A Coexistence Model of IEEE 802.15.4 and IEEE 802.11b/g

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***Abstract*—IEEE 802.15.4 was developed to meet the needs for low-rate wireless communication. However, due to its low power, IEEE 802.15.4 is potentially vulnerable to interference by other wireless technologies having much higher power and working in the same Industrial, Scientific, and Medical (ISM) band such as IEEE 802.11b/g. The paper therefore focuses on the coexistence impact of IEEE 802.11b/g on the IEEE 802.15.4.**

In this paper, we present a coexistence model of IEEE 802.15.4 and IEEE 802.11b/g, which exposes the interactive behavior between these two standards and therefore accurately explains their coexistence performance. The model focuses on two aspects, namely power and timing. These two aspects jointly impose different impacts on the performance of IEEE 802.15.4 networks, depending on coexistence situations. To classify the coexistence situations, we introduce a concept of coexistence range, by extending the concept of sensing and interference ranges across different wireless standards. We characterize the coexistence behavior in each coexistence range and identify for each range the underlying coexistence mechanism and protocol interactions. Analytical models are proposed for the case of saturated traffic and simulation results are presented to validate the model.

I. Introduction

As a low-power and low-cost technology, IEEE 802.15.4, is establishing its place on the market as an enabler for the emerging wireless sensor networks (WSNs) [1]. Like IEEE 802.11b and IEEE 802.11g, IEEE 802.15.4 is also used in the 2.4 GHz ISM band. Due to supporting complimentary applications, they are very likely to be collocated within the interfering range of each other and therefore their ability to coexist needs to be evaluated.

There have been some studies about coexistence between the IEEE 802.11b/g and IEEE 802.15.4. According to [1] [2] [4] IEEE 802.15.4 has a little impact on the IEEE 802.11 performance. However, IEEE 802.11 can have a serious impact on the IEEE 802.15.4 performance if the channel allocation is not carefully taken into account [1] [3]. While the conclusion is true in general, we believe the studies so far have dealt with only limited cases of coexistence scenarios. In [3], the Packet Error Rate (PER) of IEEE 802.15.4 under the IEEE 802.11b interference is analyzed from an assumption of blind transmissions, i.e. both IEEE 802.11b and IEEE 802.15.4 transmit packets regardless of whether the channel state is busy or not. However, in this paper, we show that this assumption is realistic in only one of the three coexistence scenarios we shall present and therefore the analysis in [3] can be refined. In [4], measurements are performed to quantify coexistence issues. The author concluded that despite its low transmit power and simple modulation technique, IEEE 802.15.4 shows a robust behavior against interference of other 2.4 GHz systems and even in the worst case conditions for frequency overlap, local distance and high traffic load for interference, some time slots remain for a successful transmission of IEEE 802.15.4. Once again, we shall quantify the valid range for this behavior which corresponds to one of three coexistence scenarios we shall present. The remainder of the paper is organized as follows: Section II gives an overview of the IEEE 802.11b/g and IEEE 802.15.4 standard. Section III presents a coexistence model to characterize the coexistence issue in various scenarios. Section IV gives an analysis of the coexistence model. Simulation results are shown in Section V. Our conclusion is drawn in Section VI.

II. IEEE 802.11b/g and IEEE 802.15.4 Overview

A. *IEEE 802.11b/g*

IEEE 802.11b and IEEE 802.11g standards define the Medium Access Control (MAC) sublayer and the Physical (PHY) layer for wireless LANs. Both standards operate at 13 overlapping channels in the 2.4 GHz ISM band and the bandwidth of each channel is 22 MHz. IEEE 802.11b/g MAC employs the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. Before initiating a transmission, an IEEE 802.11b/g node senses the channel to determine whether another node is transmitting. If the medium is sensed idle for a Distributed coordination function Inter-Frame Space (DIFS) time interval the transmission will proceed. If the medium is busy the node defers its transmission. When the medium becomes idle for a DIFS interval, the node will generate a random backoff delay uniformly chosen in an interval. This interval $[0, W]$ is called Contention Window, where W is the size of the contention window. The initial W is set to CW_{min}. The backoff timer is decreased by one as long as the medium is sensed idle for a backoff time slot. The backoff counter will become frozen when a transmission is detected on the medium, and resumed when the channel is sensed idle again for a DIFS interval. When the backoff timer reaches zero, the node transmits a DATA packet. Immediately after receiving a packet correctly, the destination node waits for a Short Inter Frame Spacing (SIFS) interval and then transmits an ACK back to the source node.

