Modeling Channel Conflict Probabilities between IEEE 802.11b and IEEE 802.15.1 Networks

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Abstract— **With the increasingly deployed Wireless Local/Personal Area Network (WLAN/WPAN) devices, channel conflict has become very frequent and severe when one WLAN/WPAN technology coexists with other WLAN/WPAN technologies in the same interfering range. In this paper, we study the coexistence issue between the most prevalent WLAN and WPAN technologies, namely the IEEE 802.11b and IEEE 802.15.1 standards. We present analytical models on the non-conflicting channel allocation probabilities, focusing on the co-existence scenarios of one IEEE 802.15.1 network coexisting with one or multiple IEEE 802.11b networks. The results show that channel allocation conflicts does occur more frequently as the number of IEEE 802.11b networks increases. Moreover, the proposed analytical model in this letter is simple and applicable to other wireless technologies, as long as the channel allocation mechanisms are known.**

I. INTRODUCTION

Wireless Local/Personal Area Network (WLAN/WPAN) technologies have fueled the development as well as the wide proliferation of wireless portable devices (e.g., laptops, PDAs, smart phones, portable media players, etc.). Yet, the popularity of these wireless devices has resulted in many forms of frequency spectrum clash amongst the different wireless technologies. To understand the performance of these wireless devices in different interference situations, it is increasingly important to study the coexistence issue amongst the existing wireless technologies.

Since the two most widely deployed WLAN and WPAN technologies (i.e., IEEE 802.11b and IEEE 802.15.1) both operate in the same 2.4GHz ISM (Industrial-Scientific-Medical) frequency band, channel allocation conflicts are inevitable when they coexist within the same radio range. The coexistence issues will become even severe while these technologies also coexist with other 2.4GHz based wireless/radio technologies (e.g. IEEE 802.15.3 devices [1], IEEE 802.15.4 devices [2], cordless phone, microwave oven, etc.). It soon becomes important to understand the characteristics of each channel allocation scheme and how each channel allocation scheme interacts with the others. Table I summarizes some of the relevant properties of the wireless standards mentioned above.

TABLE I
WIRELESS TECHNOLOGIES IN 2.4GHZ ISM FREQUENCY BAND.

IEEE Standard	802.11b/g	802.15.1	802.15.3	802.15.4
Frequency Band	2.4GHz	2.4GHz	2.4GHz	2.4GHz
rcv Bandwidth	22MHz	1MHz	15MHz	2MHz
Number of Channels	11	79	5	16
Max Rate (Mbps)	11/54	0.72	55	0.25
Transmission Range	100m	10m	10m	20m
Applications	WLAN	WPAN	HR-WPAN	LR-WPAN

The coexistence issue between 2.4GHz-based wireless technologies has been extensively studied. [3] first performed a systematical study on the coexistence of IEEE 802.11b and Bluetooth devices via testbed measurements, and [4] has studied the coexistence of Bluetooth and microwave ovens by measuring the channel error rates of Bluetooth devices. In addition, analytical models for the coexistence of Bluetooth and IEEE 802.11b have also been proposed in [5] [6] [7] at various configuration scenarios, and the discussion on the coexistence issue between IEEE 802.11 and the IEEE 802.15 based WPAN technologies has been included in IEEE standards (e.g., the IEEE 802.15.2 standard [9]). Nonetheless, previous analytical work assumed operating channels are *already* conflicted when modeling error rates between different wireless technologies, while a detailed study on modeling the probabilities of channel conflicts *on a random view basis* is still lacking.

In this paper, we study coexistence issues between two of the most widely deployed WLAN and WPAN technologies, namely the IEEE 802.11b [10] and IEEE 802.15.1 [11] standards. Unlike previous work [7] [5] [6] [3], which has extensively studied the impact of wireless interference on the packet error rate and/or data throughput based on an implicit assumption that *wireless channels are already conflicted*, it is the interest of this paper to study the "channel conflict probability" when one wireless technology 'meets' the other one in the same interfering range on a random view basis. Of course, the results of our work could be combined with previous work to relax that conflicted channels assumption and derive the packet error rate and/or expected data throughput. Finally, it should also be mentioned that the analysis presented in this letter is also useful in calculating the channel collision probability for other wireless technologies as long as their channel allocation mechanisms are known.

The rest of the paper is organized as follows. In Section II, we present an brief overview of the IEEE 802.11b and IEEE 802.15.1 technologies and their channel allocation schemes. In Section III, we present analysis on the probability of channel collision between different pairing of wireless technologies.

