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Coexistence Issues of 2.4GHz Sensor Networks with other RF devices at Home

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***Abstract*—*The IEEE 802.15.4 as one of the low layer communication standards for PANs and WSNs may be interfered by other wireless devices in the ISM frequency bands, especially at home, such as devices of IEEE 802.11b, Bluetooth, Cordless telephone, and microwave oven radiation. This paper examines the mutual interference effects of 2.4 GHz devices which are widely deployed at home, via both theoretical analysis and real-life experiment. In the paper an analytical model is proposed to estimate the Packet Error Rate (PER) of RF coexistent networks. The model is verified through a series of experiments. The Experimental results also show that Bluetooth has little impact of interference on 802.15.4 networks; the effect of microwave oven radiation on 802.15.4 devices is tolerable if the device is a few meters away from the oven; whereas 802.11b wireless networks can cause problems to 802.15.4, however the effects can be significantly reduced by a proper channel selection*

Keywords- radio Interference; IEEE 802.15.4; IEEE 802.11.b; microwave oven radiation; Bluetooth

I. INTRODUCTION

The Industrial, Scientific and Medical (ISM) radio bands are license-free for many radio systems and applications. The 2.4 GHz ISM band (2400 MHz-2483.5 MHz) can be shared by the devices of IEEE 802.15.4 (wireless personal area networks and wireless sensor networks), IEEE 802.15.1 (Bluetooth), IEEE802.11b (wireless local area networks), microwave oven, cordless telephone and others. When deploying Wireless Sensor Networks (WSNs) that uses IEEE 802.15.4 protocol at home, it is expected to have the effect of interference from other RF devices, such as laptops, cordless phones, mobile phone- supported Bluetooth, and microwave oven radiation, which may cause interferences. As an example, Figure 1 shows the frequency ranges used by 802.15.4 and 802.11b in the 2.4 GHz band. It depicts the 16 channels of IEEE 802.15.4 with bandwidth 3MHz each and the 13 channels of IEEE 802.11b with bandwidth 22MHz each. It is obvious that an IEEE 802.11b channel overlaps with 4 IEEE 802.15.4 channels in most case.

Razvan Musaloiu-E. and Andreas Terzis studied the interference between Wi-Fi and multi-hop 802.15.4 WSNs [3]. Crossbow Technology Inc. used Crossbow MICAz Zigbee running with Wi-Fi 802.11b cards [4]. Measurements showed a significant drop in the MICAz packet delivery rate due to interference from the WLAN in closely located radio channels. The drop increases notably from 5% in the low powered Wi-Fi to 20% in the high powered Wi-Fi in Channel 20. Golmie conducted experiences in high traffic environments and analyzed the effect of packet fragmentation on packet loss and access delay [5]. S. Y. Shin studied the effect of power spectral density of an IEEE 802.11b as interference to the IEEE 802.15.4, and evaluated the packet error rate, transmission delay and throughput [6]. Howitt analyzed the interference between an IEEE 802.15.4 system and IEEE 802.11b devices [7]. His work proved that the 802.15.4 has little effect on the performance of 802.11b. M. Petrova, et al focused on IEEE 802.11g/n interference on IEEE 802.15.4 and showed a disastrous impact on the performance of IEEE 802.15.4 due to the significantly bigger channel bandwidth of IEEE 802.11g/n [8].

The target of this paper is to investigate how much interference is caused by three of the most common interference sources which are microwave oven radiation, IEEE 802.15.1 (Bluetooth) [1] and IEEE 802.11b (wireless LAN) [2].

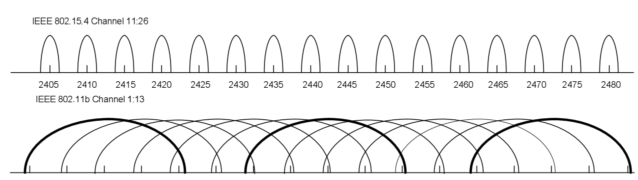

Figure 1. Frequency ranges used by 802.15.4 and 802.11b

The rest of this paper is structured as follows. The analytical models and the theoretical analysis of interference issues are described in Section II. The Experiments and evaluation results are shown in section III and conclusions are in Section IV.