B. IEEE 802.15.4

IEEE 802.15.4 standard defines the MAC sublayer and the PHY layer for low-rate wireless personal area networks. Its operational frequency band includes the 2.4 GHz ISM band.

Like IEEE 802.11b/g, IEEE 802.15.4 also employs CSMA/CA for media access control. However there is a key difference between their CSMA/CA mechanisms. Unlike in IEEE 802.11b/g, a channel in IEEE 802.15.4 is not sensed during a backoff period but only during a Clear Channel Assessment (CCA) period. Furthermore, the contention window in IEEE 802.15.4 is doubled correspondingly whenever the channel is determined busy during a CCA period. In IEEE 802.11b/g, however, the contention window remains the same size when the channel is determined busy and is doubled only when ACK is not received. This difference has a significant impact on their behavior of sharing a channel, which we shall show in detail at the following sections.

III. A Coexistence Model of IEEE 802.11b/g and IEEE 802.15.4

In this work, saturated IEEE 802.11b/g interference is always assumed. This corresponds to the presence of worst-case of interference, which in practice would occur for instance if two IEEE 802.11b/g nodes transfer video streams or large files to each other. Furthermore, only the popular unslotted IEEE 802.15.4 MAC is considered.

Under IEEE 802.11b/g interference, an IEEE 802.15.4 packet can be successfully received if either of the following two conditions is satisfied.

1) When the IEEE 802.15.4 packet overlaps an IEEE 802.11 packet, the in-band interference power from the IEEE 802.11 packet is significantly lower than the useful signal power from the IEEE 802.15.4 packet at an IEEE 802.15.4 receiver. According to the specification [6], if IEEE 802.11b/g interference is weak enough so that the in-band signal-to-interference ratio (SIR) is larger than 5-6 dB, an IEEE 802.15.4 packet could be successfully received with a probability of 99%.
2) The transmission time of an IEEE 802.15.4 packet is shorter than the inter-frame idle time, denoted by T_{idle}, between two consecutive IEEE 802.11b/g packets so that the IEEE 802.15.4 packet does not overlap an IEEE 802.11 packet.

Our coexistence model consists of the power and timing aspects, which are discussed as follows.

A. The Power Aspect

As shown in Table I, the transmission powers of IEEE 802.11b/g nodes and IEEE 802.15.4 nodes are significantly different. The differences in the transmit power and the receiver sensitivity lead to three distinct ranges, R_1, R_2 and R_3 as defined below:

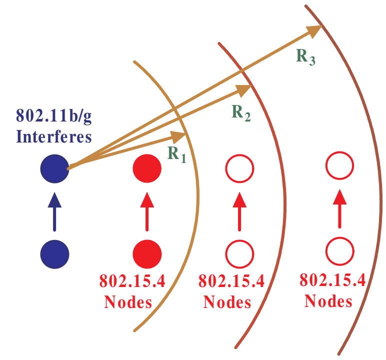

Fig. 1. Coexistence ranges of IEEE 802.15.4 and IEEE 802.11b/g

TABLE I
IEEE 802.15.4 and IEEE 802.11b/g System Parameters and Additional Parameters Used to Obtain Simulation Results

	IEEE 802.15.4	IEEE 802.11b	IEEE 802.11g
Transmit power	0 dBm	20 dBm	20 dBm
Receiver sensitivity	-85 dBm	-76 dBm	-82 dBm
Bandwidth	2 MHz	22 MHz	22 MHz
Transmit rate	250 kbps	11 Mbps	6 Mbps
Backoff unit T_{bs}	320 μs	20 μs	9 μs
SIFS	192 μs	10 μs	10 μs
DIFS	N/A	50 μs	28 μs
CCA	128 μs	N/A	N/A
CW_{min}	7	31	15
Center frequency	2410 MHz	2412 MHz	2412 MHz
Payload size	1 byte	1024 bytes	1024 bytes

