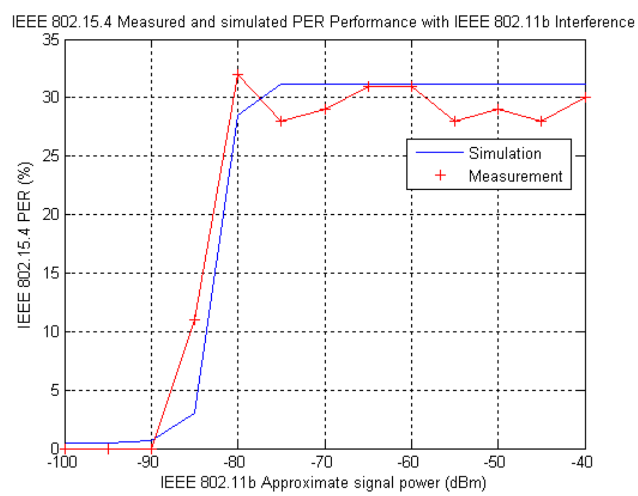


Figure 5: Comparison estimated and measured PER of CC2420 in the presence of IEEE 802.11b interferer.

Using the validated simulation we evaluated performance degradation of IEEE 802.15.4 for different scenarios. Figure 6 a,b,c show the PER for IEEE 802.15.4 when an IEEE 802.11 interferer is present. In all of these figures we assume that the interferer has a packet length of 1024 bytes, a bit rate of 5.5 Mb/s, and a transmit power of 14 dBm. We also assume that the distance between the interfering transmitter and the receiver is 50m.

To calculate average path losses we used a simple break point model where the exponential path loss factor was 2 for the distances less than 5m and 3.73 for distances above 5m. We have used this model conservatively in the past for analysis of fading margins [3].

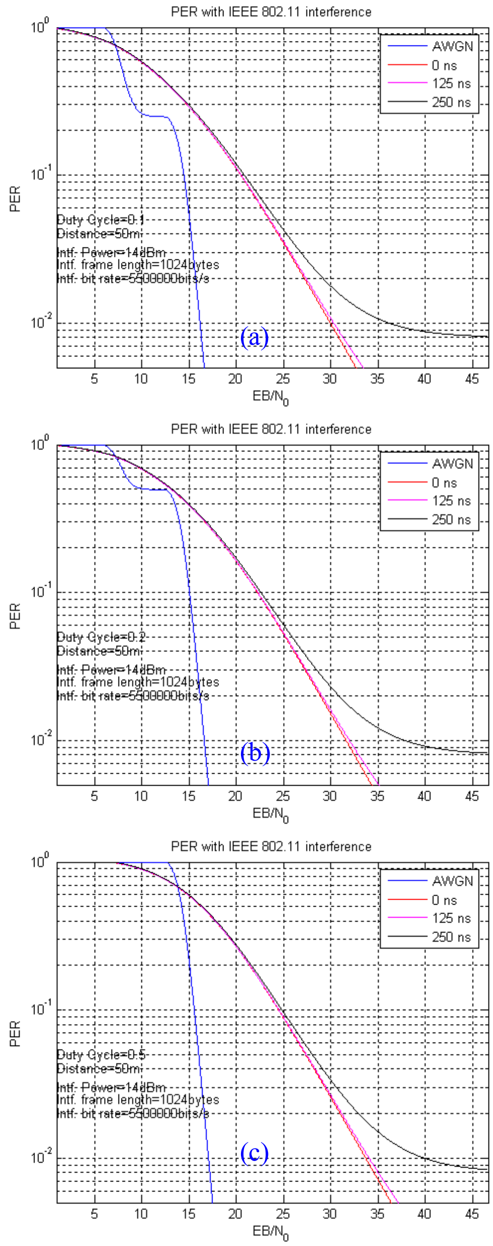


Figure 6: PER for IEEE 802.15.4 radio link in the presence of an IEEE 802.11 interferer. (a) The interferer with duty cycle equal to 10%. (b) The interferer with duty cycle equal to 20%. (c) The interferer with duty cycle equal to 50%.

