Wi-Fi (802.11b) and Bluetooth: Enabling Coexistence

Jim Lansford, Adrian Stephens, and Ron Nevo, Mobilian Corporation

Abstract

This article provides an introduction to issues of coexistence between Bluetooth and Wi-Fi™ (IEEE 802.11b), with particular attention to scenarios requiring simultaneous operation, or Sim-OP™, of both systems in very close proximity. The article explains basic interference mechanisms and quantifies their impact through both actual measurements and simulation. We have developed a detailed simulator that fully models behavior of the PHY and MAC of both Bluetooth and 802.11b; it is used to expand the analysis and project the mutual impact of collocated Bluetooth and 802.11b systems across a number of geometries, system parameter settings, and design choices, complementing efforts within the IEEE 802.15.2 Task Group, which are also discussed. The article concludes with a discussion of techniques with the potential to greatly improve the performance of collocated Bluetooth and Wi-Fi systems. A key result of this investigation is that while performance of both systems can degrade when they are collocated, a number of techniques can be employed to virtually eliminate the problems.

The 2.4 GHz industrial, scientific, and medical (ISM) band is poised for strong growth. Fueling this growth are two emerging wireless technologies: wireless personal area networking (WPAN) and wireless local area networking (WLAN). The WPAN category is led by a short-range wireless technology called Bluetooth. Designed principally for cable replacement applications, most Bluetooth implementations support a range of up to roughly 10 m, and speeds of up to 700 kb/s for data or isochronous voice transmission. Bluetooth is ideal for applications such as wireless headsets, wireless synchronization of personal digital assistants (PDAs) with computers, and wireless peripherals such as printers or keyboards. Cahners In-Stat predicts the market for Bluetooth devices will reach 800 million units by 2004 [1].

The WLAN category has several technologies competing for dominance; however, based on current market momentum, it appears that Wi-Fi (IEEE 802.11b)[1] will prevail. Wi-Fi offers speeds of 11 Mb/s and covers a range of up to 100 m. With WLANs, applications such as Internet access, e-mail, and file sharing can now be done in the home or office with new levels of freedom and flexibility. Cahners predicts WLAN shipments of more than 5 million units in 2004, implying an installed base of nearly 20 million systems [2].[2]

WPAN and WLAN are complementary rather than competing technologies. Moreover, with both of them expecting rapid growth, collocation of Bluetooth and Wi-Fi devices will become increasingly likely, especially in computing devices. While there are certainly many devices where different radio technologies can be built into the same platform (e.g., Bluetooth in a cellular phone), collocation of Wi-Fi and Bluetooth is of special significance because both occupy the 2.4 GHz frequency band. This creates the potential for interference between the two technologies, and hence the need for coexistence. In this article we will use the term *coexistence* to mean wireless systems can be collocated without significantly impacting the performance of either [3].

In recognition of the need for coexistence between these (and other) systems, the IEEE (who developed the 802.11b specification on which Wi-Fi is based) has created a coexistence task group, IEEE P802.15.2; and the Bluetooth SIG has created a Coexistence Working Group. The outcome of the work of these groups will be a set of recommended practices for the industry. Much of the work presented in this article either contributed directly to the efforts of these groups or complemented them.

Previous Work

Analysis of interference between 802.11b and Bluetooth is not new, as indicated by literature such as [4]. Early attempts to quantify the mutual interference effects [5, 6] were based on simple geometric models of Bluetooth deployment rather than actual usage models. In [7] the investigation focused on the problem of calculating the probability of an overlap, in both time and frequency, of a continuous sequence of Bluetooth packets and an IEEE 802.11b direct sequence (DS) 11 Mb/s packet. Relative power levels between BT and 802.11b packets were not considered. In [8–10], several refinements on previous assumptions were made. The efforts were continued by [5, 6]. These prior efforts did not examine in detail the full ramifications of the physical layer (PHY) (e.g., hopping, spectral masks, filter selectivity) and implementations. In addition, the geometries studied did not necessarily correspond to practical usage models.

More recent results presented by Golmie [11] model both PHY and media access control (MAC) behaviors, which is necessary to accurately predict performance; this article utilizes some of the same approaches to modeling, providing a firm foundation on which to evaluate the effectiveness of interference techniques. Much of the work of PHY modeling in this article as well as the

[1] *In this article the terms 802.11b and Wi-Fi will be used interchangeably.*

[2] *The mark Wi-Fi belongs to the Wireless Ethernet Compatibility Alliance, and the Bluetooth mark belongs to the Bluetooth SIG, Inc. The term Sim-OP is trademarked by Mobilian Corporation; other signs and marks used in this article are the property of their respective owners.*

MAC layer modeling by Golmie have been incorporated into simulation results presented in IEEE P802.15.2. The primary differences between models used in this article and the results in Golmie's work are in the tools used and the level of detail in the PHY model. The model used in this article is written in C, while Golmie's model is in Opnet. Early versions of Golmie's model used the same PHY model as in this article, but additional details were incorporated in the results given in [11].

This article gives a basic introduction to Bluetooth and Wi-Fi technologies, followed by a brief review of interference mechanisms. With that material as background, the article describes a series of measurements of the interaction between Bluetooth and Wi-Fi, and a computer model that can be used to predict effects of interference on throughput of both systems. Next, the activities in IEEE 802.15.2 are highlighted. Finally, a number of suggested techniques are described that can enhance the coexistence of these technologies, especially when collocated.

Wi-Fi and Bluetooth Interference Basics

Wi-Fi (802.11b) and Bluetooth Overview

Bluetooth was designed as a cable replacement radio frequency (RF) technology: low cost, modest speed, and short range (< 10 m). It can support *piconets* of up to eight active devices, with a maximum of three synchronous connection-oriented (SCO) links. SCO links are designed to support real-time isochronous applications such as cordless telephony or headsets. Bluetooth also supports asynchronous connectionless (ACLs) data types used to exchange data in non-time-critical applications. The Bluetooth PHY layer uses frequency-hopping spread spectrum (FHSS) at a rate of 1600 hops/s and Gaussian frequency shift keying (GFSK) modulation. Based on the applications considered for Bluetooth wireless technology, the majority of Bluetooth devices will transmit at a power level of about 1 mW (0 dBm) with a raw data rate of 1 Mb/s.

