Channel Interference in IEEE 802.11b Systems

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***Abstract*— There are many different channels defined in the IEEE 802.11 standard. However, the performance of WiFi networks still greatly suffers from the interference between users, even if they are using different channels. In this paper, we conduct some theoretical analysis of the interference between two channels, which is further verified by experiments. We show that there is indeed serious interference between two non-overlapping channels if they are close to each other.**

I. INTRODUCTION

The success of IEEE 802.11 wireless technology in the corporate and home environments is leading to more demanding usage of the 2.4 GHz ISM band. The IEEE 802.11 standard [2] establishes several requirements for the Radio Frequency (RF) transmission characteristics of an 802.11 radio. Included in these are the channelization scheme as well as the spectrum radiation of the signal. The 2.4 GHz band is divided into 11 channels for the FCC or North American domain and 13 channels for the European or ETSI domain. Two neighboring channels have a central frequency separation of 5 MHz and each channel has a channel bandwidth of 22 MHz. This is true for 802.11b products running 1, 2, 5.5, or 11 Mbps as well as for the newer 802.11g products running up to 54 Mbps. The differences lie in the modulation scheme, but the channels are identical across all of these products.

In the literature, there are many papers on designing MAC protocols and channel assignment algorithms for networks using multi-channels, such as [3], [12], [14], and [15]. It has been shown by simulations that the network performance and the spatial reuse can be improved significantly.

Generally speaking, there exists interference when we use multi-channels, which can be classified into: (a) co-channel interference where interference comes from the same channel, and (b) adjacent channel interference where the interference takes place on adjacent overlapping or non-overlapping channels.

In [8] [9], co-channel interference is analyzed to derive the spatial reuse and the capacity of wireless networks wherein a minimum SINR (signal to interference plus noise ratio) is necessary for successful communications. Xu et al. [16] indicate that virtual carrier sensing via RTS/CTS is far from enough to solve the co-channel interference and larger physical carrier sensing range can help in some degree. Finally, in [17], the optimum carrier sensing range is derived in the worst-case scenario.

In contrast, adjacent channel interference is difficult to handle because it contributes to background noise and cannot be solved through the normal channel contention technique. The authors in [5] [6] study the effect of the adjacent channel interference on the achievable performance in a multi-radio multi-hop network. Mishra et al. [10] [11] present an analytic model to study the bahavior of partial overlap between channels. They conclude that a careful use of some partially overlapped channels can often lead to significant improvements in spectrum utilization and application performance.

In this paper we quantify the interference between two channels, which is determined by the level of RF energy that leaks from one channel to the other. We first briefly describe the modulation process of a transmitted signal using Direct Sequence Spread Spectrum (DSSS) technique. Then, without loss of generality, we assume the power spectral density function of the transmitted signal to be the same as the transmission mask defined in IEEE 802.11b. Since the receiver filter is not defined in the standard, we make some assumptions on the receiver filters and calculate the interference between two channels accordingly. At last, we conduct some real experiments to show the co-channel as well as adjacent channel interference.

The rest of this paper is organized as follows. Section II studies the power spectral density function of the IEEE 802.11b transmitted signals at 1 Mbps. In Section III, we quantify the interference between two channels through theoretical analysis. In Section IV, some experimental results on the interference are shown, which are also compared with the theoretical results derived in the previous section. We finally conclude this paper in Section V.

II. ANALYSIS OF THE POWER SPECTRAL DENSITY OF THE IEEE 802.11B TRANSMITTED SIGNAL

IEEE802.11b at 1 Mbps adopts a Direct Sequence Spread Spectrum (DSSS) technique. More specifically, the baseband pulse amplitude modulation (PAM) signal, $r(t)$, is multiplied by the spreading signal $c(t)$, where [7]

$$r(t) = \sum_{n=-\infty}^{\infty} a_n g_r(t - nT)$$

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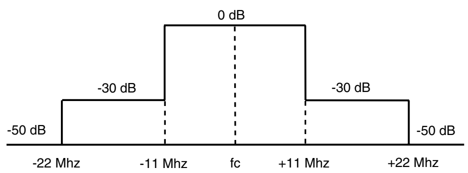