As can be seen from the figures, the PER of the IEEE 802.15.4 is significantly increased when an IEEE 802.11 interferer is present. The impact of the interferer depends on many factors. Figure 6 shows this dependency on the duty cycle of the interferer. In the figures we see that there exists an interval for EB/N_0 where the PER stays constant. The size of this interval only depends on the power of the interferer. The PER for this interval for a fixed bit rate only depends on the duty cycle of the interferer. This makes perfect sense, because if the interferer signal is stronger than the desired signal then the received packet is received with error with probability close to one. But since the interfering signal is not always present, the PER is not equal to one and depends on the duty cycle.

VI. BLUETOOTH INTERFERENCE

Unlike IEEE 802.11, Bluetooth uses a narrow band frequency hopper transmitter. The bandwidth of a Bluetooth signal is 1 MHz. The IEEE 802.15.4 channel has a bandwidth of 5 MHz, but most of the energy of the IEEE 802.15.4 signal is within a 2 MHz band. Therefore, we expect that the receiver is able to receive a packet with reasonable PER even with a Bluetooth interferer with duty cycle close to one. Figure 7 shows the result of our simulation for different duty cycles for a Bluetooth transmitter with GFSK modulation [8] transmit power equal to 5 dBm, basic bit rate equal to 1 Mb/s, and packet length equal to 200 bytes. We see that achieving 5% PER is possible even when a strong Bluetooth signal is present

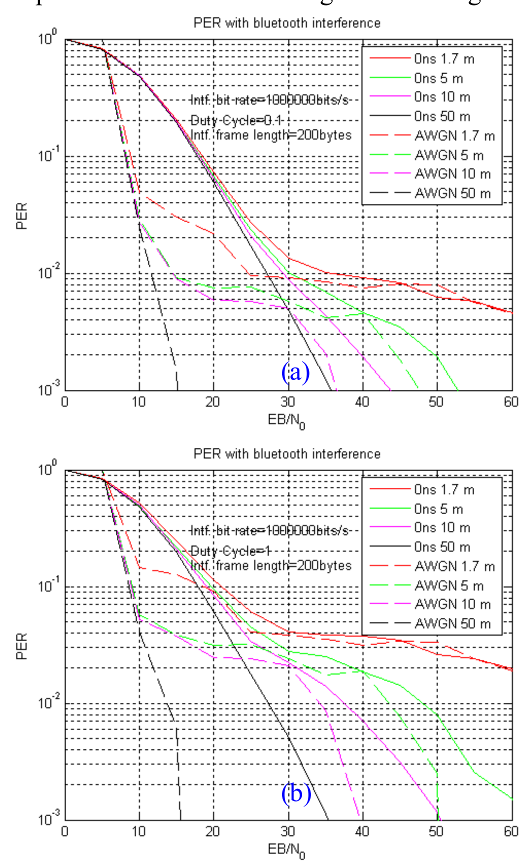


Figure 7: PER for IEEE 802.15.4 radio link in the presence of a Bluetooth interferer. (a) The interferer with duty cycle equal to 10%. (b) The interferer with duty cycle equal to 100%.

VII. MICROWAVE OVEN INTERFERENCE

Commercial and residential microwave ovens (often present in industrial settings for workers' use) operate in the ISM 2.4 GHz band. The results of extensive measurements of interference from fourteen different microwave ovens were published in the NTIA report [1]. The report demonstrates that the interference has roughly a 50% duty cycle with a 16.7 ms period. The results of the NTIA tests are informative, but because these results are taken in the spectrum analyzer's "max hold" mode, they are very conservative [9][10]. It is pointed out that the peak levels and interfering bandwidth vary considerably among ovens from different manufacturers [9][10].

To study the impact of the microwave oven interfering signal, we decided to repeat some of the measurements reported in the NTIA report. We did this because the temporal behavior of the interfering signal is not properly presented in that report. In fact, our measurements show that the peak power of the interfering signal can change significantly within a few hundred milliseconds. Figure 8 shows the measured instantaneous power of the interfering signal. The bandwidth of the spectrum analyzer for this measurement is set to 5MHz.