R_1: a range in which IEEE 802.15.4 nodes and IEEE 802.11b/g nodes can sense each other;

R_2: a range in which IEEE 802.15.4 nodes can sense IEEE 802.11b/g nodes, but not vice versa;

R_3: a range in which neither can sense the other, but IEEE 802.15.4 nodes still suffer IEEE 802.11b/g interference.

These ranges are shown in Fig. 1. To quantify these ranges, we use a path loss model [8] recommended in the IEEE 802.11.2 specification. The path loss follows free-space propagation up to 8m and then attenuates more rapidly with a coefficient of 3.3, which is adjusted to 4 in this paper to accord with the 32m indoor reliable transmission distance of IEEE 802.15.4 nodes reported in [1]. The path loss is expressed as:

$$PL(d) = \begin{cases} 20\log_{10}(\frac{4\pi d}{\lambda}) & \text{if } d \le d_0 \\ 20\log_{10}(\frac{4\pi d_0}{\lambda}) + 40\log_{10}(\frac{d}{d_0}) & \text{if } d > d_0 \end{cases} \tag{1}$$

where d is the distance between a transmitter and a receiver, and d_0, i.e. 8 m, is the length of *line-of-sight* (LOS); $\lambda = c/f_c$, where c is the light velocity and f_c is the carrier frequency. By taking the receiver sensitivities, which are shown in Table I, as the received powers, and taking the SIR of 6 dB at receivers, we obtain R_1, R_2 and R_3, illustrated in Table II. Note that for simplicity, in the computation we assumed that the power spectrum density of IEEE 802.11b/g is uniformly distributed across the 22 MHz bandwidth.

The interactive behavior of IEEE 802.15.4 nodes and IEEE 802.11b/g nodes are different in these three ranges and thereby

TABLE II
COEXISTENCE RANGES OF IEEE 802.15.4 AND IEEE 802.11b/g

Range	IEEE 802.11b	IEEE 802.11g
R_1	22 m	32 m
R_2	67 m	67 m
R_3	95 m	95 m

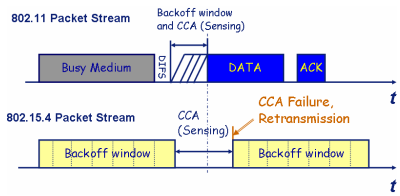

Fig. 2. In scenario 1: IEEE 802.11b/g nodes have priority over IEEE 802.15.4 nodes to access the channel

we define three scenarios, i.e. Scenario 1, 2 and 3 to describe the situations that IEEE 802.15.4 nodes and IEEE 802.11b/g nodes are in the range R_1, R_2 and R_3 respectively.

B. The Timing Aspect

Scenario 1: In this scenario, an IEEE 802.11b/g node and an IEEE 802.15.4 node can sense each other and therefore both of their CSMA/CA mechanisms work, i.e. as one is transmitting; the other has to wait.

The working CSMA/CA mechanism ensures that no overlapping of transmissions can happen if one node seizes the medium first. According to the conditions we discussed for successful transmissions, we know that the IEEE 802.15.4 throughput performance depends on how many chances it gets to transmit packets between two consecutive IEEE 802.11b/g packets. IEEE 802.15.4 nodes typically have a 10-20 times longer timing than IEEE 802.11b/g nodes, e.g. the backoff slot unit is 320 μs, 20 μs and 9 μs for IEEE 802.15.4, IEEE 802.11b and IEEE 802.11g respectively. The shorter timing gives IEEE 802.11b/g nodes priority over IEEE 802.15.4 nodes to access the channel and therefore cause unfairness to the IEEE 802.15.4 nodes. This is illustrated in Fig. 2.