Like Ethernet, Wi-Fi supports true multipoint networking with such data types as broadcast, multicast, and unicast packets. The MAC address built into every device allows a virtually unlimited number of devices to be active in a given network. These devices contend for access to the airwaves using a scheme called carrier sense multiple access with collision avoidance (CSMA/CA). The Wi-Fi physical layer uses direct-sequence spread spectrum (DSSS) at four different data rates using a combination of differential binary phase shift keying (DBPSK) for 1 Mb/s, differential quaternary phase shift keying (DQPSK) for 2 Mb/s, and QPSK/complementary code keying (CCK) for the higher speeds, 5.5 and 11 Mb/s. The RF power level can vary, but is typically between 30 and 100 mW (up to +20 dBm) in most commercial WLAN systems.

Wi-Fi and Bluetooth: Sharing the Same Frequency Band

Wireless communication systems use one or more carrier frequencies (frequency bands) to communicate. Bluetooth and Wi-Fi share the same 2.4 GHz band, which under U.S. FCC regulations extends from 2.4 to 2.4835 GHz. Under the ISM band rules defined in FCC Part 15.247 [12], this frequency band is free of tariffs. However, systems must operate under certain constraints that are intended to enable multiple systems to coexist in time and space. A system can use one of two methods in order to transmit in this band, both spread spectrum (SS) techniques. The first is FHSS, where a device can transmit high energy in a relatively narrow band but for a limited time. The second is DSSS, where a device occupies a wider bandwidth with relatively low energy in a given segment of the band, and it does not hop.

As outlined in the preceding section, Bluetooth selected FHSS, using channels of 1 MHz in width and a hop rate of 1600 times/s (625 μs in every frequency channel). Bluetooth uses 79 different channels in the United States and most of the rest of the world. IEEE 802.11b picked DSSS, using 22 MHz of bandwidth (passband) to transmit data at speeds of up to 11 Mb/s. A Wi-Fi system can utilize any of 11 22-MHz-wide subchannels across the acceptable 83.5 MHz of the 2.4 GHz frequency band, which obviously must result in overlapping channels. A maximum of three Wi-Fi networks can coexist without interfering with one another, since only three of these 22 MHz channels can fit within the allocated band without overlapping. Geographies outside of the United States may support more or fewer than 11 selectable subchannels. However, regardless of the portion of the band in which Wi-Fi operates, sharing with Bluetooth is inevitable. Two wireless systems using the same frequency band can potentially interfere with each other.

Signals and Noise

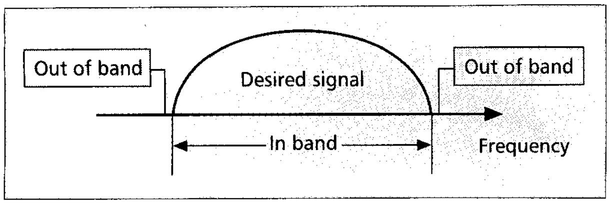
Every wireless communication system, by definition, consists of at least two nodes. At any given time one node transmits (a transmitter) and the other receives (a receiver). Both 802.11 and Bluetooth stations transmit or receive, but not both at the same time (half-duplex systems); there are other systems where a station transmits and receives at the same time (full-duplex systems); the following discussion applies to both types of systems. Successful operation of the system depends on the ability of a receiver to separate a desired signal from an undesired signal. This depends on the ratio between the energy of the desired signal and the total noise (interference) at the antenna of the receiver. This ratio is referred to as E_b/N_t (energy per bit over total noise) or signal-to-noise ratio (SNR). The job of a receiver is to maximize the ability to decode desired signals while minimizing the ability to allow undesired signals (noise) to interfere. One of the most important characteristics of a communication system is the minimum SNR at which the receiver can still successfully decode the signal (the E_b/N_t threshold of the system). The lower the E_b/N_t threshold, the greater the system's immunity to interference. The lower the SNR, the more likely the undesired signal will cause unacceptable errors in data packets that force retransmission (and delays inherent in that process) or affect voice quality. There are also situations where noise is so strong that the receiver cannot begin to recover the desired signal.

The noise at the receiver's antenna can be divided into two categories, defined here and illustrated in Fig. 1:

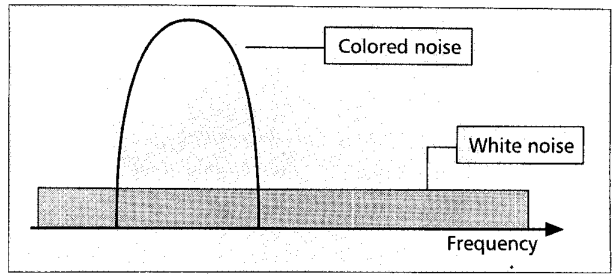
- **In-band noise** — *undesired* energy in frequencies the transmitter uses to transmit the desired signal
- **Out-of-band noise** — *undesired* energy in frequencies the transmitter does not use

Both in-band and out-of-band noise can degrade the performance of a wireless communications system. Out-of-band noise can usually be filtered out because the energy in the system's frequency band does not carry any useful information. In-band noise, as discussed in subsequent sections, is much more problematic.

