TEXAS INSTRUMENTS

White Paper

# Wi-Fi (IEEE 802.11b) and Bluetooth

## Coexistence Issues and Solutions for the 2.4 GHz ISM Band

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This white paper presents information related to the IEEE 802.11b Wireless Local Area Networking standard (Wi-Fi) and the Bluetooth Wireless Personal Area Networking standard. Both Wi-Fi and Bluetooth products utilize the unlicensed 2.4 GHz ISM band. Due to their dependence on the same band, the potential for interference exists. This documents describes how products based on these technologies currently coexist and changes that can be made to further improve their level of coexist. This white paper is organized as follows:

- ☐ Overview of IEEE 802.11b and Bluetooth
- ☐ Description of 2.4GHz ISM Band
- ☐ Coexistence Testing Results
- ☐ Methods for Improved Coexistence
    - o Solutions for IEEE 802.11b
    - o Solutions for Bluetooth
    - o Solutions for Devices with IEEE 802.11b and Bluetooth
- ☐ Standards Activity
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# 1 Overview of Wi-Fi and the IEEE 802.11b Standard

The IEEE 802.11b standard [9] is a specification for Wireless Local Area Networks (WLAN). The Wireless Ethernet Compatibility Alliance (WECA) acts as a certification organization for products that interoperate with one another via the IEEE 802.11b standard. Products that achieve certification are deemed Wi-Fi compliant.

Wi-Fi systems transmit data in the unlicensed 2.4GHz ISM band. Data is transmitted on BPSK and QPSK constellations at 11Msps. A relatively large bandwidth expansion factor is allowed, which results in a typical spectral mask for an IEEE 802.11b system as shown in Figure 1-1.

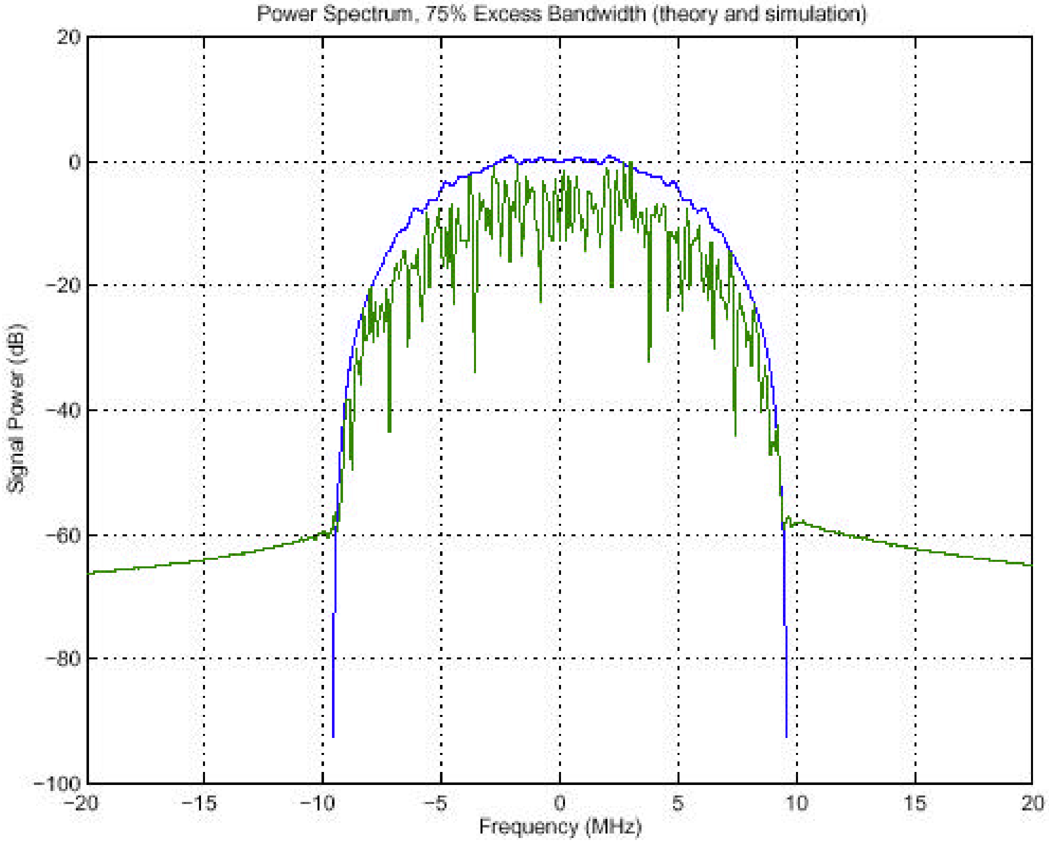

Figure 1-1 Typical Wi-Fi (IEEE 802.11b) Baseband Signal Power

Wi-Fi products transmit at data rates up to 11Mbps. Typically, Wi-Fi devices operate at distances up to 100 meters, however, range varies as a function of transmit power and environment, e.g. indoors versus outdoors.

