On the Impact of Channel Sensing Methods to IEEE 802.15.4 Performances under IEEE 802.11b Interference

Soo Young Shin and Hong Seong Park

Abstract: **In this paper, the impact of channel sensing methods to IEEE 802.15.4 under the interference of IEEE 802.11b are analyzed. Two different channel sensing methods, energy detection and carrier sense, are considered. An average transmission delay, a throughput, and a power drain rate are used as performance measures. Those performance measures of IEEE 802.15.4 under the interference of IEEE 802.11b are analyzed mathematically. The simulation results are shown to validate the analytic results.**

Index Terms: **Analysis, carrier sense, channel sensing methods, energy detection, IEEE 802.11b, IEEE 802.15.4, interference, performance.**

I. INTRODUCTION

IEEE 802.15.4, a low rate wireless personal area network, has been standardized recently [1], [2]. To provide the global availability, IEEE 802.15.4 exploits the 2.4 GHz industrial scientific and medical (ISM) unlicensed band.

Because this ISM band is commonly used for the low cost radio devices such as IEEE 802.11b [3], an unrestricted access to the ISM band exposes the IEEE 802.15.4 devices to a high level of interference. Since the IEEE 802.11b has been designed for the different purposes, they can coexist within the communication range of each other. Because the IEEE 802.11b was standardized earlier and applied already, the newly deployed IEEE 802.15.4 devices can experience the interference from the IEEE 802.11b. Therefore, the performances of the IEEE 802.15.4 under the interference of the IEEE 802.11b need to be evaluated.

Like IEEE 802.11b, IEEE 802.15.4 adopts carrier sensing multiple access as its medium access control method. There are two core methods of channel sensing—notably energy detection (ED) and carrier sense (CS)—that are collectively known by the general term: Clear channel assessment (CCA). Although the default CCA of IEEE 802.11b is CS mode [4], ED mode is adopted as the default for limited battery devices such as IEEE 802.11b card in laptop [5]. Because IEEE 802.15.4 aims the low power consumption, the power consumption characteristics of both ED and CS methods are needed to be evaluated. Therefore, this paper focuses on the impact of CCA methods to the performances of IEEE 802.15.4 under IEEE 802.11b interference.

Some related papers investigate the performance of IEEE 802.15.4 under IEEE 802.11b interference [6]–[9]. In [6] and [7], PER, end-to-end delay, and throughput of IEEE 802.15.4 under the interference of IEEE 802.11b are analyzed using mathematical modeling and validated via simulations with varying the distance and mean frequency of IEEE 802.11b. However, it only considered CS method. In [8], the performance of the IEEE 802.15.4 under the interference of IEEE 802.11b is evaluated using simulation only. Along with PER, MAC delay and goodput were also obtained using two different CCA methods under different application scenarios such as FTP, HTTP, and e-mail. However, there were no considerations about the distance and mean frequency of IEEE 802.11b. In [9], the packet error rates (PERs) of the IEEE 802.15.4 under IEEE 802.11b, Bluetooth, and microwave oven are obtained by experiments. PERs under IEEE 802.11b interference were examined with varying the mean frequency of IEEE 802.11b, the packet length of IEEE 802.15.4, distance and two channel sensing methods. However, there were no comparisons in the performances of IEEE 802.15.4 when two different CCA methods, ED and CS, were applied. In addition, there were no considerations about IEEE 802.15.4 power consumptions.

In this paper, the performances of IEEE 802.15.4 under IEEE 802.11b interference are analyzed and compared under two different CCA methods: CS and ED. For each channel sensing method, the average transmission delay, the throughput, and the power drain rate are analyzed as performance measures. The average transmission delay is defined as the elapsed time from the time for a source station to access a channel to the time to receive an acknowledgement packet transmitted by a destination station. The average transmission delay is extracted from the PER and the packet transmission/retransmission time. The throughput is the amount of data transferred from one station to another station during a specified amount of time. The power drain rate is defined as the power consumption per second. The obtained analytic results are compared with the simulation results.

The paper is organized as follows. There is a brief overview of IEEE 802.15.4 in Section II. Section III explains the coexistence problem of IEEE 802.11b and IEEE 802.15.4. In Section IV, performance measures such as average transmission delay, throughput, and power drain rate are analyzed with two different CCA methods ED and CS. Analytic results obtained in Section IV are compared to simulation results in Section V. This paper will be concluded in Section VI.

II. 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

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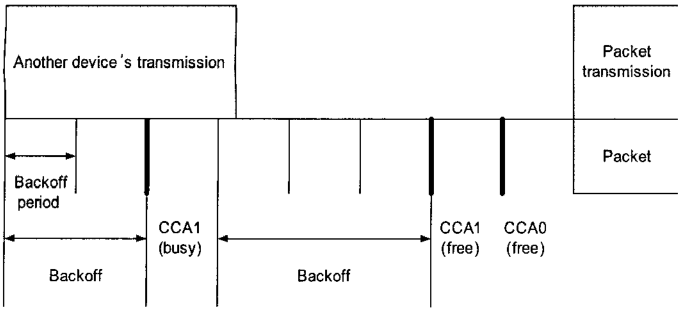

Fig. 1. An example of slotted CSMA/CA in IEEE 802.15.4.