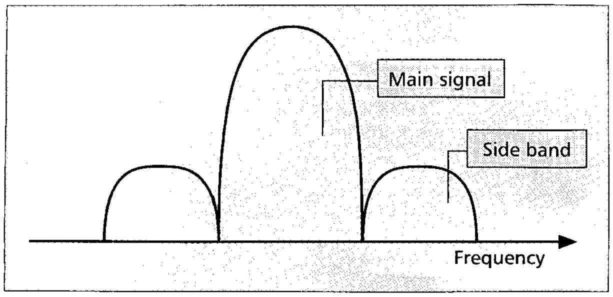
Noise can be further categorized as either *white* or *colored*. White noise generally describes wideband (i.e., wider than the desired signal) interference from multiple sources without any coordination between them. It can be modeled as a Gaussian random process where successive samples of the process are statistically uncorrelated. Typically, the energy associated with white noise is distributed evenly across the frequency band and does not have any deterministic behavior over time or frequency. Colored noise is usually narrowband (i.e., relative to the desired signal) interference transmitted



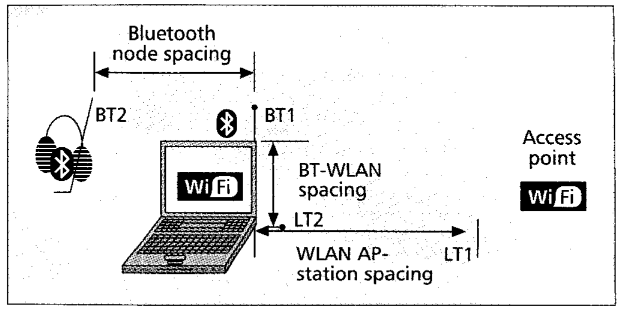
■ Figure 1. *In-band vs. out-of-band noise.*



■ Figure 2. *White noise vs. colored noise.*



■ Figure 3. *A typical transmit mask.*

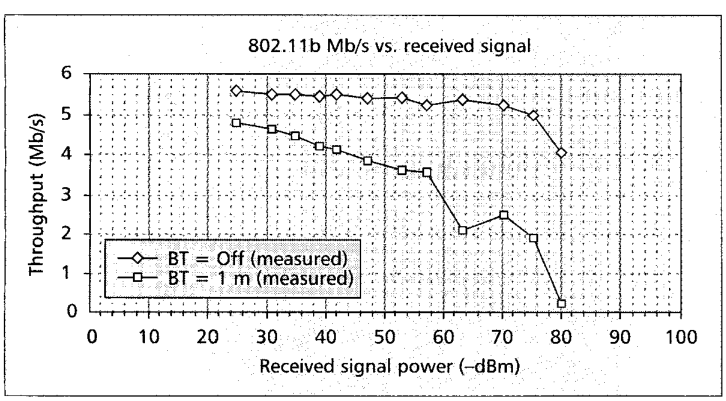


■ Figure 4. *Geometry of the measurement environment.*

by intentional radiators, and has a specific behavior in time and frequency. Figure 2 illustrates the difference between white and colored noise.

Most wireless communication systems assume that the only type of in-band noise is white noise. Other intentional radiators are assumed to transmit out-of-band. Receiver designs with their associated filtering techniques are optimized around these assumptions. We use the term *intentional radiator* to differentiate signals deliberately emitted to communicate from those that are spurious emissions. Unfortunately, where two intentional radiators such as Bluetooth and Wi-Fi share the same frequency band, receivers must also address the case of in-band colored noise.

Every transmitter is supposed to transmit only within a limited bandwidth; however, this is not physically possible without injecting noise to adjacent frequencies (sideband signals), as shown in Fig. 3. The amount and nature of sideband signals created during transmission are determined by what is referred to as the transmitter's *transmit mask*. Sideband signals must be considered when evaluating interference between wireless systems sharing a frequency band. In addition, receiver filters cannot be perfectly rectangular, meaning that the filter cannot precisely differentiate between signal and noise just inside and outside the passband. The combined impact of these transmit and receive masks explains what is referred to as *adjacent channel interference*.



■ Figure 5. *Measured throughput of Wi-Fi in the presence of Bluetooth.*

Bluetooth and Wi-Fi Interference Cases

If Bluetooth and Wi-Fi operate at the same time within the same frequency band, they will interfere with each other (collide). Specifically, these systems transmit on overlapping frequencies (including the effect of sidebands), creating in-band colored noise for one another. Interference between Bluetooth and 802.11b occurs when either of the following is true:

- An 802.11b receiver senses a Bluetooth signal at the same time as an 802.11b signal is being sent to it. The effect is most pronounced when the Bluetooth signal is within the 22-MHz-wide passband of the 802.11b receiver.
- A Bluetooth receiver senses an 802.11b signal at the same time as a Bluetooth signal is being sent to it; the effect is most pronounced when the 802.11b signal is within the passband of the Bluetooth receiver.

It is worthwhile to note that neither Bluetooth nor Wi-Fi was designed with specific mechanisms to combat the interference each creates for the other, except for some limited interference immunity due to the nature of spread spectrum technology. As a fast frequency hopping system, Bluetooth assumes that it will hop away from bad channels, minimizing its exposure to interference. The 802.11b MAC layer, based on the Ethernet protocol, assumes that many stations share the same medium, and if a transmission fails, it is because two Wi-Fi stations tried to transmit at the same time. Later, we will discuss how this assumption drives system behavior that actually worsens the impact of interference from Bluetooth.

Interference Measurements

Prior to diving into the details of the various interference mechanisms, it is worthwhile to provide a few simple measurements that demonstrate the potential magnitude of the interference issue in a usage scenario consistent with Sim-OP.

Measurement Environment

The geometry of the measurement environment is shown in Fig. 4. The configuration was intended to be representative of a laptop (a device that will frequently need Sim-OP) equipped with collocated 802.11b and Bluetooth interacting simultaneously with an 802.11b access point (AP) and another Bluetooth node. The nodes participating in the measurements are described in Table 1. The links between these nodes are described in Table 2. The main variable in these measurements is the AP-to-laptop distance.

Ganymede Chariot (the program used by the Wireless Ethernet Compatibility Alliance, WECA, in its Wi-Fi compliance testing) was used here to control the load placed on the WLAN and measure throughput.

It should be noted that while tests using specific manufacturers' equipment are described in this article, these results are common across tests of many different vendors' systems.

