Lecture Notes in Computer Science: Packet Error Rate Analysis of IEEE 802.15.4 under IEEE 802.11b Interference

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Abstract. In this paper, the packet error rate (PER) of IEEE 802.15.4 low rate wireless personal area network (WPAN) under the interference of IEEE 802.11b wireless local area network (WLAN) is analyzed. The PER is obtained from the bit error rate (BER) and the collision time. The BER is obtained from signal to noise and interference ratio. The power spectral density of the IEEE 802.11b is considered in order to determine in-band interference power of the IEEE 802.11b to the IEEE 802.15.4. The simulation results are shown to validate the numerical analysis.

1 Introduction

Recently, a low rate wireless personal area network (LR-WPANs), IEEE 802.15.4, has been standardized[1],[2]. The goal of the IEEE 802.15.4 is to provide a standard, which has the characteristics of ultra-low complexity, low-cost and extremely low-power for wireless connectivity among inexpensive, fixed, and portable devices such as sensor networks and home networks. To provide the global availability, the IEEE 802.15.4 devices use the 2.4GHz industrial scientific and medical (ISM) unlicensed band. Because this ISM band is commonly used for the low cost radios such as IEEE 802.11b (WLAN)[3] and IEEE 802.15.1 (Bluetooth)[4], an unrestricted access to the ISM band exposes the IEEE 802.15.4 devices to a high level of interference. Since the IEEE 802.15.4 and the IEEE 802.11b have been designed for different purposes, they can be coexisted within the communication range of each other. For example, the IEEE 802.15.4 network is used for a sensor and control network and the IEEE 802.11b network is used for a audio/video (A/V) network within a home. When a notebook is capable of supporting these two standards, the coexistence distance may be smaller than 1 m. Therefore, the coexistence performance of the IEEE 802.15.4 and the IEEE 802.11 needs to be evaluated.

Some related reseaches study the coexistence problem between the IEEE 802.15.4 and the 802.11b[5],[6],[7]. In [5], the packet error rate (PER) of the IEEE

802.15.4 under the IEEE 802.11b and IEEE 802.15.1 is obtained by experiments only. In [6], the impact of an IEEE 802.15.4 network on the IEEE 802.11b devices is analyzed. However, the PER of the IEEE 802.15.4 packets is not considered. In [7], the PER of IEEE 802.15.4 under the interference of IEEE 802.11b is evaluated using simulation. To the best knowledge of the authors, the analysis of the PER of the IEEE 802.15.4 under the interference of the IEEE 802.11b has not been reported yet in the literature.

In this paper, the PER of the IEEE 802.15 4 under the interference of the IEEE 802.11b is analyzed using the bit error rate (BER) and the collision time. The BER is obtained from signal to interference and noise ratio (SINR). The collision time is defined as the time that an IEEE 802.15.4 packet experiences the interference by packets of the IEEE 802.11b. For accurate analysis, in-band interference power ratio of the IEEE 802.11b is obtained from the power spectral density of the IEEE 802.11b and the frequency offset. The frequency offset can be defined as the difference between the center frequencies of the IEEE 802.15.4 and the IEEE 802.11b. The analytic results are compared with the simulation results.

This paper is organized as follows. Section 2 briefly overviews the IEEE 802.15.4. In Section 3, the BER of the IEEE 802.15.4 under the IEEE 802.11b is evaluated. Section 4 describes the interference model of the IEEE 802.15.4 and the IEEE 802.11b. The PER is obtained in Section 4. In Section 5, comparisons between analytic and simulation results are shown. Finally, this paper concludes in Section 6.

2 IEEE 802.15.4 Overview

A new IEEE standard, 802.15.4, defines both the physical layer (PHY) and medium access control (MAC) sublayer specifications for low-rate wireless personal area networks (LR-WPANs), which support simple devices that consume minimal power and typically operate in the personal operating space (POS) of 10 m or less. Two types of topologies are supported in the IEEE 802.15.4: a one-hop star or a multi-hop peer-to-peer topology. However, the logical structure of the peer-to-peer topology is defined by the network layer. Currently, the ZigBee Alliance is working on the network and upper layers [8].