# 2 Overview of Bluetooth 1.0

The Bluetooth standard is a specification for Wireless Personal Area Networks (WPAN). Although products based on the Bluetooth standard are often capable of operating at greater distances, the targeted operational area is the area around an individual, e.g. within 10 meters of the user. The spectral mask of a Bluetooth signal is 1 MHz wide at the 20dB points, as is shown if Figure 2-1.

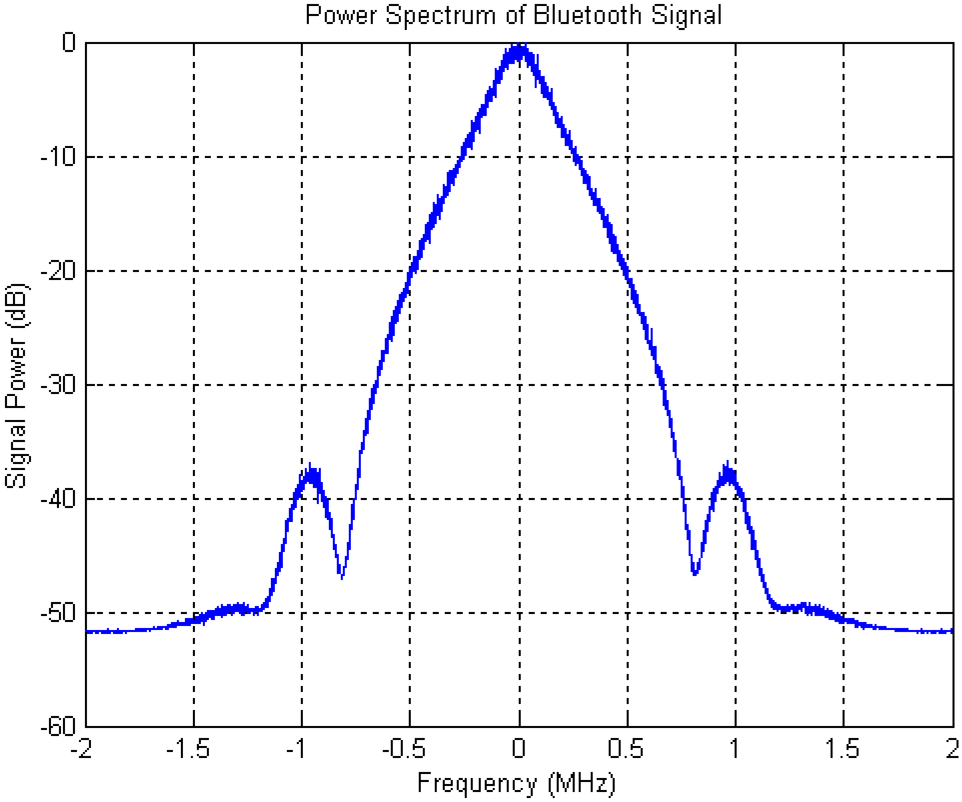

Figure 2-1Typical Bluetooth Signal Power

The Bluetooth standard is based on frequency hopping spread spectrum technology. Although at any point in time, the Bluetooth signal occupies only 1MHz, the signal changes center frequency (or hops) deterministically at a rate of 1600Hz. Bluetooth hops over 79 center frequencies, so over time the Bluetooth signal actually occupies 79MHz.

# 3 The 2.4GHz ISM Band

Wi-Fi and Bluetooth products both operate in the 2.4GHz band. Although specifications and allowable uses for the band vary based on local regulations, the FCC regulations for the 2.4GHz band are a representative case of regulations worldwide. Thus the FCC regulations can be used to facilitate discussion of the coexistence of Bluetooth and Wi-Fi products.

Although there are many regulations that apply to operation of products within the 2.4GHz ISM band, Section 15.247 of the FCC regulations contains the key definitions and the crux of what is allowed in the band. The 2.4GHz ISM band is 83.5MHz wide with a lower limit of 2.400GHz and an upper limit of 2.4835GHz.

Current 2.4GHz ISM band regulations limit operation in the band to direct sequence spread spectrum (DSSS) and frequency hop spread spectrum (FHSS) technologies. Wi-Fi products are based on DSSS technology, and Bluetooth devices are based on FHSS technology.

Current 2.4GHz regulations for FHSS devices require devices to hop over 75 MHz and limit the maximum bandwidth of each hopping channel to 1MHz. Bluetooth devices hop over 79 frequencies that are 1MHz wide. Thus over time, Bluetooth devices occupy 79MHz, but at any specific time only 1MHz is occupied.