Fig. 1. The IEEE 802.11b transmission mask.

$$c(t) = \sum_{n=-\infty}^{\infty} \sum_{i=0}^{V-1} c_i g(t - iT_c - nT)$$

Besides, a_n is the nth transmitted bit, $T = 1\ \mu s$ is the bit-time, $g_r(t)$ is the rectangular pulse of duration T, $\{c_0, c_1 ... c_V\}$ is the spreading sequence, V is the spreading factor, $T_c = T/V$ is the chip time, and $g(t)$ is the rectungalar pulse of duration T_c. In the considered case, the adopted spreading sequence is the Barker sequence with $V = 11$, i.e., $\{c_0, c_1 ... c_{10}\} = \{+1, -1, +1, +1, -1, +1, +1, +1, -1, -1, -1\}$. The spread spectrum signal becomes

$$x(t) = \sum_{n=-\infty}^{\infty} a_n g_m(t - nT) \tag{1}$$

where

$$g_m(t) = \sum_{i=0}^{V-1} c_i g(t - iT_c) \tag{2}$$

From (1), we can note that $x(t)$ is still a PAM signal with modulation pulse $g_m(t)$ given by expression (2). Assuming $\{a_n\}$ is independent and ergodic, we can state that the two-sided power spectral density of $x(t)$ is given by

$$X(f) = E\{a^2\} \frac{|G_m(f)|^2}{T}$$

$$G_m(f) = G(f) \sum_{i=0}^{V-1} c_i e^{-j2\pi i f T_c}$$

where $G_m(f)$ and $G(f)$ are the Fourier transform of $g_m(t)$ and $g(t)$, respectively. For the Differential Binary Phase Shift Keying (DBPSK)[1] modulation scheme adopted by IEEE 802.11b at 1 Mbps, the two-sided power spectrum of the modulated signal is, ignoring a scale factor, the translation of $X(f \pm f_0)$ with f_0 being the carrier frequency. We conclude that in order to derive the power spectrum of the modulated signal we can refer to $X(f)$ without losing generality.

In Fig. 1, the transmit spectrum mask defined by the standard is reported. In order to fulfill the requested mask, the modulated signal is passed through a transmission filter with baseband equivalent amplitude characteristic $|H(f)|$. So the power spectrum of the transmitted signal is

$$S(f) = X(f)|H(f)|^2. \tag{3}$$

This process is briefly shown in Fig. 2.

[1]The simplest form of PSK uses two carrier waves, shifted by a half cycle relative to each other. One wave, the reference wave, is used to encode a 0; the half-cycle shifted wave is used to encode a 1.

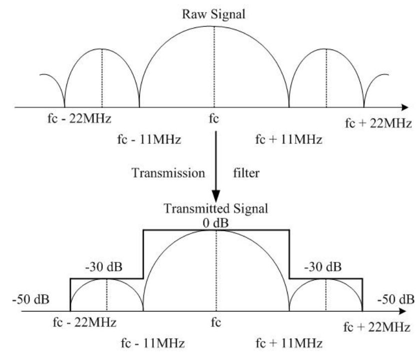

Fig. 2. Illustration of the process at the transmitter side to fit a transmitted signal into a transmission mask.

The IEEE 802.11b standard also provides 2 Mbps data rate adopting a Differential Quadrature Phase Shift Keying (DQPSK) modulation scheme. As far as Complementary Code Keying (CCK)[2] is concerned, it can be viewed as a coded DQPSK modulation based on the same pulse $g_m(t)$ and the same transmit spectrum mask as for the DSSS case. The evaluation of the power spectral density follows the classical result for QPSK [13].