Node	Type	Power level
LT1:	WLAN access point (Cabletron)	30 mW
LT2:	WLAN station/client (Cabletron)	30 mW
BT1:	BT master Laptop containing PC card from Digianswer	1 mW
BT2:	BT slave Laptop containing PC card from Digianswer	1 mW

■ Table 1. *Nodes participating in the measurement environment.*

Link	Distance	Link type
BT1-BT2	1 m	DH5 (master→slave)
LT2-BT1	10 cm	No "user" data exchanged, although these nodes could "collaborate" to manage interference between the other links
LT2-BT2	1 m	No communication
LT1-LT2	Varies	TCP/IP traffic; the data packet size is 1500 bytes, corresponding to the Ethernet packet size

■ Table 2. *Link types used in the simulation.*

Measurement Results

Figure 5 presents two sets of measurement results that capture Wi-Fi throughput as a function of received signal strength at the Wi-Fi station (LT2). The diamond marked line shows Wi-Fi performance with all Bluetooth turned off (baseline). The square marked line shows Wi-Fi throughput with Bluetooth active.

Ultimately, our interest is in understanding the impact on Wi-Fi performance over distance. However, given that distance is highly dependent on the actual physical environment, the received signal strength was selected. In this way results can be extended across environments by making simpler physical energy-level measurements rather than having to reproduce and execute full test suites. Table 3 shows a mapping of received signal strength to distance for a particular office environment with cubicles. The *degradation vs. baseline* column shows the percentage of performance reduction of the Wi-Fi link in the presence of the Bluetooth interferer. The *distance (m) free space* column shows the distance between the two Wi-Fi nodes assuming a free-space path loss. The *distance (m) and # of cubicle walls* column shows the distance between the two Wi-Fi nodes assuming an office environment in which cubicle walls have to be penetrated.

Brief Discussion of Results

In the scenarios measured, even Wi-Fi stations less than 5–7 m (free space) from their access point will suffer more than 25 percent degradation in throughput. This degradation exceeds 50 percent by the 30 m mark. Within an office environment with cubicles, the range associated with each throughput level will be significantly reduced. When cubicles must be penetrated, Wi-Fi loses almost one-third its expected throughput within the first couple of meters. Erosion of performance in excess of 50 percent takes place with stations less than 8 m from their AP. The focus of this particular experiment was on Bluetooth's impact on Wi-Fi. However, subsequent simulations will demonstrate that while the impact of Wi-Fi on Bluetooth is not as significant as that of Bluetooth on Wi-Fi, coexistence issues can substantially degrade Bluetooth voice performance.

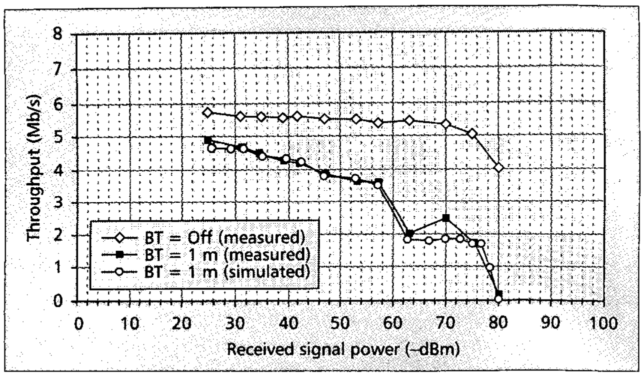
It should be stressed that interference between radio systems is highly variable and depends on a number of factors, primarily geometry of the nodes. Given the nature of radio-wave propagation and implementation limitations of receiver design, it is always possible to construct scenarios that will give pathologically poor performance (or unrealistically excellent performance). The scenario outlined in the preceding discussion, as well as the simulation scenarios that follow, represent neither extreme, but are indicative of the results that led the industry to look for solutions.

Interference Simulation

Using knowledge of the characteristics of Bluetooth and Wi-Fi, a detailed simulation environment was created to make quantitative assessments of the mutual impact of interference. This simulation can reinforce understanding of interference mechanisms and help develop and evaluate high-impact coexistence techniques.

Received signal strength (dBm)	Degradation vs. baseline (%)	Distance (m) free space	Distance (m) and # of cubicle walls
–25.62	14.33	1	
–31.64	16.26	2	
–35.17	19.23	3	
–39.61	24.01	5	
–42.53	25.11	7	
–46.93	30.11	10	
–52.74	34.29	15	2 m — 1 wall
–56.86	32.60	20	4 m — 2 walls
–62.67	62.88	30	6 m — 3 walls
–69.99	53.78	50	8 m — 4 walls
–74.82	63.63	70	
–79.93	95.50	100	20 m — down a corridor; 2 office walls

■ Table 3. *Received signal strength vs. distance.*



■ Figure 6. *Calibration of simulation and experimental trials.*

Simulation Overview

We have created the simulation model used in this article for the purpose of characterizing Bluetooth and Wi-Fi interference effects and driving solutions that enable coexistence and simultaneous operation; its operation is similar to the NIST model described by Golmie [11]. This highly flexible C program accurately models the behavior of both the PHY and MAC layers of both Bluetooth and Wi-Fi. In fact, most of the key parameters discussed in the next section can be varied to simulate different scenarios.

The typical scenario involves a Sim-OP laptop interacting with a Wi-Fi Access Point and a Bluetooth node. Both additional Bluetooth piconets and additional Wi-Fi stations can be added. Distances between AP and laptop, between laptop and Bluetooth node, and between laptop and other Bluetooth piconets can easily be varied. Wi-Fi data rates and packet sizes, along with Bluetooth modes of operation, can also be defined and varied.

Scenario Setup and Calibration

We have calibrated the simulation to the measurement data shown in Fig. 5 in order to verify the accuracy of the model. As with the measured data, in each simulated scenario the Wi-Fi-AP-to-Wi-Fi-station distance varies. The objective of the first scenario was simply to replicate the results obtained through the actual experiment as a way of validating the simulation setup. Wi-Fi station (STA) to collocated Bluetooth distance is fixed at 10 cm. The complementary Bluetooth node is located 1 m away. Table 4 documents additional parameter values used to produce the simulation results presented in this article.