However, once IEEE 802.15.4 nodes seize the channel, they can transmit packets free from interference because the IEEE 802.11b/g nodes will defer for the packet transmission of IEEE 802.15.4 nodes in this scenario. Therefore, the sufficient coexistence condition for this scenario is that a CCA of IEEE 802.15.4 happens during the period of the idle time, t_{idle}, between two consecutive IEEE 802.11b/g packets.

Now we see whether this sufficient coexistence condition could be satisfied. According to the specification [6],

$$t_{idle} \triangleq DIFS + t_{bo} = DIFS + m \cdot T_{bs} \quad (2)$$

where t_{bo} is a random period of time for an additional deferral time before transmitting and $t_{bo} \triangleq m \cdot T_{bs}$, where T_{bs} is a backoff unit and m is a random integer drawn from a uniform distribution over the interval [0, CW_{min}]. The values of these parameters are shown in Table I.

When $m \geq 4$ and 12 for IEEE 802.11b and IEEE 802.11g respectively, $t_{idle} \geq CCA$. Thus, when m is chosen to be a value in [4, 31] and [12, 15] for IEEE 802.11b and IEEE 802.11g respectively, t_{idle} is long enough for performing a CCA. The performance of an IEEE 802.15.4 network under IEEE 802.11b/g interference will be quantified in Section IV.

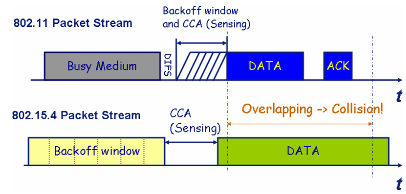

Fig. 3. In scenario 2: IEEE 802.11b/g nodes fails to sense IEEE 802.15.4 nodes

Scenario 2: In this scenario, IEEE 802.15.4 nodes can sense IEEE 802.11b/g nodes but not vice versa, because the transmit power of IEEE 802.11b/g nodes is much higher than that of IEEE 802.15.4 nodes. Thus, when IEEE 802.11b/g nodes are transmitting, IEEE 802.15.4 nodes have to wait; but when IEEE 802.15.4 nodes are transmitting, IEEE 802.11b/g nodes are not aware and they simply proceed to transmit, probably causing an overlapping in packet transmissions. This is shown in Fig. 3.

To check whether IEEE 802.15.4 nodes can have successful transmissions here, we shall first see whether non-overlapping transmissions can happen in this scenario.

Similar to the Scenario 1, an IEEE 802.15.4 node has to seize the channel so that its transmission can start. Hence, t_{idle} also needs to be longer than a CCA period in this scenario. Moreover, as IEEE 802.11b/g nodes do not defer anymore for IEEE 802.15.4 packets, to ensure non-overlapping transmissions, the following condition needs to be satisfied:

$$t_{idle} \triangleq DIFS + m \cdot T_{bs} \geq CCA + t_p + SIFS + ACK \quad (3)$$

where t_p is the transmission time of an IEEE 802.15.4 packet.

It can be shown that the inequality (3) cannot hold in any case, including the case that ACK is not employed. Thus, the condition for non-overlapping transmissions can never hold. Thus, successful transmissions of IEEE 802.15.4 packets can happen if and only if the power condition 1) is satisfied.

Scenario 3: In this scenario, neither IEEE 802.15.4 nodes nor IEEE 802.11b/g nodes can sense the other. However, IEEE 802.15.4 nodes may still suffer from the IEEE 802.11b/g interference, because a range in which a wireless device can cause interference to others is usually larger than that where it can be sensed by the others. This means both of IEEE 802.15.4 nodes and IEEE 802.11b/g nodes can freely transmit packets without deferring for the other, which is described as the assumption, called blind transmissions in [3].