III. Quantifying the Interference

In wireless networks, interference from nearby channels has a significant negative impact on the system throughput. This effect is also called adjacent channel interference and it is the result of imperfect receiver filters which allow the power on nearby frequencies to leak into certain frequency band. We can roughly classify the adjacent channel interference problem into two parts exploiting the simple topology as shown in Fig. 3.

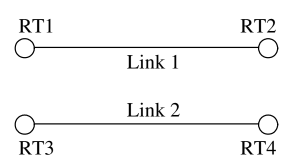

Fig. 3. Topology of the experiment on non-overlapping channels.

The first problem arises if RT 1 is transmitting to RT 2 in very close range to RT 3, which attempts to receive a signal from RT 4. The transmission of RT 1 causes serious interference on the reception of RT 3, even if they use two different channels. This makes the SINR (Signal-to-Interference and Noise Ratio) at RT 3 very low and it cannot correctly receive packets. The second problem occurs when both RT 1 and RT 3 are transmitters which transmit to RT 2 and RT 4, respectively. In this case, the transmission of RT 1 will be detected by RT 3 through physical carrier sensing, which makes RT 3 defer its own transmission.

[2]CCK is based on sophisticated mathematical transforms that allow the use of a few 8-bit sequences to encode 4 or even 8 bits per code word, for a data throughput of 5.5 Mbps or 11 Mbps.

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Both the adjacent channel interference problems can be mitigated through careful filtering. Many real-world radios, however, are not good enough since they allow the power on other frequency bands to leak into the ongoing channel. In the following, we quantify the interference between two channels.

Referring to Fig. 3, we consider a simple topology where a transmitting station RT 1 is placed on channel x and it is connected in ad-hoc mode to RT 2. The other link (i.e., RT 3 - RT 4) is set on channel y. The amount of overlap between channel x and y is defined as [11]

$$I(x,y) = I(\mu) = \int_{-\infty}^{\infty} S_{RT1}(f) Z_{RT3}(f-\mu) df \quad (4)$$

where $S_{RT1}(f)$ is the transmitted signal given by (3), $Z_{RT3}(f)$ denotes the band-pass filter's frequency response of RT 3, and $\mu = |F_x - F_y| = 5|x-y|$, with F_x and F_y representing the transmitted central frequency and the received central frequency, respectively. Thus, equation (4) specifies the amount of interference between a transmission and a reception on any two frequencies. Moreover $\mu = 0$ represents that both the incoming signal of the transmitter and band-pass filter of the receiver have the same carrier frequency.

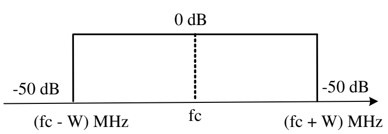

Fig. 4. A band-pass receiver filter with bandwidth $2W$.

Since different signals have different power density functions, in order to analyze the interference between two channels, without loss of generality, we assume the transmitted signal's power distribution coincides with the transmission spectrum mask. Moreover, we also assume four different receiver filters in order to calculate the $I(\mu)$ according to (4): (R1) the receiver filter is the same as the transmit spectrum mask as shown in Fig. 1; (R2) the receiver filter is a band-pass filter as shown in Fig. 4, with a bandwidth of $2W = 30MHz$; (R3) the receiver filter is a band-pass filter (Fig. 4) with a bandwidth of $2W = 40MHz$; (R4) the receiver filter is a band-pass filter (Fig. 4) with a bandwidth of $2W = 44MHz$. The calculated values for $I(\mu)$ are shown in Fig. 5.

A general power propagation model is introduced in [13] to predict the received signal strength, i.e.,

$$P_r(d) = P_t h(h_t, h_r, L, \lambda) \frac{G_t G_r}{d^\alpha},$$

where P_t and P_r are the transmitted power and the received power, respectively, G_t and G_r are the gain factors for the transmitter's antenna and the receiver's antenna, respectively, h_t and h_r are the antenna heights of the transmitter and the receiver, respectively, d is the distance between the transmitter and the receiver, L is the system loss factor not related to propagation $(L \geq 1)$, λ is the wavelength, $h(\cdot)$ is a function, and α is the path loss exponent.