The instantaneous power of the interfering signal also depends on the frequency band of the desired signal. Residential microwave ovens have one magnetron that is on only in one half cycle of the 60 Hz power line. The measurements show that at the transition times of off-to-on and on-to-off the interference is a broadband signal and is seen in the entire ISM band. This broadband signal only lasts about 20 microseconds. During the rest of the 8.35 ms of the half cycle the interference is narrowband. Therefore, many of IEEE 802.15.4 channels do not suffer from interference during this period. The central frequency of this narrow band signal is more likely between 2445 MHz and 2470 MHz. This central frequency can change even for the same microwave oven.

To generate the microwave oven interfering signal we used the real data collected from two different microwave ovens. For these measurements we connected a monopole antenna to a spectrum analyzer and then we measured the instantaneous

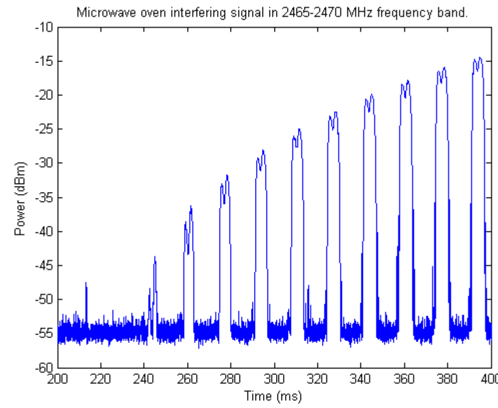


Figure 8: Instantaneous power of a microwave oven interfering signal in the 2465-2470 MHz frequency band.

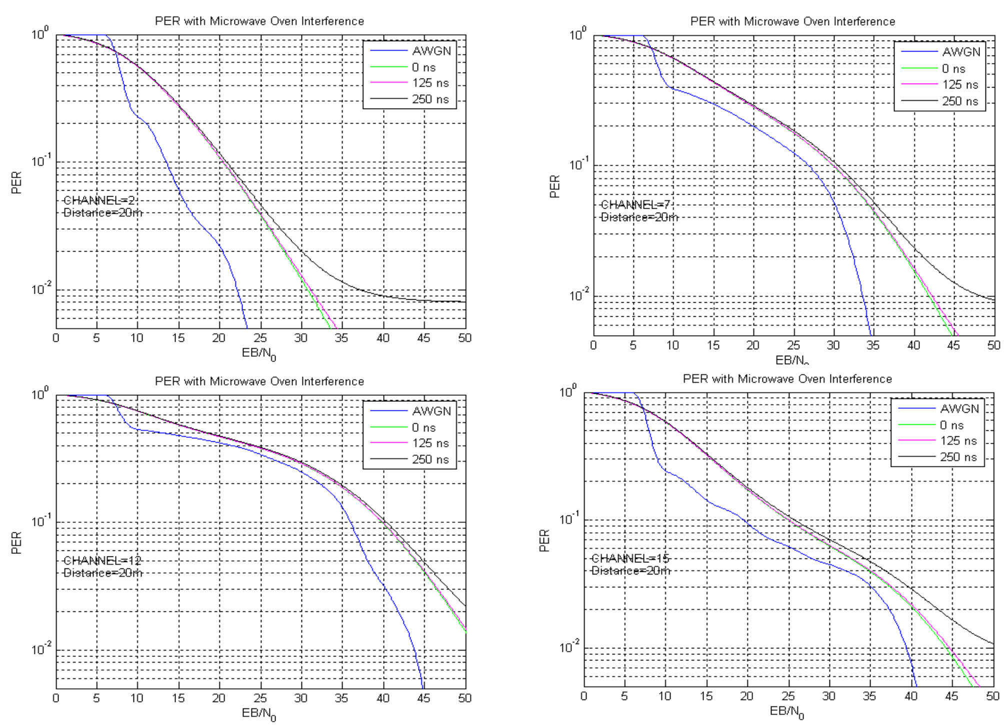


Figure 9: PER for IEEE 802.15.4 in the presence of microwave oven interference. The distance between the Microwave oven and the receiver is 20 m.

power of the received signals in 5 MHz chunks covering the entire spectrum of the ISM band. Then we scaled the signal power so that this power is similar to the one documented in the NTIA report. We modeled the interference as filtered AWGN (i.e. colored noise with a 5 MHz bandwidth). This model is a good model for the transition period, but it is not an accurate model during the time that the magnetron is on and stable. To account for this inaccuracy we added a margin of 5 dB.