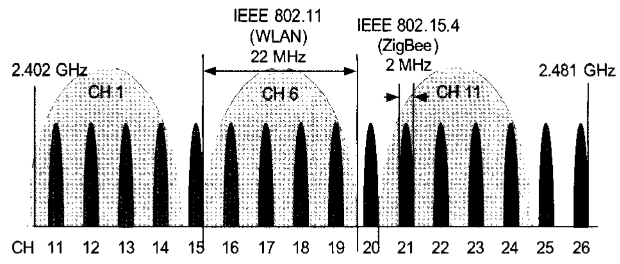

Fig. 2. Bandwidth allocation of IEEE 802.11b and IEEE 802.15.4 at 2.4 GHz ISM band.

power and typically operate in the personal operating space (POS). Two types of topologies are supported in the IEEE 802.15.4: A one-hop star or a multi-hop peer-to-peer topology. The network and upper layers were defined by the ZigBee Alliance [2].

The standard offers two PHY options based on the frequency band. Both are based on direct sequence spread spectrum (DSSS). The data rate is 250 kbps at 2.4 GHz with offset quadrature phase shift keying (OQPSK), 40 kbps at 915 MHz and 20 kbps at 868 MHz with binary phase shift keying (BPSK). There is a single channel between 868 and 868.6 MHz, 10 channels between 902.0 and 928.0 MHz, and 16 channels between 2.4 and 2.4835 GHz. Receiver sensitivities are -85 dBm for 2.4 GHz and -92 dBm for $868/915$ MHz.

An IEEE 802.15.4 system consists of several components. The most basic is the device. A device can be a full-function device (FFD) or reduced-function device (RFD). A network shall include at least one FFD, operating as the PAN coordinator. The FFD can operate in three modes: A personal area network (PAN) coordinator, a coordinator or a device. An RFD is intended for applications that are extremely simple and do not need to send large amounts of data.

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.

IEEE 802.15.4 adopts carrier sense multiple access with collision avoidance (CSMA/CA) for the medium access mechanism (MAC). There are also two medium access control mechanisms, unslotted and slotted version, however, the slotted CSMA/CA is focused on in this paper. Fig. 1 shows an example of packet transmission with slotted CSMA/CA in IEEE 802.15.4.

If an IEEE 802.15.4 station has data to send, it performs random backoff. The backoff window is based on a random value uniformly distributed in the interval $[CW_{\min}, CW_{\max}]$, where $CW_{\min}$ and $CW_{\max}$ represent the contention window parameters. After finishing the backoff, the IEEE 802.15.4 station checks the medium using clear channel assessment (CCA) period. If the medium is sensed idle, it sends its packet. Upon the successful reception of a packet, the destination station returns an ACK packet after a turn-around-time. If the medium is determined busy during CCA period, it doubles the backoff window size and repeat the basic access procedures.

III. COEXISTENCE OF IEEE 802.11B AND IEEE 802.15.4

The IEEE 802.15.4 defines two physical layers such as 868/915 MHz and 2.4 GHz. Especially, the unlicensed industrial scientific medical (ISM) 2.4 GHz band is available worldwide and adopted by IEEE 802.11b. In this paper, only 2.4 GHz band is focused on.

When an IEEE 802.15.4 network is collocated with an IEEE 802.11b network, devices of one network can experience an inteference power from the transmissions of the other network and vice versa. This mutual interference degrades the performance of both IEEE 802.11b and IEEE 802.15.4 network.

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 Fig. 2. IEEE 802.11b generally uses three channels such as channel 1, 6, and 11. To prevent interference between IEEE 802.15.4 and IEEE 802.11b, IEEE 802.15.4 standard recommends using two IEEE 802.15.4 channels falling in the guard bands between the two IEEE 802.11b channels (channel 15, 20) or two IEEE 802.15.4 channels above of the IEEE 802.11b channel 11 (channel 25, 26) [1]. However, if there are more IEEE 802.15.4 networks, these four channels are not enough. Hence, the IEEE 802.15.4 network can experience interferences from the IEEE 802.11b and vice versa.

In this paper, the following two assumptions are made for the IEEE 802.11b.

- Assumption 1 : The packet transmissions of the IEEE 802.11b are assumed to be error-free.
- Assumption 2 : The IEEE 802.11b is assumed to be in carrier sense mode to determine the channel state.

Because the IEEE 802.15.4 signal is relatively narrow band and low-power compared to that of the IEEE 802.11b, it can be assumed not to be strong enough to corrupt the IEEE 802.11b transmissions.[1] Usually, the default clear channel assessment (CCA) of IEEE 802.11b is carrier sense (CS) which reports that the channel is busy upon detection of a DSSS signal [4]. Therefore, assumptions 1 and 2 can be made without loss of generality. Then, the backoff time of the IEEE 802.11b is assumed to be uniformly distributed within 0 and $(2^{CW_{\min}} - 1)$, where the $CW_{\min}$ is the minimum contention window of the IEEE 802.11b, 32.

[1]It is shown in [10] that the interference of an IEEE 802.15.4 network to an IEEE 802.11b network is ignorable when the distance between two IEEE 802.11b nodes, i.e., $d(W0, W1)$, is smaller than 3 m even in the case of $d = 0$ m.