2.1 OPERATION IN THE ISM BANDS AND AT VARIOUS DATA RATES

The IEEE 802.15.4 defines two PHY layers, the 2.4 GHz and 868/915 MHz band PHYs. The unlicenced industrial scientific medical (ISM) 2.4 GHz band is available worldwide, while the ISM 868 MHz and 915 MHz bands are available in Europe and North America respectively. A total of 27 channels with three different data rates are defined for the IEEE 802.15.4: 16 channels with a data rate of 250 kbps at the 2.4 GHz band, 10 channels with a data rate of 40 kbps at the 915 MHz band, and 1 channel with a data rate of 20 kbps at the 868 MHz band.

The relationship between the IEEE 802.11b (non-overlapping sets) and the IEEE 802.15.4 channels at the 2.4 GHz is illustrated in Figure 1.

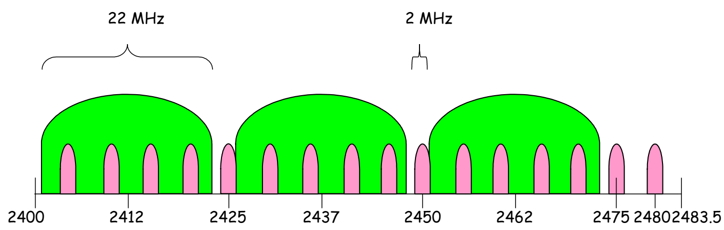

Fig. 1. IEEE 802.11b and IEEE 802.15.4 Channel Selection

To prevent the interference between the IEEE 802.15.4 and the IEEE 802.11b, the standard of the IEEE 802.15.4 recommends to use the channels that fall in the guard bands between two adjacent the three IEEE 802.11b channels or above these channels. While the energy in this guard space will not be zero, it will be lower than the energy within the channels; and operating an IEEE 802.15.4 network on one of these channels will minimize interference between systems. However, if there will be more IEEE 802.15.4 networks, these four channels are not enough.

2.2 DIFFERENT DATA TRANSMISSION METHODS AND LOW POWER CONSUMPTION

An IEEE 802.15.4 network can work in either beacon-enabled mode or non-beacon-enabled mode. In beacon-enabled mode, a coordinator broadcasts beacons periodically to synchronize the attached devices. In non-beacon-enabled mode, a coordinator does not broadcast beacons periodically, but may unicast a beacon to a device that is soliciting beacons.

A superframe structure is used in beacon-enabled mode. The format of the superframe is determined by the coordinator. A superframe consists of an active part and an optional inactive part, and is bounded by the beacons. The length of a superframe (i.e., beacon interval, BI) and the length of its active part (i.e., superframe duration, SD) are determined by the beacon order (BO) and superframe order (SO), respectively. The active part of a superframe is divided into aNumSuperframeSlots (with the default value of 16) equal-sized slots, and a beacon frame is transmitted at the first slot of each superframe.

The active part can be further classified into two periods, a contention access period (CAP) and an optional contention-free period (CFP). The optional CFP may accommodate up to seven guaranteed time slots (GTSs) to provide the data with quality of service (QOS), and a GTS may occupy more than one slot period.

However, a sufficient portion of the CAP shall remain for contention-based access of other networked devices or new devices wishing to join the network. A slotted CSMA-CA mechanism is used for channel access during the CAP. All contention-based transactions shall be completed before the CFP begins. Moreover, all transactions using GTSs shall be done before the time of the next GTS or the end of the CFP.