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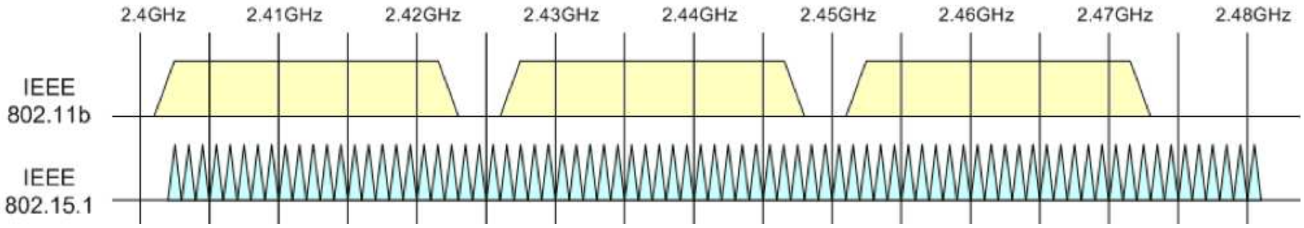

Fig. 1. Channel allocations of IEEE 802.11b and IEEE 802.15.1 technologies.

Finally, Section IV concludes the paper.

II. OVERVIEW

To proceed to the analysis of our study, we briefly recap the channel allocation mechanism of the IEEE 802.11b and IEEE 802.15.1 standards. Basically, IEEE 802.11b employs Direct Sequence Spread Spectrum (DSSS) technique, and it defines 14 channels with 22 MHz bandwidth for each one. In U.S. and most of the countries in the world, the first 11 channels are used; whereas, the first 13 channels are used in Europe and Singapore, and all of the 14 channels are used in Japan. The central frequencies of IEEE 802.11b channels are separated by 5 MHz as shown in Eq. 1.

$$f_{IEEE802.11b} = 2412 + 5k \ ; \ k = 0 \ldots 13 \tag{1}$$

However, since adjacent IEEE 802.11b channels are partially overlapped, the so-called *adjacent channel interference* will happen if two IEEE 802.11b nodes in close operate using adjacent channels [12]. In this case, the overall network performance will become degraded. Therefore, in practice, only the maximum non-overlapping channels (i.e., channel 1, 6, and 11) are employed in most of nowadays IEEE 802.11b networks. Therefore, the analysis presented in this letter would be based on the assumption that only the maximum non-overlapping channels are used in IEEE 802.11b networks (as shown in Fig. 1).

On the other hand, IEEE 802.15.1 employs Frequency Hopping Spread Spectrum (FHSS) technique. There are 79 hopping frequencies[1], each having a bandwidth of 1MHz. The 79 hopping frequencies (as shown in Fig. 1) are:

$$f_{IEEE802.15.1} = 2402 + k \ ; \ k = 0 \ldots 78 \tag{2}$$

The frequency hopping sequence is determined by a hopping kernel. In each time, the hopping kernel first selects a segment of 64 adjacent channels (note that the last channel, i.e., k=78, is adjacent to the first channel, i.e., k=0, as illustrated in Figure 2) and then hops to 32 of them without repetition in a random order. Next, a different 32-hop sequence is chosen from another segment of 64 adjacent channels, and etc. As a result, a pseudo-random sequence of frequency hopping slides through the 79 available channels.

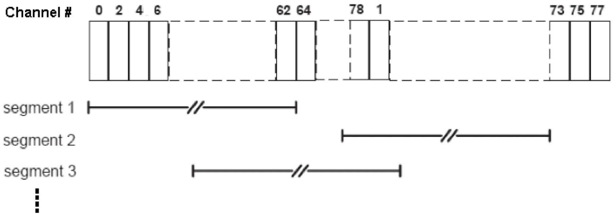

Fig. 2. An example of the sequence selection of IEEE 802.15.1 frequency hopping.

Note that, in addition to the basic hopping kernel defined in the IEEE 802.15.1 standard, a new Adaptive Frequency Hopping (AFH) kernel has been proposed in the follow-up Bluetooth spec [13][14]. In AFH, the 79 channels are classified into two groups. One of them is the group of channels which shall be *unused* (i.e., these channels might have been heavily interfered), and the other is the group of channels which should be *used*. Using the basic hopping kernel, if the selected channel belongs to the *unused* group, AFH employs a mapping function, which uniformly maps *unused* channels to *used* channels, to replace the selected channel to a *used* channel. As a result, only *used* channels will be used in AFH, and the *unused* channels are avoided. However, though AFH is promising in alleviating interference to Bluetooth networks, we do not include AFH in our analysis since it is not specified in IEEE 802.15.1 standard yet. We intend to evaluate the channel confliction issue with AFH in the near future.