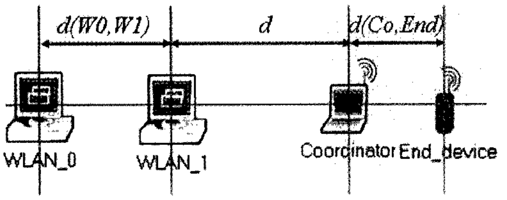

Fig. 3. Interference model among IEEE 802.11b and IEEE 802.15.4.

Fig. 3 shows a coexistence model, where IEEE 802.11b and IEEE 802.15.4 can interfere with each other.

Each network consists of two nodes. WLAN_0 and WLAN_1 form a WLAN network with $d(W0, W1)$ apart. WLAN_1 transmits IEEE 802.11b data packets to WLAN_0 and WLAN_0 responds with ACK packets. An IEEE 802.15.4 network consists of Coordinator and End_device with $d(Co, End)$ apart. End_device transmits IEEE 802.15.4 packets to coordinator, and coordinator may respond with ACK packets. A distance between the IEEE 802.15.4 and the WLAN network is a variable, d.

Table 1. Parameters of the interference model.

T_Z	average inter-packet time	7208 μs
L_Z	duration of 802.15.4 packet	4128 μs
t_{TA}	turn-around time	$(192, 512)$ μs
T_{CCA}	CCA time	640 μs
$T_{ACK,Z}$	duration of a ZigBee ACK packet	352 μs
$t_{ackwait}$	maximum wait duration for a ZigBee ACK packet	864 μs
B_Z	average backoff time of 802.15.4	1120 μs
U_Z	unit backoff time of 802.15.4	20 μs
T_W	average inter-packet time	varying
L_W	duration of 802.11b packet	1303 μs
t_{SIFS}	short IFS of 802.11b	10 μs
t_{DIFS}	DCF IFS of 802.11b	50 μs
$T_{ACK,W}$	duration of 802.11b ACK packet	304 μs
B_W	average backoff time of 802.11b	310 μs
U_W	slot time of IEEE 802.11b time	20 μs

IV. AVERAGE TRANSMISSION DELAY, THROUGHPUT, AND POWER DRAIN RATE ANALYSIS OF IEEE 802.15.4 UNDER IEEE 802.11B INTERFERENCE

IEEE 802.15.4 defines three mechanisms for the CCA.

- CCA mode 1: Energy above threshold. CCA shall report a busy medium upon detecting any energy above the ED threshold. The ED threshold shall be at most 10 dB above the specified receiver sensitivity.
- CCA mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. This signal may be above or below the ED threshold.
- CCA mode 3: Combination of CCA mode 1 and 2.

In a slotted CSMA-CA, the CCA shall start on a backoff period boundary and performs twice, i.e., CCA1 and CCA0. In this paper, the CCA mode 1, energy detection (ED), and mode 2, carrier sense (CS), are focused on. Note that the receiver sensitivity of the IEEE 802.15.4 is −85 dBm at 2.4 GHz. The packet error rate (PER), P_E, of the IEEE 802.15.4 under the interference of the IEEE 802.11b is already obtained in [6], [7]. The parameters of the IEEE 802.11b and 802.15.4 are listed in Table 1.

A. Performance Analysis of IEEE 802.15.4 Carrier Sense Mode

In the case of the CCA mode 2 of IEEE 802.15.4, i.e., CS, the IEEE 802.15.4 signal is hidden to that of the IEEE 802.11b signal and vice versa because both protocols use different carrier and modulation. Accordingly, the transmissions of the IEEE 802.15.4 and IEEE 802.11b are independent and the backoff exponent (BE) of the IEEE 802.15.4 is not changed by the CCA procedure. Therefore, the backoff size of the IEEE 802.15.4 will be chosen within 0 and $2^{BE} - 1$ where $BE = 3$.

Then, the probability of successful packet transmission using the $(i-1)$th retransmission can be expressed as $P_E^{(i-1)}(1 - P_E)$. In this paper, the number of retransmissions is assumed to be infinity for the analytic simplicity. For the successful packet transmission, End_device must perform a random backoff, a two consecutive CCA, transmit the desired packet, and wait the ACK packet, which takes t_s. Otherwise, End_device has to retransmit the desired packet after the random backoff time plus the CCA time, which takes t_f

$$\begin{aligned} t_f &= L_Z + t_{ackwait} + B_Z + 2U_Z, \\ t_s &= L_Z + t_{TA} + T_{ACK} + B_Z + 2U_Z. \end{aligned} \tag{1}$$

Then, the average packet transmission delay of the IEEE 802.15.4 is obtained as

$$E\left[T_{avg,\mathrm{CS}}\right] = t_f \sum_{i=0}^{\infty} i P_Z^i \left(1 - P_E\right) + t_s. \tag{2}$$

