Experimental Study on Co-existence of 802.11b with Alien Devices

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Abstract- **Several kinds of wireless communication systems, such as IEEE 802.11, BT, HomeRF, and cordless telephones, have been developed to run in the 2.4 GHz ISM band. In many cases, these technologies are complementary rather than competing, and are likely to co-exist in the same environment. This paper presents experimental results of the co-existence tests among these different systems working in the 2.4 GHz ISM band. The main goal of this work is to determine how the performance of 802.11b is degraded in the existence of such other devices in the neighborhood. This should be the first step towards a better co-existence solution for IEEE 802.11b WLAN in this band.**

I. INTRODUCTION

With the growth in demands for wireless ubiquitous data communications, many technologies have been developed. Because of wide bandwidth requirements, many of these technologies operate in the relatively high radio frequency (RF) bands (1-3 GHz). The ISM (industrial, scientific and medical) band at 2.4 GHz can be used for communications in an unlicensed manner, as long as the regulatory requirements, such as not exceeding the maximum transmission power, are met. Due to this attractiveness, many wireless communication devices have been developed and standardized to operate in this band. These include IEEE 802.11(b), HomeRF, Bluetooth, and some proprietary cordless telephones. In many cases, these technologies are complementary rather than competing, and hence are likely to be deployed in the same environment. Therefore, to understand and analyze how they perform when they co-exist is the first and important step towards a better co-existence solution if one does exist.

The IEEE 802.11b standard is the fastest (with 1, 2, 5.5, and 11 Mbps transmission rates) and most popular Wireless LAN (WLAN) technology as of today. We envision that as the price of implementing the standard becomes cheaper, more and more IEEE 802.11b devices will be adopted and deployed in many different environments including office, home, and public environments. This paper presents and discusses the throughput measurements made with an IEEE 802.11b Wireless LAN (WLAN) in co-existence with three different types of wireless devices, namely, Bluetooth, HomeRF, and cordless telephone.

The rest of this paper is organized as follows. Section 2 introduces the IEEE 802.11 Physical Layer (PHY) and the Distributed Coordination Function (DCF) of the Medium Access Control (MAC). Section 3 presents an overview of the alien devices used in the experiments. Section 4 shows the indoor WLAN configuration used for the measurements. Results and discussions are presented in Section 5, with conclusions in Section 6.

II. IEEE 802.11 WLAN

The IEEE developed the 802.11 WLAN standard to provide an Ethernet-like wireless networking technology [1]. It defines a MAC sublayer, MAC management protocols and services, and physical layers (PHYs). The increasing number of wireless users combined with the demand of high-speed multimedia services led to the requirement of higher data rates and bandwidths to be supported.

A. IEEE 802.11 PHYs

IEEE 802.11 originally defined three Physical Layers, operating at 1 and 2 Mbps, including Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and an Infrared specification (IR). Two new high-speed layers were additionally defined in 1999: 802.11a and 802.11b. The IEEE 802.11b is the most widely used and accepted WLAN technology today. 802.11b WLAN devices were used in the experiments.

The DSSS technique uses an 11-bit Barker chipping sequence that results in a signal spread over a wider bandwidth at a reduced RF power. This system helps to immunize the signal against narrow-band interference. Each channel occupies 22 MHz of bandwidth, thus allowing three non-overlapping channels in the 2.4 GHz band.

The 802.11b PHY is an extension of the original DSSS PHY. It operates in the same 2.4 GHz ISM band, providing 5.5 and 11 Mbps data rates in addition to the 1 and 2 Mbps rates already supported in the original DSSS PHY. To provide the higher data rates, 8 complex chip *Complementary Code Keying* (CCK) is employed as the modulation scheme. The chipping rate is 11 Mbps, which is the same as the original DSSS PHY, thus occupying the same channel bandwidth.

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B. *IEEE 802.11 MAC*

The IEEE 802.11 MAC sublayer provides a fairly controlled access to the shared Wireless Medium (WM) through two different access mechanisms: the basic access mechanism, called the Distributed Coordination Function (DCF), and a centrally coordination function, called Point Coordination Function (PCF). In this paper, we focus on the DCF access mechanism since it is the one implemented in the devices used for the experiments.