III. ANALYSIS

In this section, we present analysis on the non-conflicting channel allocation probability, i.e., P_{good}, when an IEEE 802.15.1 network coexists with n IEEE 802.11b networks. For simplicity, we assume the employed channels of the n IEEE 802.11b networks are not conflicted (i.e., non-overlapping channels and $n \leq 3$). Note that we do not consider scenarios consisting of multiple IEEE 802.15.1 networks, since such scenarios can be solved by combining our analysis and previous studies [15] [16].

We define random variable R as the number of conflicting channels in the selected 64 adjacent segment in IEEE 802.15.1, and K as the number of conflicting channels in the selected 32-hop channel sequence (out of the R-conflicted segment). The random variable S denotes the channel status (0: no channel allocation conflict occurred; 1: channel allocation

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[1] In some countries, e.g., France, there are only 23 hopping frequencies available for IEEE 802.15.1 technology.

conflict occurred). We define $P_{good} = P[S = 0]$ and study the coexistence issues in three cases as follows.

A. Case 1: $n = 1$

From Fig. 1, when there is only one coexisting IEEE 802.11b network (i.e., either channel 1, 6, or 11 is utilized), we can obtain $P[R = r]$ (i.e., the probability such that there are r conflicting channels in the selected segment of 64-adjacent channels) for each of the three cases (via counting) by Eq. 3, 4, and 5. We assume these three cases are uniformly distributed. Therefore, the overall $P[R = r]$ is obtained by summing up the three cases as shown in Eq. 6.

(a) channel 1 is utilized

$$P_a[R = r] = \begin{cases} \frac{44}{79} & ; r = 21 \\ \frac{2}{79} & ; 7 \leq r \leq 20 \\ \frac{7}{79} & ; r = 6 \\ 0 & ; \text{otherwise} \end{cases} \tag{3}$$

(b) channel 6 is utilized

$$P_b[R = r] = \begin{cases} \frac{43}{79} & ; r = 22 \\ \frac{2}{79} & ; 8 \leq r \leq 21 \\ \frac{8}{79} & ; r = 7 \\ 0 & ; \text{otherwise} \end{cases} \tag{4}$$

(c) channel 11 is utilized

$$P_c[R = r] = \begin{cases} \frac{43}{79} & ; r = 22 \\ \frac{2}{79} & ; 8 \leq r \leq 21 \\ \frac{8}{79} & ; r = 7 \\ 0 & ; \text{otherwise} \end{cases} \tag{5}$$

$$\begin{aligned} P[R = r] &= \frac{1}{3}P_a[R = r] + \frac{1}{3}P_b[R = r] + \frac{1}{3}P_c[R = r] \\ &= \begin{cases} \frac{86}{237} & ; r = 22 \\ \frac{16}{79} & ; r = 21 \\ \frac{2}{79} & ; 8 \leq r \leq 20 \\ \frac{6}{79} & ; r = 7 \\ \frac{7}{237} & ; r = 6 \\ 0 & ; \text{otherwise} \end{cases} \end{aligned} \tag{6}$$

Given r conflicted channels in the 64 adjacent channels, the probability of k channel conflict out of the selected 32-hop sequence ($k \leq r$) is obtained by:

$$P[K = k | R = r] = \frac{32!32!}{64!} \binom{r}{k} \binom{64 - r}{32 - k} \tag{7}$$

In addition, given k channel conflict in the selected 32-hop sequence, the probability of channel conflict while selecting one channel from the 32-hop sequence is defined as:

$$P[S = 1 | K = k, R = r] = \frac{k}{32} \tag{8}$$

To sum up all conditions of possible r and k values (shown in Eq. 9 and 10), one can obtain P_{good}, i.e., the probability of no channel confliction, by Eq. 11, and the non-conflicting channel allocation probability is around 0.725738.

$$\begin{aligned} &P[S = 1 | R = r] \\ &= \sum_{k=1}^{r} (P[S = 1 | K = k, R = r] P[K = k | R = r]) \end{aligned} \tag{9}$$

$$\begin{aligned} P[S = 1] &= \sum_{r=6}^{22} (P[S = 1 | R = r] P[R = r]) \\ &\approx 0.274262 \end{aligned} \tag{10}$$

$$P_{good} = 1 - P[S = 1] \approx 0.725738 \tag{11}$$

B. Case 2: $n = 2$

When there are two distinct IEEE 802.11b networks ($n = 2$) occupying two distinct channels, either channel (1, 6), (6, 11), or (1, 11) is utilized. The $P[R = r]$ of these three cases are shown in Eq. 12, 13 and 14. We assume these three cases are uniformly distributed. Therefore, the overall $P[R = r]$ is obtained by summing up the three cases as shown in Eq. 15.