Denote P_{t_f} and P_{t_s} be the average power consumption for t_f and t_s time duratioin. Then, P_{t_f} and P_{t_s} can be expressed as

$$\begin{aligned} P_{t_f} &= B_Z P_i + E_{ir} + 2U_Z P_{rx} + L_Z P_{tx} \\ &\quad + t_{ackwait} P_{rx} \\ P_{t_s} &= B_Z P_i + E_{ir} + 2U_Z P_{rx} + L_Z P_{tx} \\ &\quad + \left(t_{TA} + t_{ACK,Z}\right) P_{rx} \end{aligned} \tag{3}$$

where P_i, P_{rx}, and, P_{tx}, are the power consumption in idle, receive, transmit state, respectively. The E_{ir} is the power consumption for the transition from idle to receive state. The power consumption for one successful packet transmission in CS can be expressed as

$$E[P_{\mathrm{CS}}] = \frac{P_{t_f}}{1 - P_E} + P_{t_s}. \tag{4}$$

Then, the power drain rate, $E[D_{\mathrm{CS}}]$, is defined as

$$E[D_{\mathrm{CS}}] = \frac{E\left[P_{\mathrm{CS}}\right]}{E\left[T_{avg,\mathrm{CS}}\right]}. \tag{5}$$

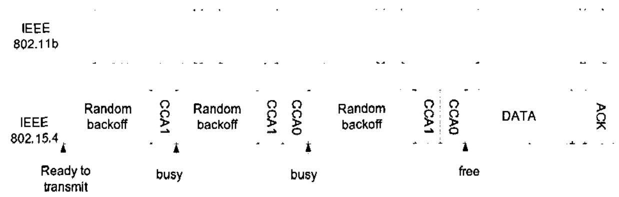

Fig. 4. Packet transmission of IEEE 802.15.4 under IEEE 802.11b interference.

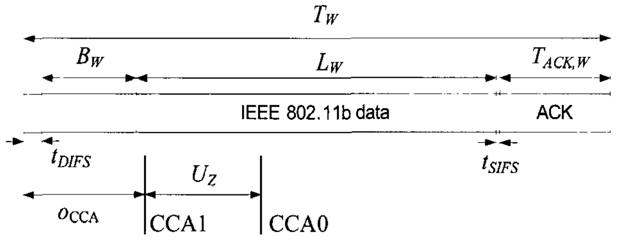

Fig. 5. Timing diagram between IEEE 802.11b packet and the CCA of the IEEE 802.15.4.

Another measure of performance of the IEEE 802.15.4, a throughput, can be obtained easily from the average transmission delay. The throughput of the IEEE 802.15.4, ρ, is defined as the total size of packets received during a specified time at the Coordinator of IEEE 802.15.4. Therefore, the throughput, $\rho_{\rm CS}$ can be expressed as

$$\rho_{\rm CS} = \frac{L_Z/b}{E[T_{avg,\rm CS}]} \tag{6}$$

where b is the bit duration of the IEEE 802.15.4.

B. Performance Analysis of IEEE 802.15.4 Energy Detection Mode

In the case of the CCA mode 1 of IEEE 802.15.4, i.e., ED, an IEEE 802.15.4 device determines the channel to be busy when it hear an IEEE 802.11 packet transmission. When the channel is busy, the IEEE 802.15.4 device will repeat a random backoff and CCA until the channel is free as shown in Fig. 4.

Fig. 5 illustrates the detailed CCA procedure under the IEEE 802.11b packet transmissions where $B_W = iU_W$ is backoff size of the IEEE 802.11b and $i = 0, 1, \cdots, 31$. For simple analysis, the decision by each CCA is assumed to be performed instantly while it takes eight IEEE 802.15.4 symbol time.

Note that the BE of the IEEE 802.15.4 is increased by one only when the channel is determined to be busy during the CCA procedures. In slotted CSMA/CA of the IEEE 802.15.4, the channel is sensed twice. Hence, a busy channel probability consists of two components. One is a busy probability of the first CCA (CCA1), $p_{\rm CCA1}$, and the other is a busy probability that the CCA1 determines free and the second CCA (CCA0) determines busy, $p_{\rm CCA0}$.

Assume that the time offset, $o_{\rm CCA}$, is distributed uniformly from 0 to T_W and $B_W = iU_W$, where $i = 0, 1, \cdots, 31$. Then, $p_{\rm CCA1}$ can be expressed as (7)

$$p_{\rm CCA1}(i) = \frac{L_W + T_{ACK,W}}{T_W} \tag{7}$$

which means the first CCA, CCA1, will be performed while the packets (both data and ACK) of IEEE 802.11b is transmitted. If sum of t_{DIFS} and $B_W (= iU_W)$ is smaller than U_Z, the CCA0 always determines the channel is busy even when CCA1 says the channel is free. In other words, if CCA1 is performed between 0 to $t_{DIFS} + iU_W$, the channel will be detected as busy by CCA0. For $t_{DIFS} + B_W > U_Z$, only when the CCA1 is performed less than U_Z before the transmission of IEEE 802.11b data packet, the channel is determined as busy by CCA0. Therefore, $p_{\rm CCA0}$ can be obtained as

$$p_{\rm CCA0}(i) = \begin{cases} \frac{t_{DIFS} + iU_W}{T_W}, & i \le \frac{U_Z - t_{DIFS}}{U_W}, \\ \frac{U_Z}{T_W}, & i > \frac{U_Z - t_{DIFS}}{U_W}. \end{cases} \tag{8}$$

From (7) and (8), the probability that the channel is busy, P_B, can be calculated as (9).

$$P_B = \frac{\sum_{i=0}^{CW_{\min}-1} (p_{\rm CCA1}(i) + p_{\rm CCA0}(i))}{CW_{\min}}. \tag{9}$$

According to the P_B, the BE can be changed like Fig. 6.