The DCF access mechanism is based on *Collision Sense Multiple Access with Collision Avoidance* (CSMA/CA). When a station wishes to transmit a MAC frame, it senses the medium to determine if it is busy. If it is busy, the station defers until the channel becomes idle, then transmit the frame after a fixed time period, called DIFS (see below), plus a randomly selected period of time (i.e., a back-off). If the medium has been idle more than DIFS, the station can transmit the frame immediately. Priority access to the medium is controlled through the use of *Inter Frame Space* (IFS) intervals, i.e. time intervals between the transmission of consecutive frames. This system allows every station access to the medium at the correct moment when sending a frame, but does not allow one station to transmit data with preference over others. The standard defines four different IFS intervals: *Short IFS* (SIFS), *PCF IFS* (PIFS), *DCF IFS* (DIFS), and *Extended IFS* (EIFS). A basic medium access method is illustrated in Figure 1.

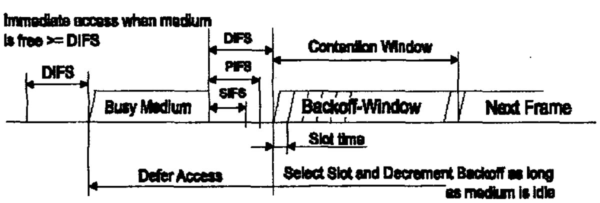

Fig. 1. Basic Access Method of 802.11

III. ALIEN DEVICES IN THE 2.4 GHZ ISM BAND

A. *Bluetooth (BT)*

Bluetooth wireless technology is a short-range and low cost wireless interface, optimized for mobile devices providing very low power consumption. It is applicable to the Wireless Personal Area Network (WPAN). Although it was designed principally for cable replacement applications, it can also establish an ad-hoc wireless network for both voice and data transmissions using its point-to-multipoint link functionality. A Bluetooth ad-hoc wireless network is called a *piconet*, where all data packets are exchanged between one master (controlling device in the network) and each slave

Most Bluetooth devices support a range of up to 10 meters, and speed of up to 700 Kbps for data and isochronous voice transmissions. The nominal transmission power level is specified to be 0 dBm (1mW), but can be increased up to 20 dBm (100mW), if necessary, to expand its communication range up to 100m. The Bluetooth physical (PHY) layer uses FHSS PHY at a rate of 1600 hops/sec, occupying 79 different channels of 1 MHz in the US. Gaussian Frequency Shift keying (GFSK) is used as the modulation scheme.

B. *HomeRF*

HomeRF 1.0 products are based on the Shared Wireless Access Protocol (SWAP). This protocol is designed to carry both voice and data traffic, and to interoperate with the Public Switched Telephone Network (PSTN) and the Internet. It uses a FHSS PHY at a rate of 50 hops/second, and supports both Time-Division Multiple Access (TDMA) for voice and other time-critical services, and CSMA/CA for data. The CSMA/CA MAC for data is similar to the mandatory part of the 802.11 MAC. Constant envelope Frequency Shift Keying (FSK) modulations are used to support data rates of 1 Mbps (BFSK) or 2 Mbps (QFSK) with 1 MHz frequency slots. The transmission power is 100 mW (20 dBm).

C. *Cordless Telephone (CT)*

The cordless telephones, which we used for our experiments, use non-standardized propietary solutions, based on FHSS technology.

IV. MEASUREMENT ENVIRONMENT

The indoor WLAN configuration used for the experiments is shown in Figure 2. A network was constructed using an 802.11b PC card (referred to as STA in the following) and an 802.11b Access Point (AP). The AP is connected to a Windows NT workstation with a crossover cable via the 100 Base-T Ethernet Port. The Ethernet runs at 100 Mbps, so it should not be the bottleneck for the network performance. The 802.11 PC Card is installed in a Windows 98 laptop. We use the default 802.11 configuration, including: (1) RTS/CTS off; (2) power management off; and (3) encryption disabled.