[1] Work done during the joint PhD training in JTH, Sweden

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II. MODEL OF COEXISTENCE

Figure 2 illustrates the scenarios of 2.4 GHz interference sources on IEEE 802.15.4 at home.

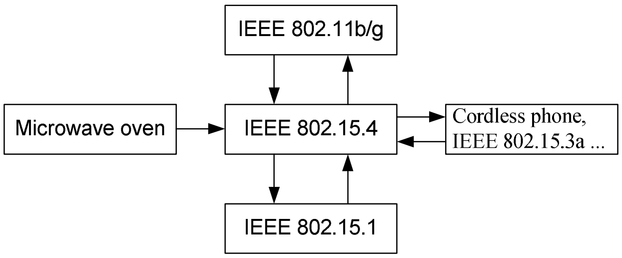

Figure 2. The scenarios of 2.4 GHz interference on IEEE 802.15.4.

The 2.4 GHz ISM frequency band is divided into 16 separated IEEE 802.15.4 channels, Channels #11-26. A WSN can select one single channel of 5 MHz bandwidth to operate [1]. IEEE 802.15.4 devices at home will likely operate with much lower transmit power, 0 dBm or less typically. O-QPSK modulation and direct sequence spread spectrum (DSSS) schemes are adopted.

IEEE 802.11 is a set of standards for wireless local area networks (WLAN) [9]. We are more interested in IEEE 802.11b because the 11b was approved first and it got to WLAN market first. The 4 GHz ISM frequency band is divided into 14 partly overlapped IEEE 802.11b channels, Channels 1-14, bandwidth of 22 MHz each. A WLAN can select one single channel to operate. M-ary QAM modulation and DSSS schemes are adopted. The transmission power is 12 dBm or 18 dBm selectable.

Bluetooth also operates in the 2.4GHz ISM band. The frequency band is divided into 79 channels of 1 MHz each for frequency hopping spread spectrum (FHSS), 1600 hops/second. BFSK/FHSS modulation is adopted. The transmission power is selectable 0, 4 and 20 dBm.

The leakage of microwave oven radiation can be simply represented as one peak of -9.6 dBm power at 2450 MHz frequency [9].

Inspired by Appendix E in [1], let us formulate a general presentation of Packet loss or Error Rate (PER) of IEEE 802.15.4 in the interference environment. Let The received signal power at the distance d_s from the transmitter can simply be modeled as

$$\mathrm{P_r(d)} = \mathrm{P_r(d_0)} - 10\mathrm{n}\log\left(\frac{d_s}{\mathrm{d_0}}\right), d > d_0 \tag{1}$$

where, d_0 is the reference distance and n the path loss exponent. We can get the power- distance equation:

$$d = d_0(10^{\frac{P_r(d_0)-P_r(d_s)}{10n}}), d > d_0 \tag{2}$$

Define the Signal to Interference-plus-Noise Ratio (SINR) as

$$SINR = 10\log\left(\frac{P_r(d_s)}{N_0+\rho_x(\mathrm{f})I_r(d_r)}\right) \tag{3}$$

where N_0 denotes the in-band additive white Gaussian noise (AWGN) power, $I_r(d_r)$ is the received interfering power at distance d_r from the interfering transmitter if the offset frequency is zero, and $\rho_x(\mathrm{f})$ is the offset frequency factor in which x means the different protocol and f in MHz. For the spectral density of different protocols [1] [2], the offset frequency factor is given in Equation (4); see the last page of this paper.

Given the modulation and demodulation schemes and the signal to interference-plus-noise radio, the Bit Error Rate (BER) for deferent standard receivers can be calculated in Equation (5), also see the last page of this paper, where the *Q(x)* function is defined as the area under the tail of the Gaussian probability density function with zero mean and unit variance, as shown in Equation (6),

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(-\frac{u^2}{2}\right)du \tag{6}$$

Assume error detection codes are used in the date link layer. The packet error rate (PER) can be calculated

$$PER_x = 1 - (1 - BER)^{8L_x} \tag{7}$$

where Lx denotes the packet length in bytes, and x means the different protocol.