3 Bit Error Rate Evaluation of IEEE 802.15.4 under IEEE 802.11b

The PHY of the IEEE 802.15.4 at 2.4 GHz uses offset quadrature phase shift keying (OQPSK) modulation with half-sine pulse shaping, which is equivalent to MSK[9]. Denote the E_b/N_o be the ratio of the average energy per information bit to the noise power spectral density at the receiver input, assuming an additive white Gaussian noise (AWGN) channel. Then the bit error rate (BER), P_B, can be expressed as

$$P_B = Q\left(\sqrt{\frac{2\gamma E_b}{N_o}}\right), \quad Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{u^2}{2}\right) du \tag{1}$$

where $\gamma \simeq 0.85$[9].

In this paper, the indoor propagation model is assumed, and then, the path loss between transmitter and receiver can be expressed as:

$$L_p(d) = \begin{cases} 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) & , \ d \le d_0 \\ 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 10n\log_{10}\frac{d}{d_0} & , \ d > d_0 \end{cases} \tag{2}$$

, where d and d_0 are the distance between the transmitter and receiver and length of line-of-sight (LOS), respectively, and λ is c/f_c, where c is the light velocity and f_c is the carrier frequency. Once the transmitter power is fixed like $P_{T,x}$, then the received power is obtained as $P_{R,x} = P_{T,x} \cdot 10^{-\frac{L_p(d)}{10}}$ where x is either IEEE 802.15.4 or IEEE 802.11b.

The bandwidth of the IEEE 802.11b is 22 MHz, which is much larger than that of the IEEE 802.15.4, 2 MHz. So the signal of the IEEE 802.11b, interferer, can be modeled as bandlimited AWGN to the IEEE 802.15.4 signal, user[10]. Then, the SINR can be determined by

$$SINR = \frac{P_c}{P_{N_o} + P_i} + ProcGain \tag{3}$$

where P_c, P_{N_o}, and P_i denote the power of the desired signal, the noise power, and interferer power, respectively. The $ProcGain$ is the spreading gain of IEEE 802.15.4. By replacing Eb/No in Eq. (1) with SINR in Eq. (3), the BER of the IEEE 802.15.4 under the IEEE 802.11b can be obtained.

Because the bandwidth of the IEEE 802.11b is 11 times that of the IEEE 802.15.4, in-band interference power of the interferer to the user is usually calculated as $P_{R,IEEE802.11b}/11$. However, the power spectral density of the IEEE 802.11b is not uniformly distributed across 22 MHz as illustrated in Figure 2 [11].

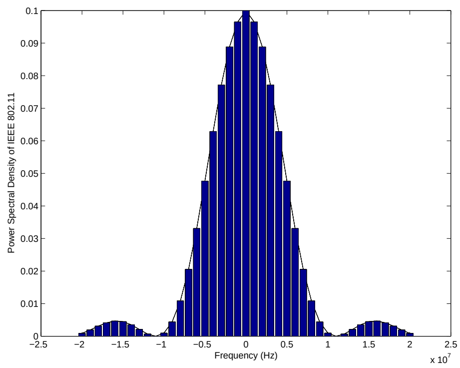

Fig. 2. Power Spectral Density of the IEEE 802.11b

Since the power is concentrated around the center frequency, the in-band power of the interferer to user is dependent on the frequency offset between the center frequencies of the user and interferer. For example, if the center frequency of the IEEE 802.15.4 is 2416 MHz and that of the IEEE 802.11b is 2418 MHz, then the center frequency offset is 2 MHz. In that case, the in-band interference power to user is about 17 % of the total power of the IEEE 802.11b.

4 Packet Error Rate Analysis of the IEEE 802.15.4 and the IEEE 802.11b

In this paper, IEEE 802.15.4 users are assumed to be transparent to IEEE 801.11b users, and vice versa. In other words, they transmit the packets without consideration of the channel state whether busy or not to make the worst case interference environments. If both standards use the carrier detection method (CCA mode 2) to determine the channel state rather than the energy detection (CCA mode 1), the transparency can be assumed without loss of generality.

Then, the interference model can be illustrated as shown in Figure 3. In Figure 3, T_X, L_X, and U_X denote the inter-arrival time, packet duration, and average random backoff time, respectively, where the subscript X is either Z for the IEEE 802.15.4 and W for the IEEE 802.11b. The other parameters are listed in Table 1. The T_C is the collision time.