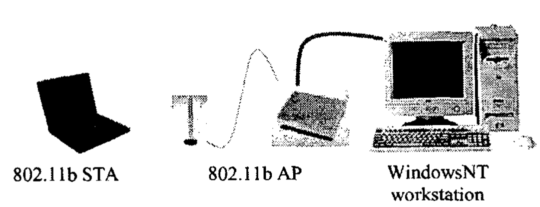

Fig. 2. Basic WLAN configuration using 802.11b devices

We measure the throughput performance between the AP and the 802.11b STA for different Received Signal strengths (RSS) by varying the distance between them. The Chariot Software from NetIQ was used to measure the throughput. This software allows us to (1) generate any source traffic pattern artificially, (2) transmit from a source to a destination in the network using a specific network protocol, and (3) measure the performance at the destination node. In the experiments, 1500 byte-long packets are sent continuously from the NT workstation to the STA using TCP/IP.

The received signal strength, i.e., RSS, is measured using the software tool provided with the 802.11b devices. In all the tests, the RSS in the AP and the STA are measured to be about the same.

V. Analytical and Measurement Results

A. *Theoretical Bound*

We first derive the throughput performance analytically as a reference. This is the theoretical maximum throughput, measured at the interface between the MAC and higher layers at the receiver, which can be achieved with the 802.11b WLAN. To simplify our analysis, we make the following assumptions:

1. There is only one sender and one receiver running in DCF mode with no interfering stations nearby. Therefore there are no collisions in the WM.
2. The sender sends 1500-byte long MAC frames at 11 Mbps continuously.
3. The channel is error-free.
4. The propagation delays are neglected.

With these assumptions, under the DCF of the IEEE 802.11 MAC, the *transmission cycle*, composed of the following phases, repeats over time: the DIFS deferral phase, the Back-off/contention phase, the data transmission phase, the SIFS deferral phase, and the ACK transmission phase.

The time to transmit an 802.11b data frame with L-byte payload at m Mbps PHY rate is given by

$$T_{data}^{m}(L) = tPLCPPreamble + tPCLPHeader + \frac{8*(28+L)}{m*1000000}, \quad (1)$$

and the time to transmit an ACK frame at n Mbps PHY rate is given by

$$T_{ack}^{n} = tPLCPPreamble + tPCLPHeader + \frac{8*14}{n*1000000}. \quad (2)$$

With these assumptions, the throughput (in bps) of the system, when the data frames are transmitted at m Mbps and the ACK frames are transmitted at n Mbps, is given by

$$T(m,n) = \frac{8*L}{aDIFSTime + \overline{T}_{bk} + T_{data}^{m}(L) + aSIFSTime + T_{ack}^{n}}, \quad (3)$$

where the average backoff time is given by

$$\overline{T}_{bk} = \frac{CW\min}{2} * aSlotTime \cdot \quad (4)$$

Using the values given in Table 1 for 802.11b and considering a packet length of 1500 bytes and transmission rates of 11Mbps for data and 2 Mbps for the ACK, we obtain a throughput of 6.24 Mbps. This value has been used for the throughput curve found in Figure 3.

The reason we get only about 6 Mbps compared to 11 Mbps transmission rate is due to (1) physical layer overheads from the preamble and header, and (2) MAC overheads from header/CRC, back-off process, and acknowledgement transmissions.

TABLE I
IEEE 802. 11b PHY Characteristics

Parameters	**802.11b**	**Comments**
aSlotTime	20usec	Slot time
aDIFSTime	50usec	DIFS time
aCWmin	31	Min contention window size in unit of *aSlotTime*
TPLCPPreamble	144usec	PLCP preamble duration
TPLCPHeader	48usec	PLCP header duration

B. *802.11b Throughput without Interference*

Figure 3 shows the measured performance of the 802.11b WLAN constructed in Figure 2 without any other alien devices around as well as the theoretical throughput performance.