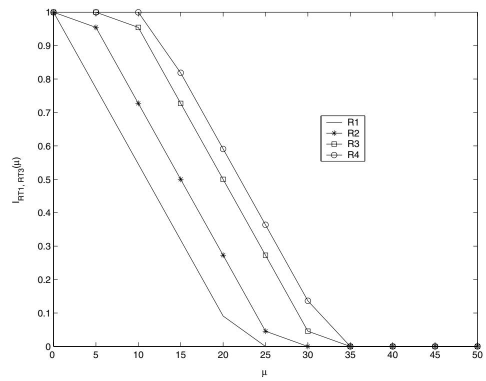

Fig. 5. The values of $I(\mu)$ for four different receiver filters denoted by R1, R2, R3, and R4, respectively.

Thus, exploiting the equation (4), the power received at RT 3 which is separated from the interfering node (i.e., RT 1) by distance d, is given by

$$P_{r,RT3}(d) = P_{t,RT1} h(h_t, h_r, L, \lambda) \frac{G_t G_r I(x,y)}{d^\alpha} \quad (5)$$

where $P_{t,RT1}$ is the transmitted power of RT 1, $P_{r,RT3}(d)$ is the received power at RT 3, and $I(x,y)$ captures the interference between channel x and channel y.

The overall energy detected by a receiver is composed of the transmitted signal, the interference from unwanted transmitters, and the noise level that is normally much less than the power level of the closest interference. Thus, the receiver RT3 can correctly receive a packet from RT 4 only if two conditions are satisfied: (a) the received desired signal is greater than the receiver sensitivity (denoted by RX_{th}); and (b) the SINR is above a threshold (denoted by $SINR_{th}$) in the presence of interference[3], i.e.,

$$\begin{cases} P_{r,RT3}(d^*) \geq RX_{th} \\ \frac{P_{r,RT3}(d^*)}{P_N + P_{r,RT3}(d)} \geq SINR_{th} \end{cases} \quad (6)$$

where P_N is the strength of the thermal noise, $P_{r,RT3}(d^*)$ is the received power from $RT4$ at distance d^*, and $P_{r,RT3}(d)$ is given by (5).

IV. Experiments On The Interference Between Channels

IEEE 802.11b standard specifies the central frequency of 11 channels, as well as a spectral mask that requires the signal be attenuated by at least 30 dB from its peak energy at 11 MHz from the center frequency, and at least 50 dB at 22 MHz from the center frequency, as shown in Fig. 1. Since the central frequencies of two neighboring channels are 5 MHz apart, two channels separated by at least 5 frequency bands can be considered to be non-overlapping. Thus, IEEE 802.11b has up to 3 non-overlapping channels. In this section, we conduct some experiments to show the

[3]In our case, $RT1$ is the only interference.

interference between both overlapping and non-overlapping channels.

A. Experiment Configurations

We first present the configuration of our experiments. Currently, we are using IEEE 802.11 Linksys WRT54GL wireless routers operating in b/g mode. The architecture of such routers is based on the MIPSEL processor family. The Linksys routers have been upgraded to run the Linux-based OpenWRT Operating System (OS). The available flash memory on our Linksys routers is 4 MB, which is large enough to fit the OpenWRT OS. The Broadcom chipset is driven by a proprietary driver (wl), which allows a reasonable degree of control over the wireless properties. Every router features a single radio interface with two antennas for spatial diversity purposes, and five wired interfaces. The default transmission power is 19 dBm. We disable the Request To Send/Clear To Send (RTS/CTS) mechanism and set the channel rate to 1 Mbps, which is supported by DBPSK modulation scheme. In order not to fall into the effects related to ground [4], we place the router approximately at the height of 1 m.