Both the IEEE 802.11b and the IEEE 802.15.4 use carrier sense multiple access with collision avoidance (CSMA/CA) for medium access control. In the both

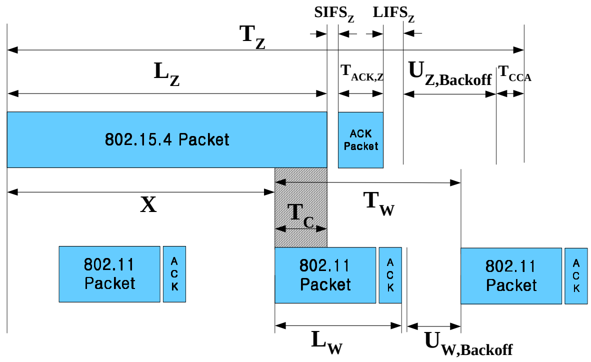

Fig. 3. Interference Model between IEEE 802.15.4 and IEEE 802.11b

protocols, nodes must perform a backoff process before transmitting a packet. However, in the IEEE 802.15.4, a channel is sensed only during the clear channel assessment (CCA) period, which occurs after finishing a backoff countdown. Accordingly, the backoff countdown occurs even during a busy channel period. The contention window of the IEEE 802.15.4 is doubled only when the channel is determined to be busy during the CCA period. On the other hand, the contention window size is reset even for a retransmission after a unsuccessful packet transmission.

Because of the transparency, the transmissions of the IEEE 802.15.4 and IEEE 802.11b are independent. Since the both protocols transmit packets without consideration of the channel state, the contention window is not changed by the busy channel. The transmission of the IEEE 802.11b packet can be assumed as error-free because the narrow band and low-power 802.15.4 signal is not bad enough to affect the transmission of the 802.11b packets. So, there is no increase of the contention window of the IEEE 802.11b. Therefore, in both protocols, the backoff time is randomly chosen within the minimum contention window, i.e, CW_{min}.

Then, the inter-arrival times, T_W, T_Z can be obtained as:

$$T_Z = L_Z + T_{CCA} + SIFS_Z + T_{ACK,Z} + U_Z \tag{4}$$

and

$$T_W = L_W + SIFS_W + T_{ACK,W} + DIFS + U_W \tag{5}$$

where T_{CCA} denote the CCA time of the IEEE 802.15.4 and $U_X = CW_{min,X}/2$.

Table 1. Parameters of the Interference Model

T_Z	inter-arrival time between two IEEE 802.15.4 packets
L_Z	duration of IEEE 802.15.4 packet
$SIFS_Z$	short IFS of IEEE 802.15.4
$LIFS_Z$	large IFS of IEEE 802.15.4
$T_{ACK,Z}$	duration of IEEE 802.15.4 ACK packet
U_Z	average backoff time of IEEE 802.15.4
T_W	inter-arrival time between two IEEE 802.11b packets
L_W	duration of IEEE 802.11b packet
$SIFS_W$	short IFS of IEEE 802.11b
$DIFS$	DCF IFS of IEEE 802.11b
$T_{ACK,W}$	duration of IEEE 802.11b ACK packet
U_W	average backoff time of IEEE 802.11b

Assume that the time offset x is assumed uniformly distributed in $[0, T_Z)$, then, the collision time, T_C can be obtained as :

$$T_C(x) = \begin{cases} L_Z - 2\left(T_W - L_W\right) - x + nT_W, \\ \quad if \quad nT_W \leq x \leq L_Z - 2T_W + nT_W \\ 2L_W\,, \\ \quad if \;\; L_Z - 2T_W + nT_W < x \leq T_W - L_W + nT_W \\ 3L_W - T_W + x - nT_W, \\ \quad if \;\; T_W - L_W + nT_W < x \leq L_Z - \left(T_W + L_W\right) + nT_W \\ L_Z - 2\left(T_W - L_W\right), \\ \quad if \;\; L_Z - \left(T_W + L_W\right) + nT_W < x \leq \min\left(T_W + nT_W, T_Z\right) \end{cases} \tag{6}$$

where $n = 0, 1, 2, 3, 4$.