By simple manipulation, the steady-state probability of each BE, π_{BE}, can be obtained.

$$\begin{aligned} \pi_3 &= 1 - P_B, \\ \pi_4 &= (1 - P_B)P_B, \\ \pi_5 &= P_B^2. \end{aligned} \tag{10}$$

Then, an average backoff time, $E[T_{\rm BO}]$, is easily calculated as

$$E[T_{\rm BO}] = U_Z \left(\sum_{\rm BE=3}^{5} \pi_{\rm BE} B_Z(\rm BE) \right) \tag{11}$$

where $B_Z(BE) = (2^{BE} - 1)/2$. The time required to perform a CCA per one backoff is dependent on $p_{\rm CCA1}$ and $p_{\rm CCA0}$ and can be expressed as (12).

$$E[T_{CCA}] = U_Z p_{\rm CCA1} + 2U_Z p_{\rm CCA0}. \tag{12}$$

Now, the time required for an IEEE 802.15.4 device to find free channel, $E[T_{free}]$, can be expressed as

$$E[T_{free}] = \sum_{j=0}^{\infty} jT_{busy}P_B^j(1 - P_B) + 2U_Z \tag{13}$$

where $T_{busy} = E[T_{\rm BO}] + E[T_{\rm CCA}]$. The first term represents that the channel is detected as free after jth channel sensing and $2U_Z$ represents the time duration for both CCA1 and CCA0 when the channel is free.

However, if an IEEE 802.15.4 device succeeds to transmit a packet, the packet can be lost with P_E due to the IEEE 802.11b interference. When the packet is lost, it will be retransmitted. For the successful packet transmission, an IEEE 802.15.4 device must perform a random back-off, a two consecutive CCA to find free channel, and then transmit a desired packet, and receive an ACK packet, i.e., T_S. Once the packet is transmitted, it waits an ACK packet during $t_{ackwait}$. If the ACK is not received during $t_{ackwait}$, it has to retransmit the desired packet by repeating the random back-off and the CCA, i.e., T_F.

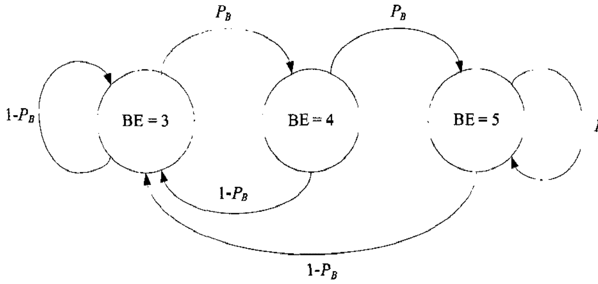

Fig. 6. State transition diagram of BE in IEEE 802.15.4.

$$\begin{aligned} T_F &= E\left[T_{free}\right] + L_Z + t_{ackwait}, \\ T_S &= E\left[T_{free}\right] + L_Z + t_{TA} + t_{ACK,Z}. \end{aligned} \tag{14}$$

Therefore, the average transmission delay of IEEE 802.15.4 with ED can be obtained as

$$E[T_{avg,ED}] = \sum_{k=0}^{\infty} kT_F P_E^k (1 - P_E) + T_S. \tag{15}$$

Denote P_{T_F} and P_{T_S} be the average power consumption for T_F and T_S time duration. Then, P_{T_F} and P_{T_S} can be expressed as

$$\begin{aligned} P_{T_F} &= P_{T_{free}} + L_Z P_{tx} + t_{ackwait} P_{rx}, \\ P_{T_S} &= P_{T_{free}} + L_Z P_{tx} + (t_{TA} + t_{ACK,Z}) P_{rx} \end{aligned} \tag{16}$$

where $P_{T_{free}}$ is the power consumption until the channel is determined to be free and expressed as

$$\begin{aligned} P_{T_{free}} = &\tfrac{P_B}{1-P_B} \left(E\left[T_{\text{BO}}\right] P_i + E_{ir} + E\left[T_{\text{CCA}}\right] P_{rx}\right) \\ &+ E\left[T_{\text{BO}}\right] P_i + E_{ir} + 2U_Z P_{rx}. \end{aligned}$$

The power consumption for one successful packet transmission in ED can be expressed as

$$E[P_{\text{ED}}] = \frac{P_{T_F}}{1 - P_E} + P_{T_S}. \tag{17}$$

Then, the power drain rate, $E[D_{\text{ED}}]$, is defined as

$$E[D_{\text{ED}}] = \frac{E\left[P_{\text{ED}}\right]}{E\left[T_{avg,\text{ED}}\right]}. \tag{18}$$

The throughput, ρ_{ED}, can be obtained easily from the average transmission delay. The ρ_{ED} can be expressed as

$$\rho_{\text{ED}} = \frac{L_Z/b}{E[T_{avg,\text{ED}}]} \tag{19}$$

where b is the bit duration of the IEEE 802.15.4.