(a) channel (1, 6) are utilized

$$P_a[R = r] = \begin{cases} \frac{19}{79} & ; r = 43 \\ \frac{2}{79} & ; 32 \leq r \leq 42 \\ \frac{15}{79} & ; r = 31 \\ \frac{4}{79} & ; 29 \leq r \leq 30 \\ \frac{15}{79} & ; r = 28 \\ 0 & ; \text{otherwise} \end{cases} \tag{12}$$

(b) channel (1, 11) are utilized

$$P_b[R = r] = \begin{cases} \frac{19}{79} & ; r = 43 \\ \frac{2}{79} & ; 32 \leq r \leq 42 \\ \frac{15}{79} & ; r = 31 \\ \frac{4}{79} & ; 29 \leq r \leq 30 \\ \frac{15}{79} & ; r = 28 \\ 0 & ; \text{otherwise} \end{cases} \tag{13}$$

(b) channel (6, 11) are utilized

$$P_c[R = r] = \begin{cases} \frac{18}{79} & ; r = 44 \\ \frac{2}{79} & ; 33 \leq r \leq 43 \\ \frac{15}{79} & ; r = 32 \\ \frac{4}{79} & ; 30 \leq r \leq 31 \\ \frac{16}{79} & ; r = 29 \\ 0 & ; \text{otherwise} \end{cases} \tag{14}$$

$$\begin{aligned} P[R = r] &= \frac{1}{3}P_a[R = r] + \frac{1}{3}P_b[R = r] + \frac{1}{3}P_c[R = r] \\ &= \begin{cases} \frac{6}{79} & ; r = 44 \\ \frac{40}{237} & ; r = 43 \\ \frac{2}{79} & ; 33 \leq r \leq 42 \\ \frac{19}{237} & ; r = 32 \\ \frac{34}{237} & ; r = 31 \\ \frac{4}{79} & ; r = 30 \\ \frac{8}{79} & ; r = 29 \\ \frac{10}{79} & ; r = 28 \\ 0 & ; \text{otherwise} \end{cases} \end{aligned} \tag{15}$$

Similar to the analysis presented in Case 1, one can then obtain the probability of non-conflicting channel allocation for $n = 2$ case, as shown in Eq. 16 and 17. The probability turns out to be around 0.451477. Clearly, channel conflicts are very common in this scenario.

$$P[S = 1] = \sum_{r=28}^{44} \left(P[S = 1|R = r]P[R = r]\right) \tag{16}$$

$$P_{good} = 1 - P[S = 1] \approx 0.451477 \tag{17}$$

C. Case 3: $n = 3$

When there are three distinct IEEE 802.11b networks ($n = 3$) occupying all three distinct channels (channel 1, 6, and 11 are all utilized by the IEEE 802.11b networks). $P[R = r]$ in this scenario is then calculated and shown in Eq. 18. The non-conflicting channel allocation probability, P_{good}, is then obtained using the same method as in the previous cases, and it turns out to be less than 0.2 in this case. Unsurprisingly, the results show that the probability for channel conflict is much higher (or more frequent) in this scenario compared to the case where $n = 2$.

$$P[R = r] = \begin{cases} \frac{8}{79} & ; r = 58 \\ \frac{2}{79} & ; 54 \leq r \leq 57 \\ \frac{28}{79} & ; r = 53 \\ \frac{6}{79} & ; 51 \leq r \leq 52 \\ \frac{23}{79} & ; r = 50 \\ 0 & ; \text{otherwise} \end{cases} \tag{18}$$

$$P[S = 1] = \sum_{r=50}^{58} \left(P[S = 1|R = r]P[R = r]\right) \tag{19}$$

$$P_{good} = 1 - P[S = 1] \approx 0.177215 \tag{20}$$

IV. CONCLUSIONS

We in this paper present analysis on probabilities of channel conflicts between IEEE 802.11b and IEEE 802.15.1 networks. The analytical results show that the channel conflict probability does increase (almost linearly) as the number of IEEE 802.11 networks increases. Moreover, our analytical model is simple and also applicable to calculating channel conflict probabilities of other wireless technologies, as long as their channel allocation mechanisms are known. Future work of this study is to take the error models (e.g., SNR vs PER, SNR vs distance, etc.) of IEEE 802.11b and 802.15.1 technologies into account, and extend our analysis to model the packet/frame error rates for multiple coexisting WPAN/WLAN networks.

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