The experimental data is collected using Fujitsu notebooks of model P7010D, which are equipped with a 1.20 GHz Intel Pentium M processor together with 512 MB of memory. The notebooks run Linux 2.6 with a Debian distribution. We use a freely available software tool called the Jugi's Traffic Generator (JTG) [1] to generate Constant Bit Rate (CBR) traffics.

B. The Topology of the Experiments

Our experiments are carried out in a small playground where there is no other interferences, like access points. The topology of our experiments is the same as that shown in Fig. 3. The transmission on Link 1 is from RT1 to RT 2, which acts as the interference. On Link 2, which is the main link, RT 3 receives packets from RT 4. Both links are set to have a length of about 20 meters due to space limitation. We set the transmission power to be 79 mW. We also set the data rate of Link 1, the interfering link, to 500 kbps, and the data rate of Link 2, the main link, to 1 Mbps. Link 1 always uses channel 1, and we change the channel of Link 2 from channel 1 to channel 8. Each time, the CBR traffic with packets of 1460 Bytes lasts for 60 seconds, and we collect the throughput of Link 2 to check the interference introduced by Link 1 when RT 1 is 1 meter, 2 meters, and 3 meters away from RT 3, respectively.

C. Experimental Results

The experimental results are shown in Fig. 6. We can find that when the distance between RT 1 and RT 3 is fixed, the throughput of Link 2 increases as Link 2 changes from channel 1 to channel 8; and when the channel on Link 2 is fixed, the throughput of Link 2 increases as RT 1 moves far away from RT 3.

Moreover, when Link 2 uses channel 1, 2, 3, and 4, the interference on Link 2 is so serious that the throughput of

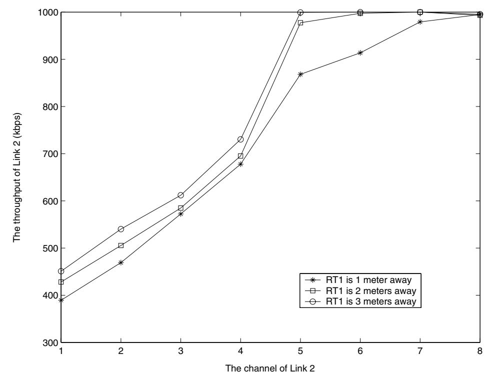

Fig. 6. The throughput on Link 2 when the channel it uses changes from channel 1 to channel 8.

Link 2 is degraded much. When Link 2 uses channel 5 and 6, the interference caused by Link 1 is greatly reduced when RT 1 is no less than 2 meters away from RT 3. Notice that, when Link 2 is on channel 6, a non-overlapping channel of channel 1, the interference introduced by Link 1 is still significant when RT 1 and RT 3 is only 1 meter away from each other. When Link 2 uses channel 7 and 8, the interference on Link 2 due to Link 1 is negligible even when RT 1 is just 1 meter away from RT 3.

D. Comparison with Theoretical Results

When the channel rate is 1 Mbps supported by DBPSK modulation scheme, the SINR and the receiver sensitivity should be more than -2.92 dB and -89 dBm, respectively, in order to correctly receive a signal. Since our experiments are carried out in a small playground where the routers are placed close to each other, we specify the general power propagation model in (5) as the free space power propagation model to estimate the received power, i.e.,

$$P_{r,RT3}(d) = \frac{P_{t,RT1} G_t G_r \lambda^2 I(x,y)}{(4\pi)^2 d^2 L} \tag{7}$$

In equation (7), we have

$$\begin{aligned} P_{t,RT1} &= 79mW, G_t = G_r = 1, \\ \lambda &= \frac{c}{f_c} = \frac{3 \times 10^8 m/s}{2.412 \times 10^9/s} = 0.124 \text{ m}. \end{aligned}$$

We also assume $L = 1$, i.e., no system loss. Thus, the interference at RT 3 caused by RT 1 is

$$\begin{aligned} P_{r,RT3}(d) &= \frac{0.079 \times 1 \times 1 \times 0.124^2 \times I(x,y)}{(4\pi)^2 d^2} \\ &= 7.69 \times 10^{-6} \frac{I(x,y)}{d^2} \text{ watt.} \end{aligned}$$