Figure 6 compares actual (measured) vs. predicted (simulation) results for the scenario described earlier, based on parameters that are unique to the equipment tested. With this level of agreement, we are confident that projections of system performance across other scenarios (assuming the same equipment) are accurate.

Note that this model does not directly account for multipath effects, although the path loss term beyond 8 m does take into account some of the range reduction due to reflections. As with any empirical model, it represents mean path loss values and cannot predict the specific frequency-selective effects that have a significant impact on frequency hopping systems. Such detailed simulations are highly site-specific and must employ models that predict exact signal paths, which cannot be generalized and typically require several hours to run. An empirical model such as the one used here is a highly useful tool for predicting performance that can be tied to average measurements.

Simulation Scenarios

After establishing a calibrated baseline, we varied additional parameters in simulation to further understand the impact of various key parameters. In particular, simulations were con-

Parameter	Wi-Fi STA and AP	Bluetooth nodes
Path loss model (path loss in dB, distance in meters)	$L_p = -40.0 - 20\log(d)$, when $d \le 8$ m $L_p = -58.5 - 33\log(d/8)$, when $d > 8$ m	$L_p = -40.0 - 20\log(d)$, when $d \le 8$ m $L_p = -58.5 - 33\log(d/8)$, when $d > 8$ m
Environmental description	Open office	Open office
Transmit power	30 mW	1 mW
Transmit mask	$11 < \|f - f_c\| < 22$: –30 dB $22 < \|f - f_c\|$: –50 dB	$0.5 < \|f - f_c\| \le 1.5$: –20 dB $1.5 < \|f - f_c\| \le 2.5$: –40 dB $2.5 < \|f - f_c\| \le = 3.5$: –60 dB $3.5 < \|f - f_c\|$: –infinity
Compression point	Ignored	Ignored
Receiver sensitivity	–83 dBm	–85 dBm
Receiver bandwidth (passband)	22 MHz	1 MHz
Receiver attenuation — adjacent/alternative channel selectivity	$11 < \|f - f_c\| < 12$: –12 dB $12 < \|f - f_c\| < 22$: –36 dB $22 < \|f - f_c\|$: –56 dB	$0.5 < \|f - f_c\| \le 1.5$: –11 dB $1.5 < \|f - f_c\| \le 2.5$: –41 dB $2.5 < \|f - f_c\|$: –51 dB
Mode/data rate/packet length	Asymmetric packet flow from AP to STA. STA sends layer 3 ACKs only. 11 Mb/s; 1500-byte packets	Varies by scenario DH5 (5-slot ACL data packet) or HV1 (1-slot SCO data packet) See [13] for a description of these packet types
MAC behavior	Reduction in data rate and fragmentation mechanisms disabled	

■ Table 4. *Simulation setup parameters.*

ducted that increased the intensity of Bluetooth activity (from DH5 to SCO HV1), added more Bluetooth piconets, and increased 802.11b transmission power from 30 to 100 mW.

Simulation Results

The Impact of SCO Links — Figure 7 demonstrates the impact of changing Bluetooth piconet activity from a high-rate basic data application to an SCO activity, as would be typical in a voice application. Note that in the range of –40 to –50 dBm, Wi-Fi performance has dropped to around 2 Mb/s, representing a more than 60 percent reduction in throughput within the first 10 m (free space) of distance from the Wi-Fi AP. Drawing from Table 2, this performance would represent a degradation of Wi-Fi throughput to approximately 1 Mb/s when the Wi-Fi STA is less than 6 m from the AP when there is a requirement to penetrate office cubicles.

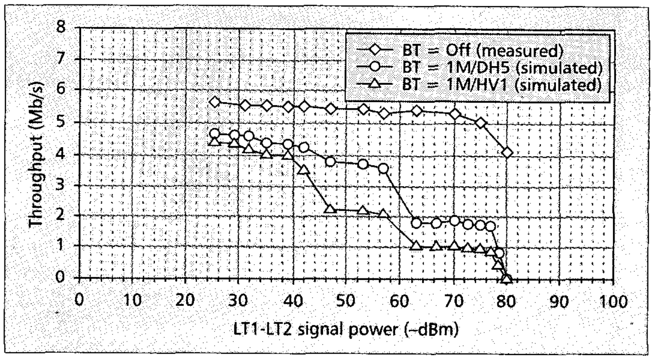
Additional Piconets (The Office Scenario) — With the help of a major computer system operating equipment manufacturer (OEM), Mobilian Corporation developed a scenario (depicted in Fig. 8) to represent four Wi-Fi and Bluetooth equipped notebook computers in a conference room and/or in adjacent cubicles where the stations are arrayed around a common shared corner. In this scenario DH5 Bluetooth is used for all piconets, and Wi-Fi throughput is measured at a single station.

Figure 9 shows the results of this scenario with Wi-Fi throughput mapped against Wi-Fi-AP-to-Wi-Fi-STA distance. Distance is calculated by comparing received-signal-strength-based values against the free space energy-distance measurements in Table 3.

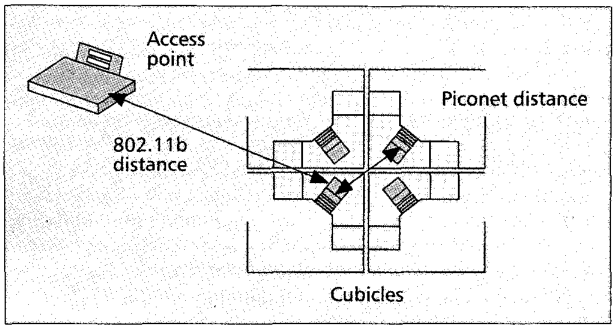
The Effect of Wi-Fi on Bluetooth — Also of importance is the degradation of Bluetooth performance in the 802.11b environment.