Figure 10 shows the PER for IEEE 802.15.4 when microwave oven interference is present. In Figure 10, the distance between the microwave oven and the receiver is 20 m and in Figure 11, this distance is 100 m. From the figures we see that the lower channels and the last higher channels are less affected by the microwave oven interference. This is because in lower channels and the last higher channels the duty cycle of the interfering signal is very small (only during the transition period is the interfering signal present) but in the channels in between the duty cycle it is close to 50%.

IEEE 802.15.4 is a packet-based communication standard. In packet-based communications when a packet is received with error often a retransmission is requested.

Figure 11 and Figure 12 show that the waiting time for retransmission can have a significant impact on the overall PER when microwave oven interference is present. In both figures the transmitter retransmits a packet at most 2 times.

In Figure 11 the waiting time is set to 6 ms, in Figure 12 the waiting time is 3 ms. We can see the performance of the system with waiting time equal to 3 ms is significantly better. This is because the length of the transmitted packet is 2.2 ms and the waiting time is 6 ms. This means that if a packet is affected by microwave oven interference, then 2.2 + 6 = 8.2 ms later it will again be affected by it, therefore, this waiting time is inappropriate for such an environment. Hence, if the system designer is at liberty to choose the waiting time for packet retransmission, and changing it doesn't deteriorate performance due to other parameters, then he should choose a waiting time that does not coincide with the microwave oven frequency.

In some instances, particularly in installations that might have employee break areas distributed around the facility microwave oven interference might be present from multiple locations. In standard wiring the phases of the ovens may separated by 120° or if an outlet is improperly wired they could be 180° out of phase. During periods of high use (such as during the lunch or dinner hour) there could be interference most of the time although it is not expected that the frequencies will be identical. Even though it is possible that in these cases interference might be present continuously, it is likely that it will not be in the same channel continuously as the ovens operating frequency meanders.

VIII. CONCLUSIONS

In this work we considered the impact of channel effects on interference and coexistence for IEEE 802.15.4 systems. To accomplish this we developed and validated simulations models for both radio performance and channel characteristics. When multipath fading and channel interference are considered together the required link margins to maintain a given packet error rate can be quite significant. IEEE 802.11 even with small duty cycle (10%) can have a significant impact. Bluetooth interference represents a much lesser threat to these types of systems. Residential microwave ovens can also have a dramatic impact but are very channel dependent. This data can be used when determining the proper link budget for a particular desired packet successful delivery rate. Also we saw that the waiting time between the retransmissions for IEEE 802.15.4 has a significant impact on PER due to microwave oven interference. A system designer may take this into account to avoid unnecessary dropped packets due to microwave oven interference.