Besides, we can also obtain

$$\begin{aligned} P_{r,RT3}(d^*) &= \frac{0.079 \times 1 \times 1 \times \lambda_y^2 \times 1}{(4\pi)^2 20^2} \\ &= 1.25 \times 10^{-6} \lambda_y^2 \text{ watt} \end{aligned}$$

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TABLE I

IEEE 802.11B CHANNEL-TO-FREQUENCY MAPPINGS

Channel Number	Central Frequency	Channel Number	Central Frequency
1	2.412	7	2.442
2	2.417	8	2.447
3	2.422	9	2.452
4	2.427	10	2.457
5	2.432	11	2.462
6	2.437		

where λ_y is the wavelength when Link 2 is on channel y. Thus, according to the central frequencies shown in Table I[4], we have

$$\begin{aligned} P_{r,RT3}(d^*) &\geq 1.25 \times 10^{-6}\lambda_{11}^2 \\ &= 1.25 \times 10^{-6}(\frac{3 \times 10^8}{2.462 \times 10^9})^2 \\ &= 1.86 \times 10^{-8} \text{ watt} \\ &= -77.3 \text{ dBm}, \end{aligned}$$

which means the received power of the transmitted signal is always larger than receiver sensitivity no matter which channel Link 2 uses.

Moreover, ignoring the noise, we are now able to calculate the SINR at RT 3 as follows:

$$\begin{aligned} SINR_{RT3} &= \frac{P_{r,RT3}(d^*)}{N + P_{r,RT3}(d)} \\ &= \frac{1.25 \times 10^{-6}\lambda_y^2}{0 + 7.69 \times 10^{-6}\frac{I(x,y)}{d^2}} \\ &= 10\log(0.1625 \times \frac{\lambda_y^2 d^2}{I(x,y)}) \text{ dB} \end{aligned}$$

where $I(x,y)$ is shown in Fig. 5, and d varies from 1 meter to 3 meters. Because in Fig. 6 it can be observed that the interference caused by RT1 decreases when Link 2 changes from channel 1 to channel 5, and RT 1 still has interference on RT3 when they are separated by 5 channels, out of the four assumed receiver filters we think R3 is more reasonable.

Using R3 as the receiver filter, the values of $SINR$ at RT 3 when the distance between RT 1 and RT 3 is 1 meter, 2 meters, and 3 meters, respectively, are shown in Fig. 7. We can easily find in this figure that when RT 1 is 3 meters away from RT 3, the SINR at RT 3 can reach -2.92 dB when Link 2 uses channel 7, which is consistent with our experimental results since in this case the throughput of Link 2 achieves the maximum.

V. CONCLUSION

In this paper, we carry out both theoretical analysis and real experiments to study the interference between two channels. We show that with an interfering link operating on channel 1, the main link still suffers from the interference when the channel it uses changes from channel 1 to channel 6 if these two links are close to each other. We believe this

[4]http://www.qsl.net/n9zia/dsss-channels.html

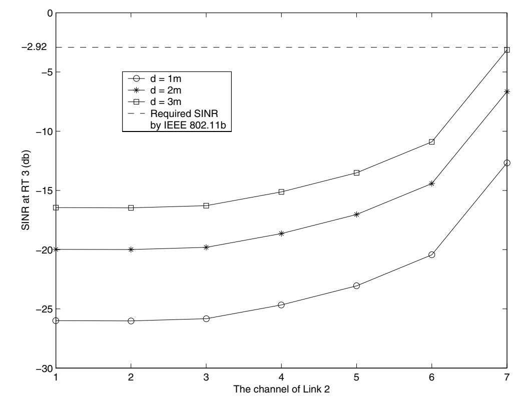

Fig. 7. The SINR at RT3 when Link 2 changes from channel 1 to channel 7.

study can provide some useful guidelines for those who are designing a wireless network using multi-channels.

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