III. EXPERIMENTS AND EVALUATION

In this section a series of experiments for further investigation of the interference effects on IEEE 802.15.4 and evaluation of the mathematical model is described. The interference sources include IEEE 802.11b, IEEE 802.15.1 and microwave oven radiation. The experiments are executed in a student apartment in a high building. The basic parameters in the experiments are listed in Table 1, where $P(d_0)$ is the received signal power at the reference distance d_0, n is the path loss exponent, N_x is the number of interfered nodes, N_y, the number of interfering nodes N_y,, and L_x is the packet length of standard *x*. The test setup is depicted in Figure 3, where d_s is the distance between the transmitter and the receiver of IEEE 802.15.4, and d_r is the distance between the interfering transmitter and the interfered receiver. The height of the AP of WLAN is 2m over the floor; all the other devices are 1.2 meters. In the tests, 2 Crossbow MICAz Motes are used as a transmitter and receiver of IEEE 802.15.4, with 1 TI-Chipcon CC2420 DK packet sniffer to collect the received packets. The transmission power of IEEE 802.15.4 sensor nodes is 1 mw; the packet transmission rate is 4 per second. Each experiment runs 150 seconds, and all the interfering and interfered devices are always active during this period.

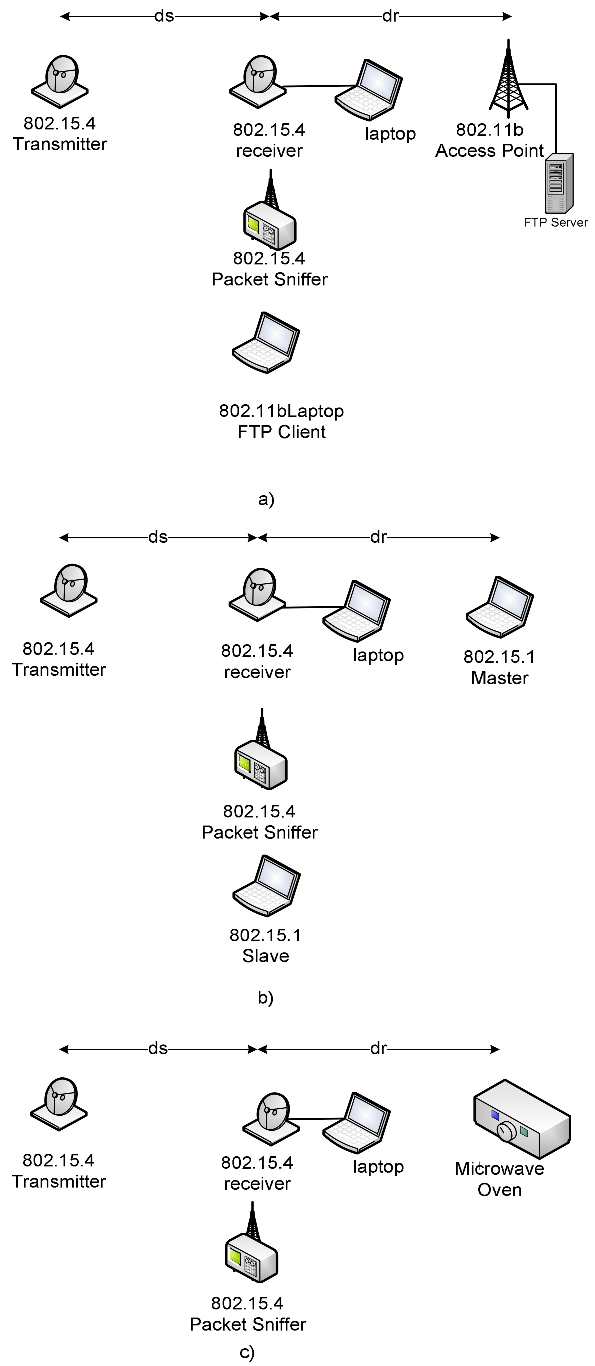

Figure 3. The test setup. a) setup for test between IEEE 802.11b and IEEE 802.15.4; b) setup for test between IEEE 802.15.1 and IEEE 802.15.4; c) setup for test between Microwave Oven and IEEE 802.15.4.