It can be shown that for the case that ACK is employed, the condition for non-overlapping transmission can never hold in this scenario. Successful transmissions of IEEE 802.15.4 packets can happen if and only if the power condition 1) is satisfied. For the case that ACK is not employed, successful transmissions of IEEE 802.15.4 packets could happen if only

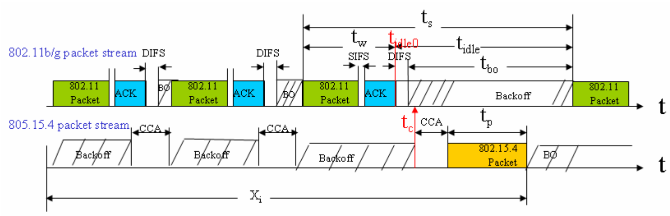

Fig. 4. Coexistence Model in Timing Aspect

the timing condition 2) is satisfied, while the power condition 1) is not necessary anymore.

IV. Throughput of IEEE 802.15.4 networks under IEEE 802.11b/g Interference in Scenario 1

For ease of analysis, we assume that there are only one pair of IEEE 802.15.4 nodes and one pair of IEEE 802.11b/g nodes. As described in Scenario 1, these two pairs of nodes are considered to be within a range where they can sense each. In each pair, one node is a transmitter and the other is a receiver. Moreover, the physical channel conditions are ideal and no packet error occurs. Therefore, the IEEE 802.11b/g transmitter can always receive ACKs after transmitting data packets, leading its contention window to keep the initial value, i.e., CW_{min}. For simplicity, we further assume that the IEEE 802.11b/g traffic is not affected by the IEEE 802.15.4 traffic. This assumption is reasonable because IEEE 802.15.4 has a little impact on the IEEE 802.11 performance according to [1] [2] [4] and our simulation. Finally, we assume that both IEEE 802.11b/g traffic and IEEE 802.15.4 traffic are in the saturation mode, which implies that there is always at least one packet awaiting transmission at the transmitters.

As shown in Fig. 4, for each transmission attempt, an IEEE 802.15.4 node performs a backoff first for an interval sampled from a uniform distribution over $[0, 2^{BE_i - 1}] (i = 0, 1, 2, 3, 4)$, where BE_i is the backoff exponent for i^{th} retransmission attempt and 0^{th} retransmission attempt means the first transmission attempt. A successful CCA will be followed by a successful IEEE 802.15.4 packet transmission. Otherwise, in the case of busy channel, the IEEE 802.15.4 node will defer for a backoff period defined by BE_{i+1} and then perform a CCA again until the default maximum retry limit, i.e. 4, is reached [5], where an error of channel access failure will be reported to the upper layer. In either case, a new transmission cycle will start with a backoff period defined by BE_0 for the next packet to be transmitted.

Owing to the assumption that the IEEE 802.11b/g traffic is not affected by the IEEE 802.15.4 traffic and the fact that the timing of IEEE 802.11b/g and IEEE 802.15.4 is significantly different, the transmission cycle times of IEEE 802.15.4 packets are considered independent of each other. Therefore, the transmission of IEEE 802.15.4 packets is essentially a renewal process. Let X denote the transmission cycle time of a packet, which either is transmitted successfully at i^{th} retransmission or fails to be transmitted eventually after the default five unsuccessful channel access attempts [5]. Thus, X is actually the inter-renewal time of the renewal process. Furthermore, let X_j denote the transmission cycle time of the j^{th} packet and let $\{W(t); t > 0\}$ be a renewal reward function for the renewal process with expected value of the inter-renewal time $\mathbb{E}(X)$. Thus according to [9], the IEEE 802.15.4 throughput S is given by

$$S = \lim_{t \to \infty} \frac{1}{t} \int_{\tau=0}^{t} W(\tau) d\tau = \frac{\mathbb{E}[W_n]}{\mathbb{E}[X]} \quad \text{with probability 1} \tag{4}$$

where $\mathbb{E}[W_n]$ is the expected value of the reward, i.e. the transmission time of one IEEE 802.15.4 packet, denoted by t_p, in the n^{th} renewal interval.