V. COMPARISONS

For simulation, the slotted CSMA/CA of the IEEE 802.15.4 model is developed using OPNET. IEEE 802.11b uses the complementary code keying (CCK) modulation with 11 Mbps. For the signal propagation, indoor propagation model is used in [8]. The length of line-of-sight, d_0, is set to 8 m and the path loss exponent, i.e., n, is set to 3.3. The payload sizes of IEEE 802.11b and 802.15.4 are 1500 and 102 bytes long, respectively. The transmission power of the IEEE 802.15.4 and 802.11b are 1 and 30 mW, respectively. The center frequency of IEEE 802.15.4 and 802.11b are 2410 and 2412 MHz, respectively.

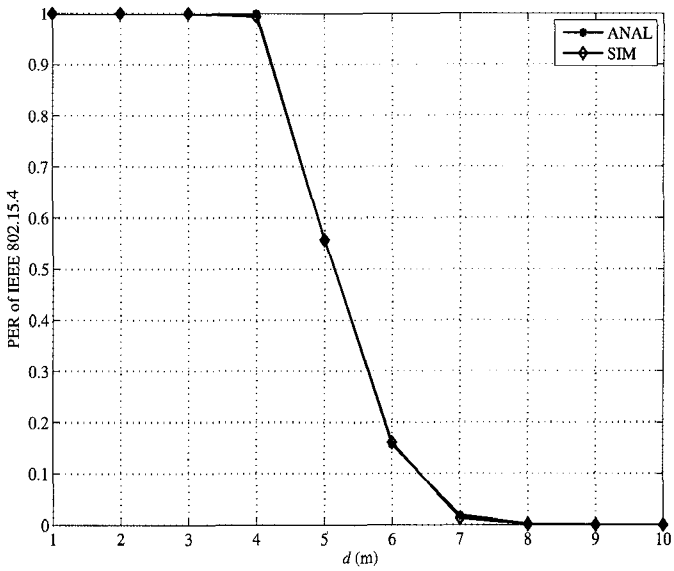

Fig. 7. PER of the IEEE 802.15.4 with/without considering IEEE 802.11b power spectral density with 2 MHz offset, $\lambda_W = 0.0001$ s.

The default ED threshold of IEEE 802.15.4, Γ_{ED}, is set to -85 dBm. For the worst case interference analysis, both IEEE 802.15.4 and IEEE 802.11b are assumed as saturated conditions. Hence, the packet inter arrival times of IEEE 802.15.4 and IEEE 802.11b has exponential distribution with mean values of $\lambda_Z = 0.001$ s and $\lambda_W = 0.0001$, respectively. The parameters of IEEE 802.15.4 radio were obtained from [11], which has idle, transmit and receive states with respective power consumptions of $P_i = 712$ μW, $P_{tx} = 31.32$ mW, and $P_{rx} = 35.28$ mW. E_{ir} is set to 6.63×10^{-6} J.

Fig. 7 shows the PER of the IEEE 802.15.4 under the interference of the IEEE 802.11b using CS mode. The $d(W0, W1)$, $d(Co, End)$ are set to 1 m, respectively. The variable, d, varies from 1 m to 10 m. In Fig. 7, the PER obtained by analytic method based on [6] and [7], ANAL, were validated by simulation, SIM.

Note that the PER of the ED mode is identical to that of the CS mode because a packet will experience the same interference from the IEEE 802.11b signals regardless of the channel sensing methods.

Fig. 8 shows the average transmission delays, $E[T_{avg}]$, of the IEEE 802.15.4 under IEEE 802.11b interference. For analysis, $\lambda_W = 0.00001$ s is used for the worst case interference scenario while 0.0001 s and 0.01 s are also used for the simulations. The average transmission delays of the IEEE 802.15.4 with the ED mode are larger than those with the CS mode because the transmissions of IEEE 802.15.4 will be deferred due to the IEEE 802.11b interference in the ED mode. Therefore, with $\lambda_W = 0.00001$ s, the average transmission delay with the ED mode is at least 11 times larger than that with the CS mode. Note that $E[T_{avg,\text{ED}}]$ with $\lambda_W = 0.01$ s is close to $E[T_{avg,\text{CS}}]$. This is because the interference of IEEE 802.11b is relatively

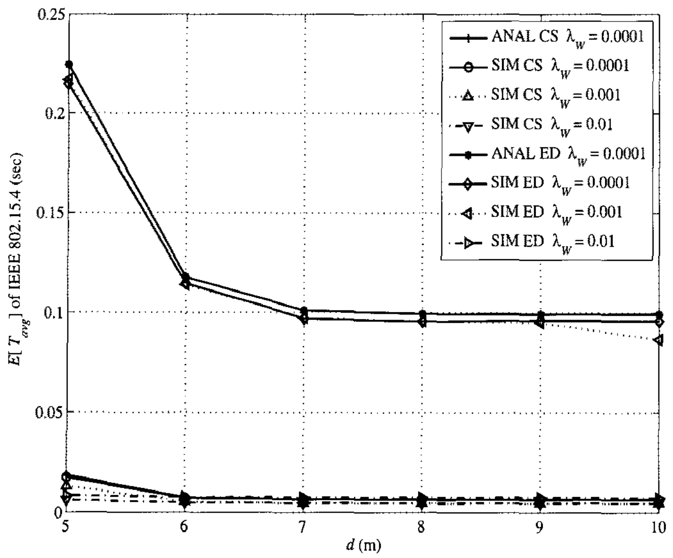

Fig. 8. Average transmission delay of the IEEE 802.15.4 under IEEE 802.11b interference with 2 MHz offset.