TABLE I. LITERAL COMPUTATION PARAMETERS

$P(d_0)$	-45dBm	**n**	2.3
d_0	0.5m	**N_x**	2
N_y	2#	**$L_{802.15.1}$**	1024Byte
$L_{802.15.4}$	22Byte	**$L_{802.11b}$**	1024Byte

#, Ny=1 for microwave oven

A. IEEE 802.11b

In this sub-section we examine the interference degree of IEEE802.11b on IEEE802.15.4 theoretically and experimentally. Figure 3a) shows the experimental setup where one Wi-Fi access point (AP) and one HP laptop with Intel PRO wireless 3945ABG (802.11a/b/g) Card are used as an interfering source. The transmission power of wireless laptops cards is P_{11b} = 10mW. d_s =10m is fixed.

Figure 4 shows the calculated result of packet error rate versus interference distance d_r and the frequency offset, according to Eq. (7) and the given parameters P_{11b} = 10mW and d_s =10m. From the figure we can find that a reliable communication in IEEE802.15.4 devices can be achieved if d_r / d_s > 6 and frequency offset $11MHz \geq f \geq 0MHz$ (main band), or if d_r/d_s> 2 and frequency offset $22MHz > f > 11MHz$ (first sideband), or if d_r/ d_r> 1 and frequency offset f $f \geq 22MHz$ (from second sideband); otherwise reliable communication for IEEE 802.15.4 is impossible under the interference of IEEE802.11b.

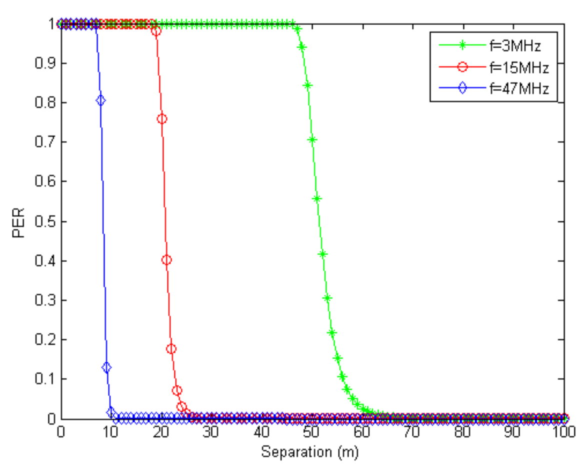

Figure 4. The calculated result of packet error rate versus interference distance in the interference of IEEE 802.11b on IEEE 802.15.4 in different frequency offset

Then we run the experiments to evaluate the model. In this experiment the IEEE802.11b operates in Channel 9 by download FTP files. We choose interference distance d_r =1 m, 10m, 30m, and 55m while the d_s= 10m is fixed. The experiments are repeated for each IEEE 802.15.4 channel from #14 to #26. The average theoretical and experimented value of packet error rate (PER) and the standard deviation is shown in Figure 5. We can get a conclusion from this figure that the maximal PER occurs at channels 19 to 21 of IEEE 802.15.4 which are covered by the main band of Wi-Fi channel 9. The reason of large difference between the theoretical results and the experimented results is that the theoretical model only considers the worst scenarios, as an upper bound for real-life communications. However the figure also shows that if an IEEE 802.15.4 channel is properly selected the PER less than 5% is achievable.