Figure 10 shows the throughput reduction of the Bluetooth node as a function of the STA-Bluetooth pair's distance from the Wi-Fi AP.

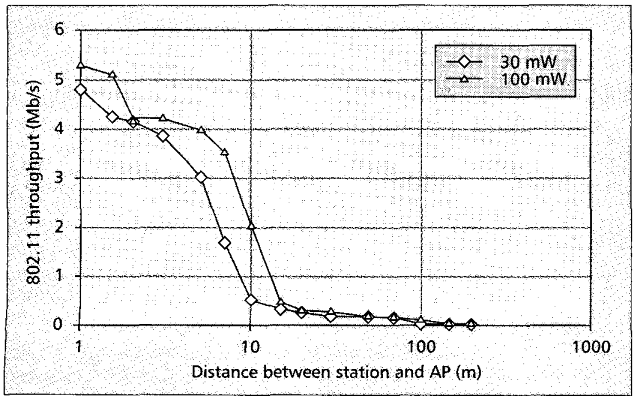
Because the 802.11b system looks like a broadband jammer to the Bluetooth node, we would expect to see voice packet failures occur more or less randomly until the AP is sufficiently far away (i.e., the SNR increases) to let the capture effect block the interference. Since the Bluetooth receiver is nonlinear, we would expect to see this transition occur sharply, and the simulation indicates that it does. It also is interesting to note that the relatively short ACKs (< 150 μs) in the STA do not seem to cause severe packet loss, while the much longer Ethernet packets from the AP do cause significant Bluetooth packet loss.



■ Figure 7. *The impact of Bluetooth DH5 vs. HV1.*



■ Figure 8. *Basic geometry of the office scenario.*



■ Figure 9. *An office scenario with varying Wi-Fi power levels.*

Interference-Reduction Techniques

As the previously supplied physical measurements and simulation results demonstrate, the coexistence problem is significant. Fortunately, a number of techniques can be employed to reduce the interference between 802.11b and Bluetooth, and are under investigation by IEEE 802.15.2. These techniques can be grouped into four general categories:

- Regulatory and standards
  - Spectrum-usage regulations
  - Specifications in standards bodies
- Usage and practices
- Technical approaches
  - General system approaches
  - Driver layers
  - MAC layers
  - Physical layers
- Alternate frequency bands
  - 5 + GHz

Regulatory and Standards

Regulatory Proposals — Under current (June 2001) FCC rules, Bluetooth is required to hop over almost the entire ISM band from 2.400 to 2.4835 GHz. Furthermore, it must occupy a minimum of 75 MHz, and each channel in Bluetooth is 1 MHz wide. The Bluetooth specification actually calls for 79 channels, so it must cover virtually the entire band as it pseudorandomly hops around. This band coverage is the reason time-frequency collisions between Bluetooth and 802.11b are inevitable.

A rule change has been proposed by the FCC that would allow wireless systems using 1-MHz-wide channels to hop over only part of the ISM band; for example, a piconet might hop over only a segment of the band. While a host of technical details remain to be worked out, this proposal would in principle allow 802.11b and Bluetooth to completely avoid each other in some scenarios (although it may not help much in dense environments such as the fully loaded enterprise scenario where two or three Wi-Fi networks on different frequency bands coexist); adaptive hopping may not offer improvement when Wi-Fi and Bluetooth are collocated. Since rule changes can often take a significant amount of time, and details of the final Report and Order are impossible to predict in advance, it is difficult to assess the timing and effectiveness of these proposals. However, based on experience in the cordless telephone industry, there is reason to believe that a properly designed adaptive hopping system can improve coexistence in many cases.

Standards/Industry Bodies — As awareness of the coexistence issues has grown, progressive groups within the industry have begun to address the problem and look for solutions. The most active group is IEEE 802.15.2, which issued a formal call for proposals in September 2000, and is expected to publish a "Recommended Practices" document in 2001 that will address a range of coexistence solutions. This group will publish recommended practices for *collaborative* and *noncollaborative* coexistence; the former means there is direct communications between the two systems, while the latter means they must indirectly infer the interference environment. The Bluetooth SIG has a Wireless LAN Coexistence Working Group that is also actively involved in seeking solutions to the coexistence problem. Finally, WECA has an ad hoc task force addressing coexistence issues, and will be publishing white papers to outline the magnitude of the problem and recommended solutions.

Work in IEEE 802.15.2 has made rapid progress toward providing a suite of coexistence tools to enhance performance; the group will only publish one collaborative coexistence mechanism, which was selected in March 2001 [14]. Multiple noncollaborative mechanisms such as adaptive frequency hopping can be published, and these are under review by the group for publication later in 2001.

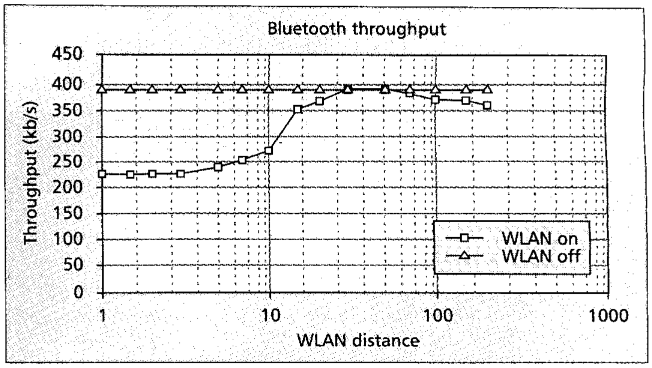
Usage and Practices

One solution some companies have chosen for Bluetooth-802.11b coexistence is to ban Bluetooth. One could also imagine a ban on 802.11b in environments where Bluetooth is considered mission-critical. This is not an especially workable solution, since people will want to use tools that make them more productive. Since these two technologies complement each other, such a drastic solution will soon prove itself impractical and unenforceable.