We observe that there is approximately a 1 Mbps difference from the theoretical bound of 6.25 Mbps, even with high RSS. This difference seems to come from the overheads of the TCP/IP headers and TCP acknowledgements. We can also see that –70 dBm can be considered as the minimum RSS at which the 802.11b WLAN throughput is not affected. The throughput starts decreasing beginning at 70 dBm due to transmission errors, subsequent retransmissions, and switching to low PHY rates.

C. *Effect of Bluetooth on 802.11b*

To determine the effect of the Bluetooth interference in the 802.11b WLAN, we set two different scenarios.

There are many devices, such as laptops, that might use Bluetooth for connection to peripheral devices and 802.11b for network access by equipping both networking components. Ideally, these two wireless subsystems should be collocated and should be able to operate simultaneously. For this reason, we set this first scenario: There are two BT devices; one is just next to the 802.11b STA and the other is about 1 m away. The 802.11b STA and these two BT devices are moved together to take the measurements for different RSS.

The result is shown in Figure 4 (*BT collocated).* The 802.11b throughput degrades slowly up to –60 dBm, then decreases at a much higher rate for RSSs below this level. The reason behind this measured degradation is that the AP and the BT devices become separated by a distance that is large enough for the AP not to sense the BT devices. Therefore, the AP senses the medium idle and starts the transmission, resulting in low throughput due to some collisions between the BT packets and 802.11b frames from the AP in the 802.11b STA. Note that the 802.11 MAC is based on carrier sensing.[1] This scenario is the most likely to be seen in the real world in the near future, so this result is the most applicable. It should be noted that the effect of BT in this scenario really depends on the distance between the two 802.11b devices, i.e., the AP and STA in our setup. When the RSS is high, i.e., the separation is small, the effect of BT is not that severe, but when the RSS is low, i.e., the separation is high, the effect of BT becomes severe.

In the second scenario, we attempt to determine the effect of Bluetooth on the 802.11b AP. Two BT devices were set up; one (i.e., BT master) is located 1 meter away from the AP, and the other (i.e., BT slave) is located 1 meter away from the 802.11b STA. In Figure 4 (*BT near the AP),* we observe that the 802.11b throughput decreases gradually, but after –70 dBm, it starts increasing, and eventually the effect of BT becomes not significant at –80 dBm. This is due to the lower transmission power (and accordingly, shorter transmission range) of BT, which is 0 dBm in the BT devices we used. When the BT devices becomes out of range from each other, the connection between them is lost, and the interference to the 802.11b disappears.

D. Effect of HomeRF and CT on 802.11b

Now, we analyze the effect of other two different FHSS systems on 802.11b. These two devices have a transmission power comparable to the signal from the 802.11b STAs and the results clearly show the effect of a FHSS modulation on 802.11b.

Due to the similar target applications, HomeRF and 802.11b are competing rather than complementary, so are not likely going to co-exist within the same environment since (1) HomeRF will not be used in the enterprise/public environment, and (2) in the home environment, the customer will most likely only choose one of them. However, they may still co-exist in a way. For example, two neighboring families in a multi-family building may use two different WLAN technologies for their home networking. To capture this scenario, we place a pair of HomeRF devices in a room next to the room where the 802.111b WLAN is located. The results of the experiment are shown in Figure 5.

[1] While the 802.11 also defines an optional polling-based PCF as well, most commercial 802.11b devices such as the one we used run only the mandatory DCF, which is based on carrier sensing.

In case of cordless telephone (CT), we set the following scenario: the CT base station is near the 802.11b AP and the CT handset is near the 802.11b STA. So, the topology of this situation is very similar to the "BT near the AP" case.

We observe that the throughput performance degrades very slowly or somewhat steadily until it starts decreasing faster due to low RSS. This behavior is due to the characteristics of the FHSS modulation. That is, the FHSS signal will interfere, at most, a third of the whole operation time: 802.11b works in one of the three non-overlapping channels at the 2.4 GHz ISM band occupying about 22 MHz band, while FHSS device hops around the whole ISM band occupying a 1 MHz frequency slot at a time. Considering this, we can expect the maximum throughput degradation of 33%.