Now, the packet error rate (PER) is easily obtained from the BER and the collision time, T_C. For simplicity, acknowledgement (ACK) packets of both IEEE 802.11 and IEEE 802.15.4 are not considered. Let's denote the P_B and P_B^I be the BER without and with interference, respectively. If the bit duration of the IEEE 802.15.4 is b, then the PER, P_P, is expressed as

$$P_P = 1 - \left(1 - \left(1 - P_B\right)^{L_Z - \lceil T_C/b \rceil}\right)\left(1 - \left(1 - P_B^I\right)^{\lceil T_C/b \rceil}\right). \tag{7}$$

5 Comparative Evaluation

For simulation, the slotted CSMA/CA of the IEEE 802.15.4 model is developed using OPNET. The complementary code keying (CCK) modulation with 11 Mbps is used for the IEEE 802.11b. The payload size of the IEEE 802.15.4 is 105 bytes, and that of the IEEE 802.11 is 1500 bytes. The length of LOS, d_0, is 8 m and the path loss exponent, i.e. n, is 3.3. The transmitter power of IEEE 802.15.4 is 1 mW and that of IEEE 802.11b is 30 mW. The simulation scenario is shown in Figure 4.

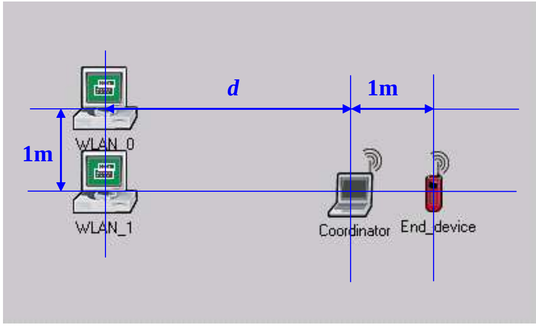

Fig. 4. Simulation Model between IEEE 802.15.4 and IEEE 802.11b

For simplicity, only the IEEE 802.15.4 End_device and IEEE 802.11b WLAN_1 transmit data packets. The other nodes send only the ACK packets for the corresponding data packets. The distance between two IEEE 802.15.4 devices and that of the two IEEE 802.11b devices are fixed to 1 m. The distance between IEEE 802.15.4 Coordinator and the IEEE 802.11b WLAN_1 is d, which is variable.

Figure 5 shows the PER of the IEEE 802.15.4 under the interference of the IEEE 802.11b with 0 frequency offset. The distance between Coordinator and WLAN_1, d, varies from 1m to 10m.

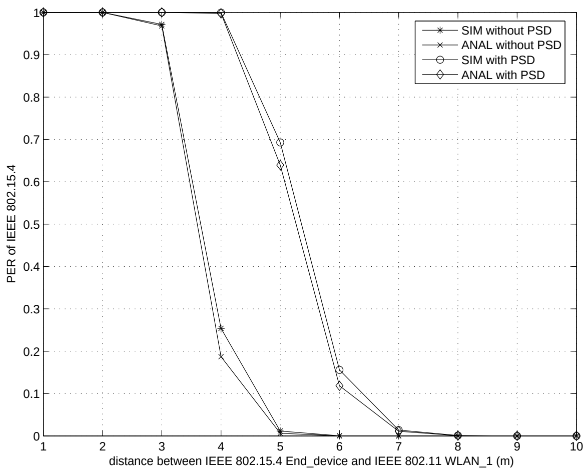

Fig. 5. PER of the IEEE 802.15.4 with/without considering the power spectral density of the IEEE 802.11b