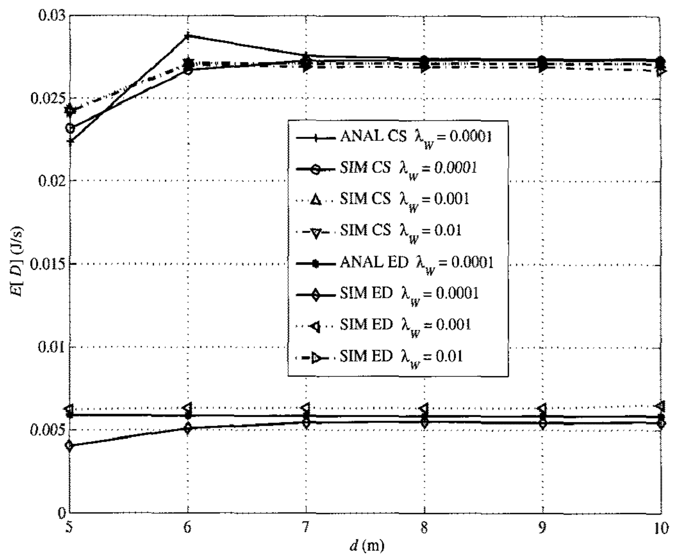

Fig. 10. Power drain rate of the IEEE 802.15.4 under IEEE 802.11b interference with 2 MHz offset.

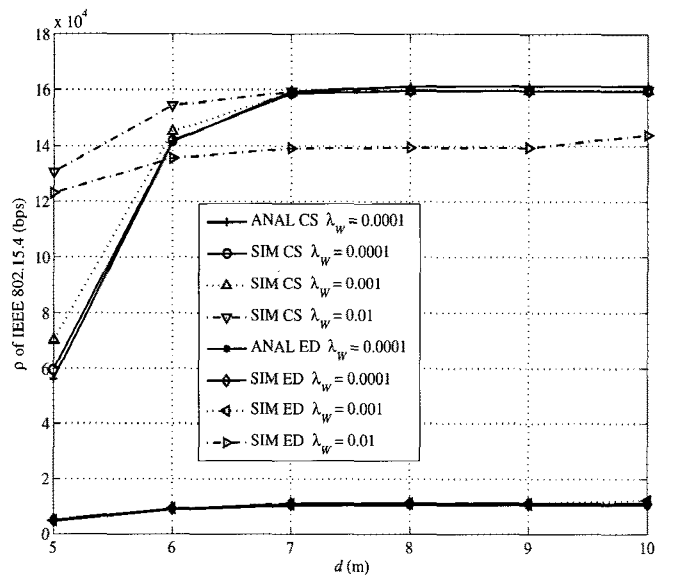

Fig. 9. Throughput of the IEEE 802.15.4 under IEEE 802.11b interference with 2 MHz offset.

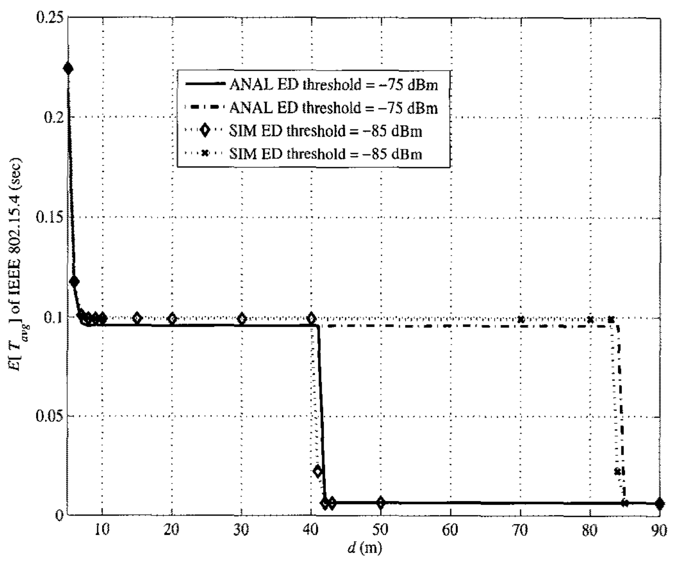

Fig. 11. Effect of ED threshold to average transmission delay of the IEEE 802.15.4 under IEEE 802.11b interference with 2 MHz offset.

small compared to the other smaller λ_W values.