At the level of the individual user, modal operation of Bluetooth and 802.11b could be practiced. This approach is reasonable where Bluetooth applications are exercised only sporadically and for short time durations (e.g., a daily sync between a PDA and a desktop). However, as densities of Wi-Fi and Bluetooth devices both grow, impact on and from neighboring cubicles become relevant considerations and tend to undermine such modal usage models. More fundamentally, any proposal that requires such high degrees of user awareness and behavior modification is unlikely to succeed.

Technical Approaches

General System Approaches — Because of the role of signal-to-noise energy levels in determining packet loss, it is tempting to explore the role of transmission power in improving coexistence. Additional simulations demonstrate that lowering the power levels in the collocated Bluetooth node does not change the basic shape of the Wi-Fi performance degradation curve, but rather shifts this curve to the right, increasing the range over which any given throughput level is possible. Many Bluetooth usage models (e.g., involving a notebook computer) require relatively short-range interaction with other Bluetooth devices such as PDAs and peripherals. Given these limited range requirements, Bluetooth systems with lower or variable power could be viable and would lessen the interference impact on Wi-Fi. Likewise, power control techniques in Wi-Fi



■ Figure 10. *Throughput reduction of Bluetooth (SCO) in the presence of Wi-Fi.*

are being investigated by several firms [15]; this effort will be necessary in the MAC for 5 GHz WLANs sold in Europe, wherethe European Telecommunications Standards Institute (ETSI) requires transmit power control (TPC).

Driver Layer — There has been some discussion within the industry about using the software layers above the MAC to switch between the Bluetooth and 802.11b systems in devices that have both installed. This approach is attractive for those systems that need only communicate with 802.11b or Bluetooth, but not both, in a time-critical application. This would support limited transfers in a ping-pong fashion, but would not be able to support 802.11b traffic while Bluetooth voice was active in the piconet. Bluetooth peripherals such as human input devices also would not function well while the WLAN is active; likewise, the polling of Bluetooth slaves by the master will be a source of constant interference. Overall, this solution is limited in its usefulness.

MAC Layer — The MAC layer is an attractive place to focus attention on improving the coexistence between Bluetooth and 802.11b, because it is where techniques such as *listen before talk* are implemented. The very fast and pseudorandom hop pattern of Bluetooth makes it difficult to base the operation of the 802.11b on either listen-before-talk techniques or history of previous failures. In addition, because there is no mechanism for Bluetooth and Wi-Fi to directly exchange information about future activities, neither has the ability to effectively plan around the other. If rule changes such as those discussed earlier on regulatory approaches were approved, some methods for minimal mutual identification/information exchange would likely be required to support implementations.

The MAC layer is where data rates are determined, so this is the place to resolve data rate vs. packet size trade-offs. Since the MAC layer comprises digital hardware and software, techniques employed there tend to be relatively inexpensive to implement. Not all problems can be solved in the MAC. For example, the MAC has no choice over timing under some conditions, such as when an 802.11b node is required to respond with an ACK within a few microseconds of the successful reception of a packet. However, given potentially deleterious MAC behavior (discussed earlier) in the face of Bluetooth interference, more intelligent backoff and fragmentation algorithms might improve Wi-Fi throughput.

Physical Layer — Collisions actually happen at the physical (PHY or radio) layer. Some time-frequency collisions cannot be avoided unless PHY layer techniques are used. For example, the 802.11b specification requires that an ACK be transmitted within a few microseconds after a packet is successfully received. If the same station is also transmitting a Bluetooth packet at that time, the node expecting the ACK may be jammed by the Bluetooth signal. Only by the use of signal processing techniques in the PHY layer can the Bluetooth signal be excised from the

802.11b passband so that the ACK can be successfully processed. PHY layer techniques tend to directly affect system costs more than MAC layer techniques, so these must be balanced.

Alternate Frequency Bands

Some in the industry have positioned coexistence problems in the 2.4 GHz frequency band as motivation to hasten the migration to 5 GHz WLAN standards such as 802.11a and/or HiperLan2. While the issues of WLAN at 5 GHz certainly warrant their own article [15], we can summarize the relevant points here:

- The physics of radio wave propagation introduce a path loss penalty of 6.9 dB going from 2.4 to 5.3 GHz. This means that almost five times as much RF power is required to cover the same distance, all other factors being equal. Since RF power amplifiers at 5 GHz are relatively expensive, 802.11a systems will either cover a smaller distance, cost more, or both.
- RF propagation through barriers such as walls is also somewhat poorer at 5 GHz, so link budgets may suffer additional losses [16]. This suggests that there is likely to be an additional power penalty above and beyond the path loss effect described earlier.
- Strictly speaking, HiperLan2 [17] and its predecessor HiperLan1 are the only systems that are legal in Europe today. Although HiperLan2 and 802.11a have very similar PHY (radio) layers, they are very different at the MAC layer; so another standards battle is possible. Under current ETSI rules, 802.11a is not legal for use in the 5 GHz bands in Europe. Efforts are underway in IEEE 802.11h to add features to the 802.11a/b MAC that will allow these WLAN systems to meet the ETSI requirements for TPC.
- FCC regulations do not prohibit other kinds of systems in these bands; both PAN systems and microwave ovens are being developed for portions of this band. This could lead to coexistence issues in this band as well, in addition to the 802.11a/HL2 issues.
- Both HiperLan2 and 802.11a use a spectrally efficient signal modulation technique called orthogonal frequency-division multiplexing (OFDM), which is also multipath-resistant. Unfortunately, OFDM also has a high ratio of peak-to-average transmit power compared to phase shift keying (PSK), which is used in 802.11b. The result of this is that the RF power amplifier (one of the most expensive components in the system) must be designed to accommodate this large signal swing, which drives up cost and power consumption, unless RF power is scaled back (shorter range).
- It is very difficult to manufacture 5 GHz systems on conventional printed circuit board material (FR4) because the loss tangent and dielectric constants yield poor performance. Consequently, more exotic (expensive) materials are generally needed.