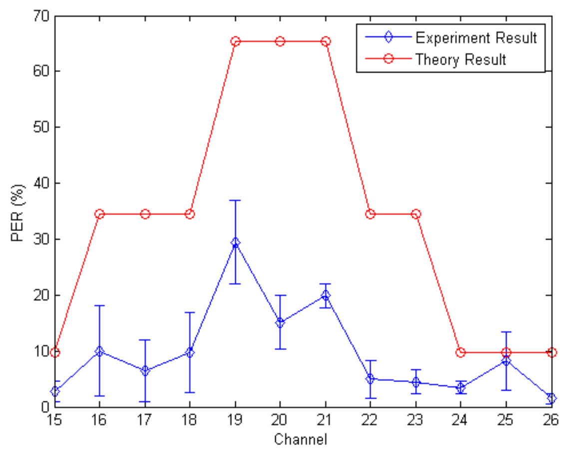

Figure 5. Average theoretical and experimental PER and standard deviation of 802.15.4 node in different channels under the interefeence of IEEE 802.11b

B. IEEE 802.15.1/Bluetooth

In this sub-section we examine the interference degree of Bluetooth on IEEE802.15.4 theoretically and experimentally. Figure 3b) shows the experimental setup where two HP laptops with Bluetooth cards are used as an interfering source. The transmission power of Bluetooth is 20 dBm.

Figure 6 shows the calculated result of average packet error rate versus interference distance d_r and setting d_s= 5m and 10m respectively, according to Eq. (1-7). From the figure we can find that a reliable communication in IEEE802.15.4 devices can be achieved if d_r / d_s > 2, otherwise reliable communication for IEEE 802.15.4 is impossible under the interference of IEEE802.11b.

In the experiment two laptops are used to generate interference by Bluetooth. The interference distance is variable d_r = 1m, 5m, and 10m while the d_s= 10m is fixed. The experiment is repeated for each IEEE 802.15.4 channel from #14 to #26. The average theoretical and experimental PER values are shown in Figure 7. From the figure we find that 4% PER in average may be caused by Bluetooth interference.

C. Microwave Oven Radiation

We consider Microwave oven radiation is also an interference source, see Figure 4c), where one Husqvarna BM4501 microwave oven of 750 W maximum powers is used to generate 2.45 GHz radiation. The experiment is repeated for two different distances d_r = 0.5m and 1.5m, while the d_s= 10m is fixed. The experiment is also repeated for each IEEE 802.15.4 channel. The averages theoretical and experimental PER values are shown in Figure 8. From the figure we find that if the interference distance is much greater than 1.5m, reliable communication is possible.

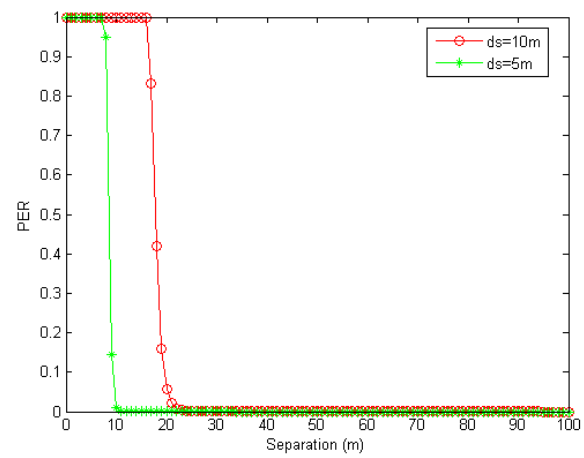

Figure 6. The calculated result of packet error rate versus interference distance in Bluetooth interference on IEEE 802.15.4

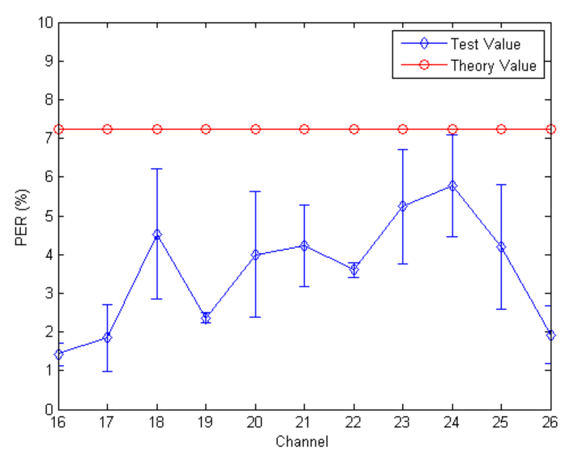

Figure 7. Average theoretical and experimental PER and standard diviation of 802.15.4 node in different channels under Bluetooth interference