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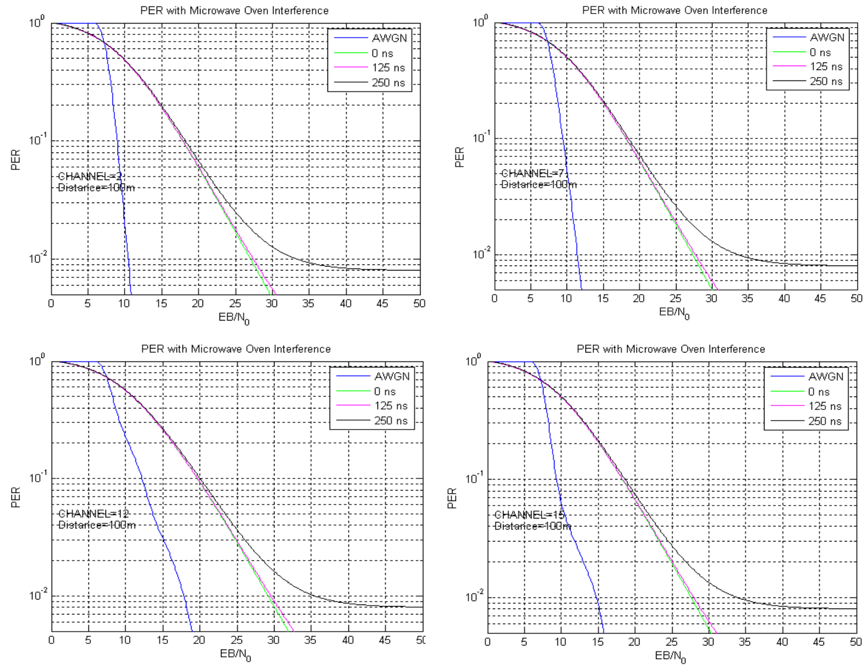

Figure 10: PER for IEEE 802.15.4 under presence of Microwave oven interference. The distance between the Microwave oven and the receiver is 100 m.

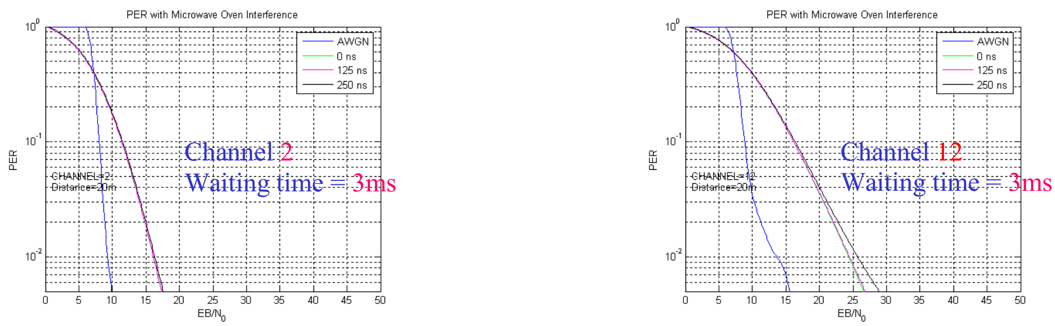

Figure 11: PER for IEEE 802.15.4 under presence of Microwave oven interference. The number of maximum retransmission is 2 and the waiting time is 3 ms.The distance between the Microwave oven and the receiver is 20 m.

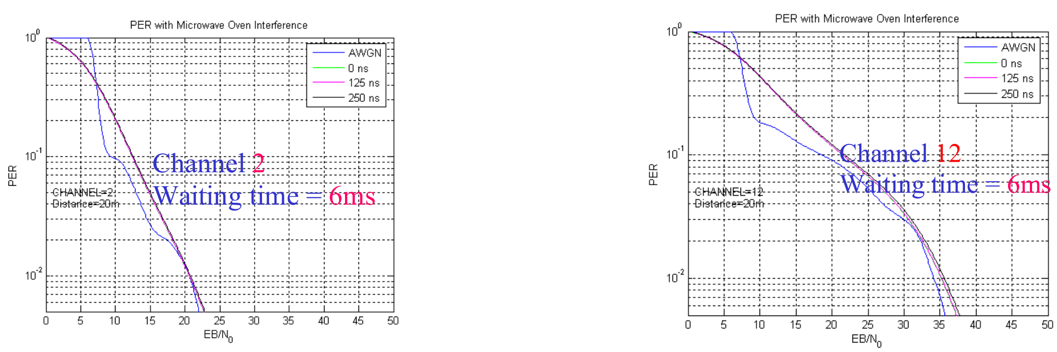

Figure 12: PER for IEEE 802.15.4 under presence of Microwave oven interference. The number of maximum retransmission is 2 and the waiting time is 6 ms.The distance between the Microwave oven and the receiver is 20 m.