The issues above notwithstanding, wireless LAN deployment in the 5 GHz band offers the potential to dramatically increase capacity in a WLAN deployment, when capacity is expressed as megabits per second per square meter.

Conclusion

Coexistence, and ultimately simultaneous operation, between 802.11b and Bluetooth is a highly desirable goal. Both technologies are expected to grow rapidly over the next few years, offering new levels of portability and convenience, and many critical usage models require collocation and simultaneous operation of both standards in the same device. System-level approaches that address coexistence through the use of antenna, PHY, and MAC techniques offer the potential to dramatically reduce if not eliminate interference between these two systems. Such robust wireless system design technology will become increasingly important in the unlicensed bands as Bluetooth, Wi-Fi, and other unlicensed wireless technologies proliferate.

Proposals submitted to IEEE 802.15.2 as well as the Bluetooth SIG will provide effective solutions to the coexistence issues highlighted in this article; these solutions will be deployed in the market quickly to meet the growing need for Wi-Fi and Bluetooth to operate in proximity to each other.

References

[1] Cahners In-Stat, *Bluetooth 2000 — To Enable the Star Trek Generation*, July 2000.

[2] Cahners In-Stat, *Enterprise Wireless LAN Market Analysis*, June 2000.

[3] D. Cypher, "Coexistence, Interoperability and Other Terms," IEEE 802.15: 99134r2P802-15TG2, Sept. 2000.

[4] A. Kamerman, "Coexistence Between Bluetooth and IEEE 802.11 CCK Solutions to Avoid Mutual Interference," Lucent Tech. Bell Labs., Jan. 1999; also available as IEEE 802.11-00/162, July 2000.

[5] N. Golmie, "Impact of Interference on the Bluetooth Access Control Performance: Preliminary Results," IEEE 802.15/00-322r0, May 2000.

[6] S. Shellhammer, "Packet Error Rate of an IEEE 802.11 WLAN in the Presence of Bluetooth," IEEE 802.15-00/133r0, May 2000.

[7] G. Ennis, "Impact of Bluetooth on 802.11 Direct Sequence," IEEE 802.11-98/319, Sept. 1998.

[8] J. Zyren, "Extension of Bluetooth and 802.11 Direct Sequence Model," IEEE 802.11-98/378, Nov. 1998.

[9] J. Zyren, "Reliability of IEEE 802.11 Hi Rate DSSS WLANs in a High Density Bluetooth Environment," *Bluetooth '99*, June 8, 1999.

[10] J. Zyren, "Reliability of IEEE 802.11 WLANs in Presence of Bluetooth Radios," IEEE 802.15-99/073r0, Sept. 1999.

[11] Nada Golmie, "Bluetooth and 802.11 Interference: Simulation Model and System Results," IEEE 802.15-01/195R0, Apr. 2001.

[12] *Code of Federal Regulations*, title 47, vol. 1, part 15, subpart C (Intentional Radiators), section 247, US Government Printing Office, in the Oct. 1, 1998 revision of 47CFR15.247, the relevant pages are 690–92, available at http://www.access.gpo.gov/nara/waisidx_99/47cfr15_99.html

[13] Specification of the Bluetooth System, v. 1.0B, Dec. 1, 1999.

[14] J. Lansford, "Collaborative Coexistence Mechanism: Mobilian META + Symbol," IEEE 802.15/01-164r0, Mar. 2001.

[15] Mobilian Corp., "2.4 GHz and 5 GHz WLAN: Competing or Complementary?," http://www.mobilian.com/documents/2.4GHz_and_5GHz_WLAN.pdf

[16] G. Durgin, T. S. Rappaport, and H. Xu, "Measurements and Models for Radio Path Loss and Penetration Loss in and Around Homes and Trees at 5.85 GHz," *IEEE Trans. Commun.*, vol. 46, no. 11, Nov. 1998, pp. 1484–96.

[17] ETR0230002 V0.2.0, "Broadband Radio Access Networks (BRAN); High Performance Radio Local Area Networks (HIPERLAN) Type 2; System Overview," http://www.etsi.org

Biographies

JIM LANSFORD (jimlans@mobilian.com) is vice president of business development at Mobilian Corporation. He is responsible for standards and regulatory issues in Mobilian, is involved in a broad spectrum of standards activities, and currently chairs the Wireless Coexistence Study Group within IEEE 802. Prior to joining Mobilian, he was a wireless system architect with Intel Corporation. He taught electrical engineering at Oklahoma State University from 1985 to 1987 and is currently an adjunct member of the faculty there; he served as an assistant professor at the University of Colorado at Colorado Springs from 1990 to 1995. He received his Ph.D. in electrical engineering from Oklahoma State University in 1988, his M.S. in electrical engineering from the Georgia Institute of Technology in 1982, and his B.S. in electrical engineering, with highest honors, from Auburn University in 1980.

ADRIAN STEPHENS (adrians@mobilian.com) is senior director for business development for Mobilian Corporation. There, his responsibilities include business development for European accounts, technical contributions to current and next-generation TrueRadio products, and representation in wireless LAN standards committees (IEEE 802.11 and ETSI BRAN). He has over 20 years of product development and research experience working for industry and government. He was previously at Symbionics Ltd. (now Tality) where he was head of software technology for wireless and multimedia design services. He was product architect for Bluetooth' and HiperLan1 developments, and technical editor of the HomeRF SWAP-CA standard for two years, taking it to successful release. He received a B.A. (1st Honors) in natural sciences (1974) and a Ph.D. in experimental physics (1981), both from Cambridge University, United Kingdom.

RON NEVO is a founder of Mobilian Corporation and director of engineering. He is largely responsible for designing the simultaneous operation technology that drives Mobilian's TrueRadio' product, allowing unhindered simultaneous operation of 802.11b and Bluetooth. Prior to Mobilian Corporation, he worked at Qualcomm designing and implementing various data and voice applications on current and future cellular networks. He also worked at IBM designing CAD tools for chip design. He received his B.S. in electrical engineering from the Technion in Israel.