We now compute $\mathbb{E}[W_n]$. Since during the n^{th} renewal interval, either only one packet or no packet is transmitted, W_n correspondingly equals either t_p or zero. Thus,

$$\mathbb{E}[W_n] = p \cdot \mathbb{E}[t_p] \cdot \sum_{i=0}^{4} (1-p)^i + 0 \cdot (1-p)^5 = p \cdot \mathbb{E}[t_p] \cdot \sum_{i=0}^{4} (1-p)^i \tag{5}$$

where $\mathbb{E}[t_p]$ is the expected value of t_p and p is the probability that the channel is sensed idle during a CCA period. According to the assumption that the IEEE 802.11b/g traffic is not affected by the IEEE 802.15.4 traffic, the IEEE 802.11b/g interference is actually an on-off autonomous process, independent of the IEEE 802.15.4 traffic. It is on for a period t_p and off for a period $DIFS + t_{bo}$, where t_{bo} is a uniform RV on $[0, CW_{min}] \cdot T_{bs}$. Therefore, between two consecutive transmission attempts of an IEEE 802.15.4 node, the state, on or off, of the interference is independent. The transmission attempt of an IEEE 802.15.4 packet can success if and only if the CCA starts and ends within the period t_{idle}. This event is denoted by E. Thus, p is given by

$$p = P\{\mathsf{E}\} = \sum_{m=a}^{CW_{min}} P\{\mathsf{E_m}\} \tag{6}$$

where $\mathsf{E_m}$ represents E when t_{bo} equals mT_{bs}, and a equals 4 and 12 for IEEE 802.11b/g nodes respectively. We get

$$\begin{aligned} P\{\mathsf{E_m}\} &= P\{t_{bo} = mT_{bs}\} \\ &\quad \cdot P\{t_{idle0} \le t_c \le t_{idle0} + DIFS + mT_{bs} - CCA\} \end{aligned} \tag{7}$$

where t_{idle0} is the start time of the idle period t_{idle}, t_c is the CCA start time, uniformly distributed over $[0, t_s]$, where t_s is the transmission cycle time of an IEEE 802.11b/g packet, i.e. $t_s = t_w + DIFS + mT_{bs}$ and t_w is the sum of an IEEE 802.11b/g packet transmission time, a following SIFS and ACK. These parameters are shown in Fig. 4.

Since the backoff time is uniformly distributed, we get

$$P\{t_{bo} = mT_{bs}\} = \frac{1}{CW_{min} + 1} \tag{8}$$

Besides,

$$\begin{aligned} P\{t_{idle0} &\le t_c \le t_{idle0} + DIFS + mT_{bs} - CCA\} \\ &= \frac{DIFS + mT_{bs} - CCA}{\mathbb{E}[t_w] + DIFS + mT_{bs}} \end{aligned} \tag{9}$$

According to (6)(7)(8)(9), p is further given by

$$p = \frac{1}{CW_{min}+1} \cdot \sum_{m=a}^{CW_{min}} \frac{DIFS + mT_{bs} - CCA}{\mathbb{E}[t_w] + DIFS + mT_{bs}} \quad (10)$$

By substituting (10) in (5), $\mathbb{E}[W_n]$ is given. We now compute $\mathbb{E}[X]$ as follows.

$$\mathbb{E}(X) = \sum_{i=0}^{4} \left[p(1-p)^i \Big(\sum_{j=0}^{i} \mathbb{E}[B_i] + (i+1)CCA + \mathbb{E}[t_p] \Big) \right] + (1-p)^5 \Big(\sum_{i=0}^{4} \mathbb{E}[B_i] + 5CCA \Big) \quad (11)$$

where $\mathbb{E}[B_i]$, is the expected value of the backoff time, B_i, for the i^{th} retransmission, and B_i is uniformly distributed in $[0, 2^{BE_i}]$, owing to the assumption that the IEEE 802.11b/g traffic is not affected by the IEEE 802.15.4 traffic.

By substituting (5) and (11) into (4), the IEEE 802.15.4 throughput S is obtained. For example, using the parameter values in Table I, we get that when IEEE 802.11b interference occurs, the throughput of IEEE 802.15.4 decreases to 5.75% of the original value.

V. Coexistence Model Evaluation

In this work, we use OPNET to evaluate the coexistence model. The values of relevant parameters are listed in Table I.