Fig. 9 shows the throughput, ρ, of the IEEE 802.15.4 under IEEE 802.11b interference. For saturated IEEE 802.11b interference, as illustrated in both Figs. 8 and 9, if the d is larger than 7 m, the $E[T_{avg}]$ and ρ are almost constant. That means if the d is larger than 7 m, the PER is nearly ignorable. By the way, as λ_W increases, in other words, the utilization of IEEE 802.11b is low, ρ of both ED and CS modes increase because IEEE 802.11b interference decreases. Especially, for $\lambda_W = 0.01$, $\rho_{\rm ED}$ approaches to about 140 kbps. However, it is still smaller than $\rho_{\rm CS}$ due to the unwanted back-offs by the interference of IEEE 802.11b.

Fig. 10 shows the power drain rates, $E[D]$, of the IEEE 802.15.4 under IEEE 802.11b interference. Using the CS mode, IEEE 802.15.4 End_device tries to access channel more greedy manner. So, the power drain rate of the CS mode is at least 5 times that of the ED mode with $\lambda_W = 0.0001$ s. For example with $d = 8$ m, using the ED mode, the network life time of an IEEE 802.15.4 network could be extended about 4.7 times longer than that of the CS mode. As λ_W increases, End_device increases the number of transmission attempts because the channel will be detected as free and as a result, $E[D_{\rm ED}]$ increases.

Therefore, CS could be an appropriate CCA method to maintain a certain throughput under the interference of IEEE 802.11b. For low battery devices designed for low throughput (less than 10 kbps even for the worst case interference of IEEE 802.11b) and non time-critical application, ED could be the best choice, which will extend the network life time up to about 5 times.

Figs. 11 and 12 show the effect of ED threshold to the average transmission delay and the throughput in IEEE 802.15.4 under IEEE 802.15.4 interference. Two different ED threshold values are used such as −85 dBm (minimum) and −75 dBm (maximum). Large ED threshold means that the possibility to detect the interference of IEEE 802.11b is small. With −75 dBm threshold, IEEE 802.15.4 End_device tends to decide that the channel is much more free compared to −85 dBm even though there are interferences from IEEE 802.11b. Therefore, when d is larger than about 42 m, the interference of IEEE 802.11b could be ignored by IEEE 802.15.4 with −75 dBm ED threshold setting. Due to free channel decided by IEEE 802.15.4 End_device, the packet transmissions occur more frequently, which results into sharp decrease of average transmission delay as Fig. 11 and sharp increase of throughput as Fig. 12 near $d = 42$ m. For −85 dBm Ed threshold setting, the same phenomenona happen when $d = 84$ m.

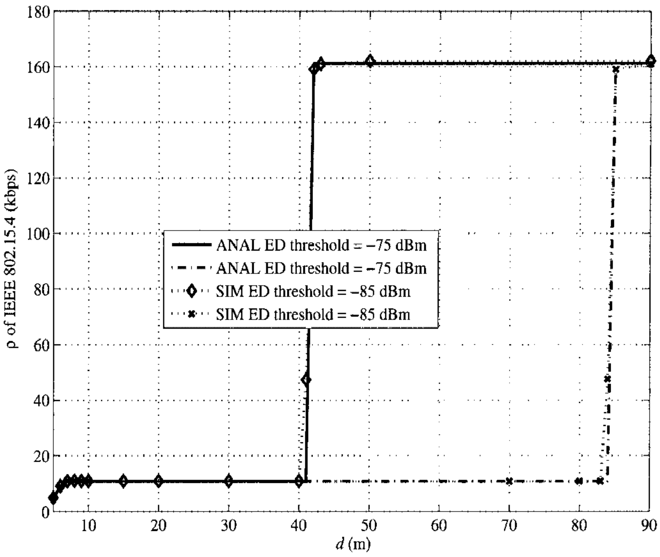

Fig. 12. Effect of ED threshold to throughput of the IEEE 802.15.4 under IEEE 802.11b interference with 2 MHz offset.

VI. CONCLUSION

In this paper, the impact of channel sensing methods to the performances of IEEE 802.15.4 under the IEEE 802.11b interference are analyzed. Two different channel sensing methods such as ED and CS are considered. As performance measures, the average transmission delay, the throughput, and the power drain rate are analyzed. By simulations, the analytic results are validated.

Under the worst case interference of IEEE 802.11b, the average transmission delay of the ED mode is about 15 times that of the CS mode. And the throughput of the ED method is at most 10 kbps, 6.5% of the carrier sensing method (about 160 kbps). This is because in ED mode, the IEEE 802.15.4 End_device defers the transmissions because of the IEEE 802.11b transmissions, while CS mode attempts to transmit in a more greedy manner. However, under the interference of IEEE 802.11b, the ED mode is more energy effective because IEEE 802.15.4 will stay more in idle state with lowest energy consumption. Therefore, the life time of IEEE 802.15.4 network with ED mode could be extended about 4.7 times longer than that with CD mode. Therefore, CS mode is appropriate CCA method to maintain a certain throughput under the interference of IEEE 802.11b. For low battery devices designed for low throughput and non time-critical application, ED mode could be the best choice.

This paper could show the criteria for the selection of channel sensing methods for designing and implementing applications using IEEE 802.15.4 under IEEE 802.11b interference.

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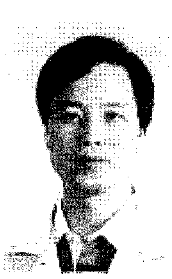

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