This behavior may be expected with BT, which is also a FHSS system. In that case (Figure 4), the 802.11 throughput experiences less degradation at high RSS, because of the low BT transmission power (0 dBm compared to the 15 dBm radiated by the 802.11 PC card used).

V. CONCLUSIONS

In this paper, we have presented the measured throughput performance of an IEEE 802.11b WLAN coexisting with other alien devices operating at the 2.4GHz ISM band. Some of the scenarios analyzed are of critical importance since some technologies are expected to co-exist and work simultaneously, e.g., BT and 802.11b WLAN.

The experimental results show how the throughput of 802.11b is degraded substantially in the existence of FHSS devices. However, we also find this degradation on an 802.11b WLAN is limited due to the PHY characteristics of FHSS in many cases. Due to the lower transmission power of BT, the effect of BT depends on the relative distance between 802.11b and BT devices. The most important result is for the case when the BT devices and the 802.11b STA are collocated, a scenario that is very likely to be found in a real world. In this case, we observed a high degradation of the 802.11b throughput when the STA and AP are within a likely distance for the 802.11b WLAN to work. Nevertheless, we believe that there are a number of techniques that could mitigate the impact of this interference.

As the experimental results show, the throughput performance degradation depends on the characteristics of the interfering signals in terms of: (1) frequency; (2) time; and (3) received interference level (which depends on the original, or transmission, power from the interference source as well as the distance from the source).

We also find that the relative topology as well as the physical distances among the interference sources and the 802.11b WLAN devices can also affect the network performance dramatically.

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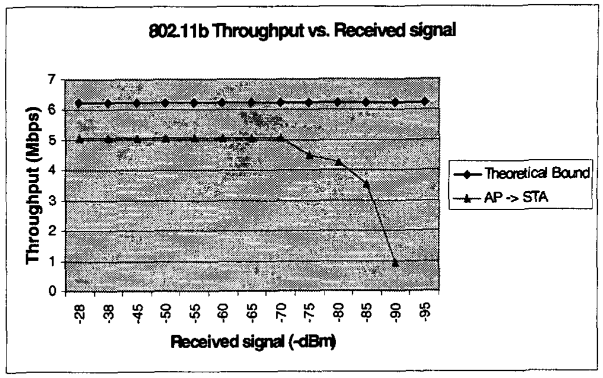

Fig. 3. 802.11b Throughput without interference

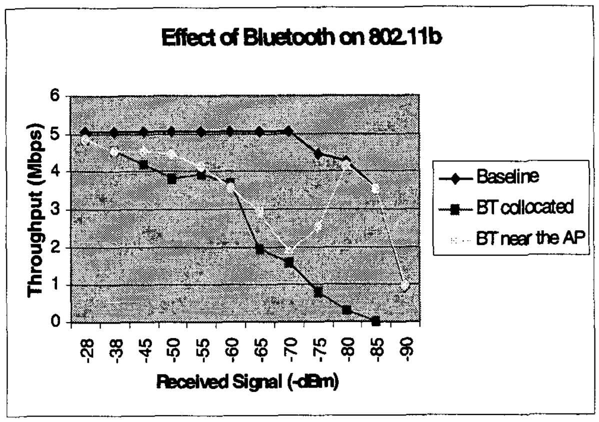

Fig. 4. Effect of Bluetooth on 802.11b

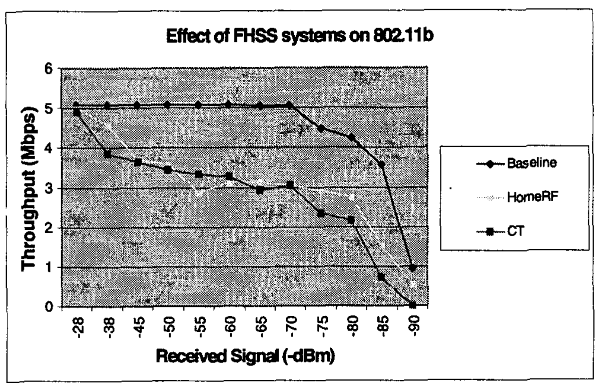

Fig. 5. Effect of FHSS systems on 802.11b