A. Simulation Scenario 1

We set the distances between two IEEE 802.11 nodes and between two IEEE 802.15.4 nodes as 2m, and the distance between IEEE 802.11 nodes and IEEE 802.15.4 nodes as 5m to ensure both can sense each other. Continuous UDP packets are transmitted between two IEEE 802.11 nodes. Only the IEEE 802.15.4 coordinator sends DATA packets, while the destination node sends only ACK.

Fig. 5 shows that when IEEE 802.11b interference occurs, the throughput of the IEEE 802.15.4 node goes from 18000 bps on average down to 1000 bps on average, i.e. only 5.56% throughput remains. This result matches the analytical result, i.e. 5.75%, in Section IV and thus verifies our analysis. According to the experiment environment in [4], there is only 1.5m between IEEE 802.11b nodes and IEEE 802.15.4 nodes, a range where both can sense each other, accounting for successful transmissions of few IEEE 802.15.4 packets.

B. Simulation Scenario 2

In Section III, the sensing ranges are 22m and 32m for IEEE 802.11b/g respectively. In Scenario 2, we set the distance between two IEEE 802.11 nodes still as 2m and that of IEEE 802.15.4 nodes as 15m to show a case that the power condition 1) is not satisfied, and the distances between IEEE 802.11 nodes and IEEE 802.15.4 nodes as 30m and 40m for IEEE 802.11b respectively, which are 8m away from their sensing ranges. Fig. 6 shows that the throughput of the IEEE 802.15.4 node goes down to zero as the IEEE 802.11b interference occurs, which verifies that the coexistence is impossible when the power condition 1) is not satisfied in Scenario 2.

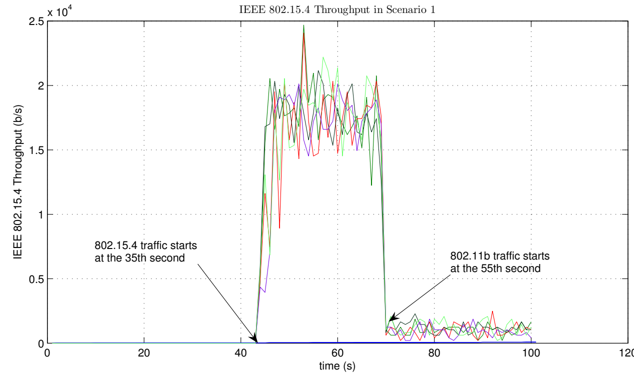

Fig. 5. Throughput of IEEE 802.15.4 nodes before and after IEEE 802.11b interference occurs in Scenario 1

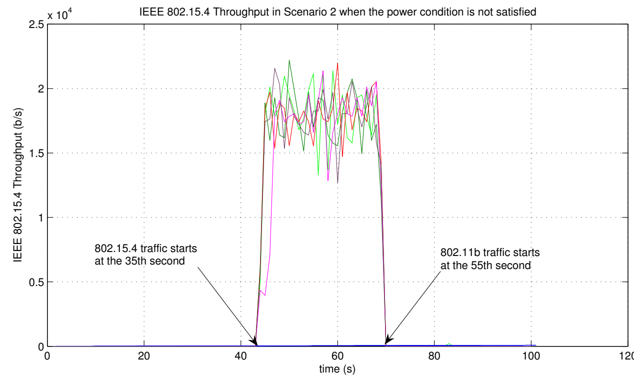

Fig. 6. Throughput of IEEE 802.15.4 nodes before and after IEEE 802.11b interference occurs in Scenario 2 when the power condition 1) is not satisfied

VI. Conclusion

In this paper, we present a coexistence model of IEEE 802.15.4 and IEEE 802.11b/g based on two aspects: power and timing. Due to the significant difference in the transmit power, three coexistence ranges can be identified. In each of these ranges, IEEE 802.11 and IEEE 802.15.4 exhibit different interactive behavior and hence different performance, which are quantified by the analysis and verified by the simulation.

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