In Figure 5, the "without PSD" term means that the in-band interference power is calculated as $P_{R,IEEE802.11b}/11$ where $P_{R,IEEE802.11b}$ is the received signal power of the IEEE 802.11b. On the other hand, the "with PSD" term means that the in-band interference power is obtained from the power spectral density of the IEEE 802.11b. Since the power of the IEEE 802.11b is concentrated at the center frequency as shown in Figure 2, the in-band interference power with 0 frequency offset is larger than $P_{R,IEEE802.11b}/11$. Therefore, the PER of the "with PSD" is larger than that of the "without PSD". Note that when the distance between the IEEE 802.15.4 Coordinator and IEEE 802.11b WLAN_1 is longer than 8m, the packet error rate of the IEEE 802.15.4 is smaller than 10^{-6} in both simulations.

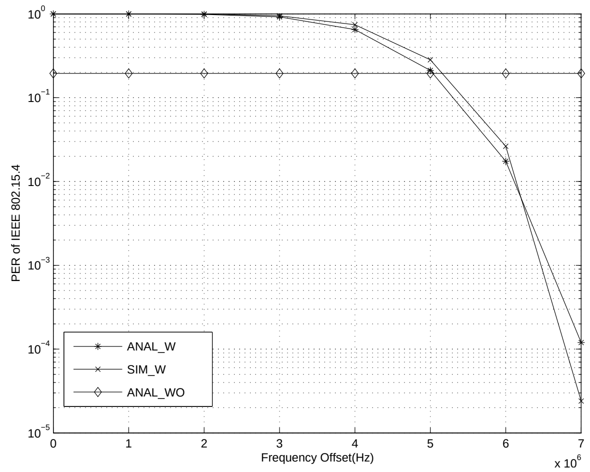

Fig. 6. PER of the IEEE 802.15.4 with the different frequency offsets to the IEEE 802.11b when d is fixed to 4m

In Figure 6, the in-band power of the IEEE 802.11b for the IEEE 802.15.4 varies with the center frequency offset between the IEEE 802.11b and IEEE 802.15.4. Since the SINR varies according to the in-band interference power, the PER varies as illustrated. If the in-band power is uniformly distributed as $P_{R,IEEE802.11b}/11$, the PER is obtained as a horizontal line, i.e, ANAL_WO, in the figure, which means that the PER is independent to the frequency offset. Note that if the frequency offset is larger than the 7 MHz, the interference of the IEEE 802.11b does not affect the PER of the IEEE 802.15.4.

6 conclusion

In this paper, the packet error rate (PER) of IEEE 802.15.4 under the interference of IEEE 802.11b is analyzed. The PER is obtained from the bit error rate (BER) and the collision time. The BER of IEEE 802.15.4 is obtained from the offset quadrature phase shift keying (OQPSK) modulation. The collision time is calculated under assumption that the packet transmissions of the IEEE 802.15.4 and the IEEE 802.11b are independent. Because the bandwidth of IEEE 802.11b is larger than that of IEEE 802.15.4, the in band interference power of IEEE 802.11b is considered as the additive white gaussian noise (AWGN) for the IEEE 802.15.4. For an accurate calculation, the in-band interference power ratio of the IEEE 802.11b is considered with different frequency offsets between IEEE 802.15.4 and 802.11b. To obtain the ratio, the power spectral density of the IEEE 802.11b is considered. The simulation results are shown to prove the analysis.

If the distance between the IEEE 802.15.4 and 802.11b is longer than 8 m, the interference of the IEEE 802.11b is almost negligible to the performance of the IEEE 802.15.4, i.e., the packet error rate is smaller than 10^{-6}. If the frequency offset is larger than 7 MHz, the interference effect of the IEEE 802.11b is negligible to the performance of the IEEE 802.15.4. Therefore, three additional channels of the IEEE 802.15.4 such as 2420 MHz, 2445 MHz, and 2470 MHz can be used for the coexistence channels under the interference of the IEEE 802.11b.

The result of this paper can suggest the coexistence criteria for the IEEE 802.15.4 and IEEE 802.11b and be useful for designing and implementing networks using both IEEE 802.15.4 and IEEE 802.11b.

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