IV. CONCLUSION

In this paper, we have discussed the coexistence interference on wireless sensor networks using IEEE 802.15.4 protocol. We examine the mutual effects of IEEE 802.15.4 and related communication standards which are widely deployed at home including IEEE 802.11b, IEEE 802.15.1 and microwave oven radiation via theoretical analysis and real-life experiments. An analytical model is proposed to estimate the Packet Error Rate caused by interference and the active-rate of the interference networks. The calculated PER can be considered as an upper bound in the worst cases. The experiments show:

- The interference of Bluetooth on 2.4 GHz WSN cannot be avoided by the channel selection due to FHSS covering the whole frequency band, but the effect is tolerable as the PER is about 4%.
- The interference of IEEE 802.11b on 2.4 GHz WSN can be minimized by channel assessment and selection, thus the PER <10% is achievable.
- The interference of microwave oven radiation on 2.4 GHz WSN cannot be, in practice, significantly reduced by channel selection, but the effect is tolerable as the PER is about 8% if the distance from the oven to the sensor node is 1.5 m.

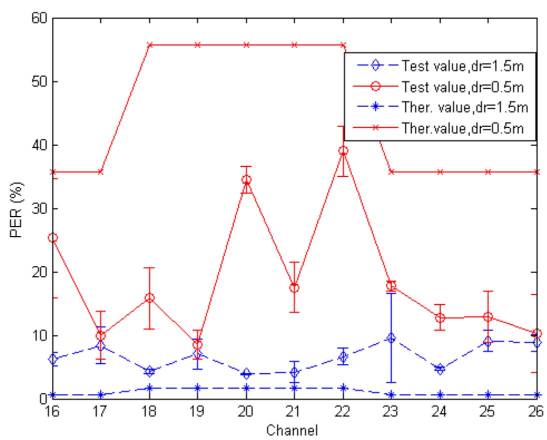

Figure 8. Average theoretical and experimental PER and standard deviation of 802.15.4 node in different channels under the interference of Microwave Oven Radiation

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$$\rho_x(f) = \begin{cases} \begin{cases} 1 & 11MHz \geq f \geq 0MHz \\ 10^{-3} & 22MHz > f > 11MHz \\ 10^{-5} & f \geq 22MHz \end{cases} & x\ for\ 802.11b \\ \begin{cases} 1 & 1.5MHz \geq f \geq 0MHz \\ 10^{-3} & 3MHz > f > 1.5MHz \\ 10^{-6} & f \geq 3MHz \end{cases} & x\ for\ 802.15.1 \\ \begin{cases} 1 & 2MHz \geq f \geq 0MHz \\ 10^{-1} & 3.5MHz > f > 2MHz \\ 10^{-3} & f \geq 3.5MHz \end{cases} & x\ for\ 802.15.4 \end{cases} \quad (4)$$

$$BER = \begin{cases} Q(\sqrt{11SINR}) & ,for 802.11b\ with\ 1Mb/s \\ Q(\sqrt{5.5SINR}) & ,for 802.11b\ with\ 2Mb/s \\ \left(\frac{8}{15}\right)(Q\left(14\sqrt{8SINR}\right) + Q\left(\sqrt{16SINR}\right)) & ,for 802.11b\ with\ 5.5Mb/s \\ \left(\frac{128}{255}\right)(24Q\left(\sqrt{4SINR}\right) + 16Q\left(\sqrt{6SINR}\right) + 174Q\left(\sqrt{8SINR}\right) & \\ +16Q\left(\sqrt{10SINR}\right) + 24Q\left(\sqrt{12SINR}\right) + Q\left(\sqrt{16SINR}\right)) & ,for 802.11b\ with\ 11Mb/s \\ (\frac{1}{2})\exp\left(\frac{-SINR}{2}\right) & ,for 802.15.1 \\ \left(\frac{8}{15}\right)(\frac{1}{16})(\sum_{i=2}^{16}(-1)^i C_{16}^i \exp\left(-20SNIR(1-\frac{1}{i}\right)) & ,for 802.15.4 \end{cases} \quad (5)$$