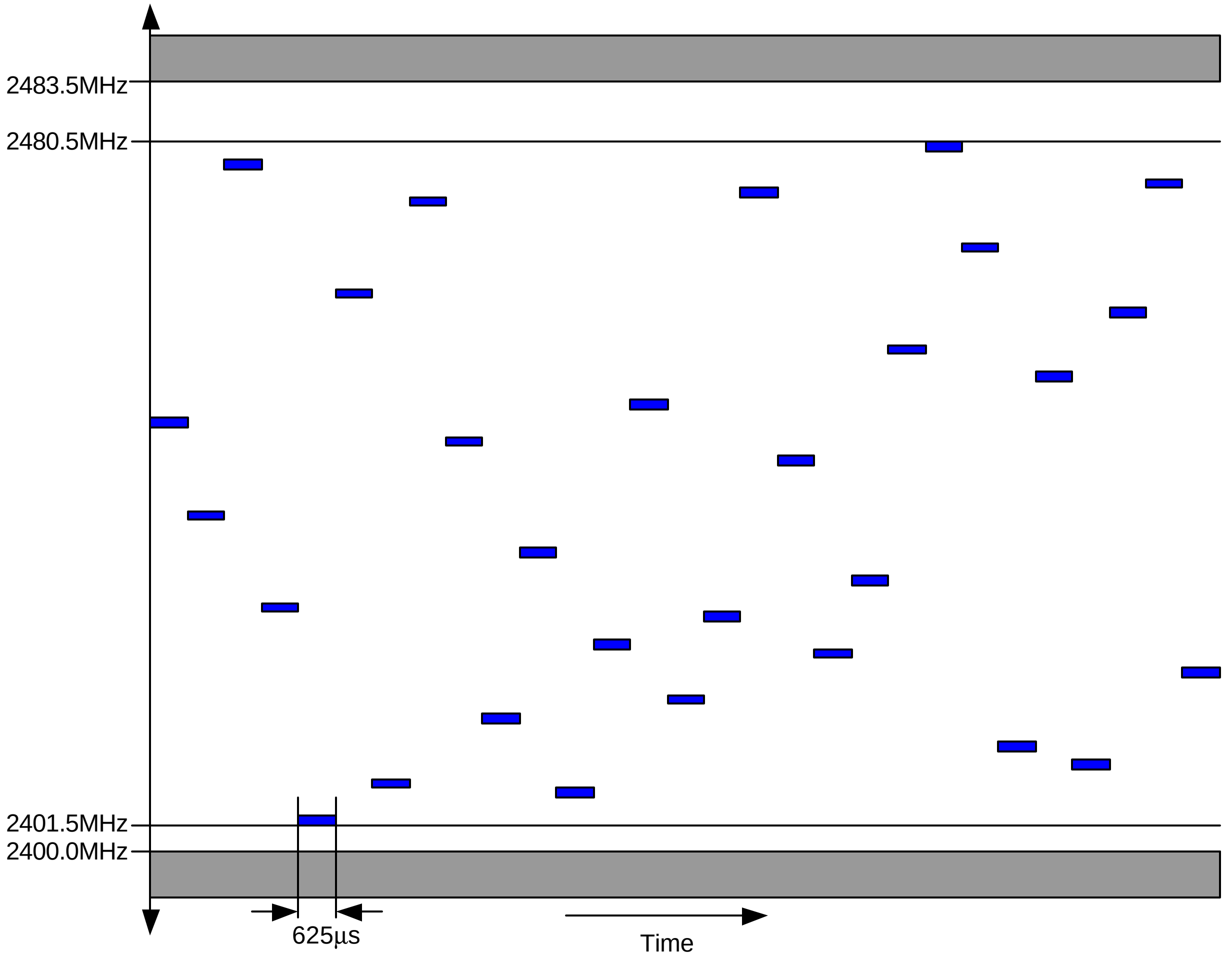

Figure 3-1 Bluetooth Frequency Occupancy Example

Figure 3-1 shows how Bluetooth hops in the 2.4GHz ISM band. Each blue rectangle represents a Bluetooth transmission. Bluetooth is a slotted protocol. Each slot is 625ms long. Although a transmission can occupy 1, 3 or 5 slots, only transmissions that are one slot long are shown in Figure 3-1.

Each Wi-Fi network maintains the same frequency usage over time and only uses a subset of the 83.5MHz available. The IEEE 802.11b standard defines 11 possible channels that may be used. Each channel is defined by its center frequency. The center frequencies are at intervals of 5MHz from one another. The associated channels are numbered from one to 11.

Since the 20dB bandwidth of an IEEE 802.11b signal could easily be as great at 16MHz, using adjacent channels in the same location would result in interference. For this reason collocated Wi-Fi networks are typically operated on channels 1, 6 and 11 to prevent interference. In such a scenario, three collocated networks would occupy approximately 3 x 16MHz = 48MHz of the available 83.5MHz in the ISM band.

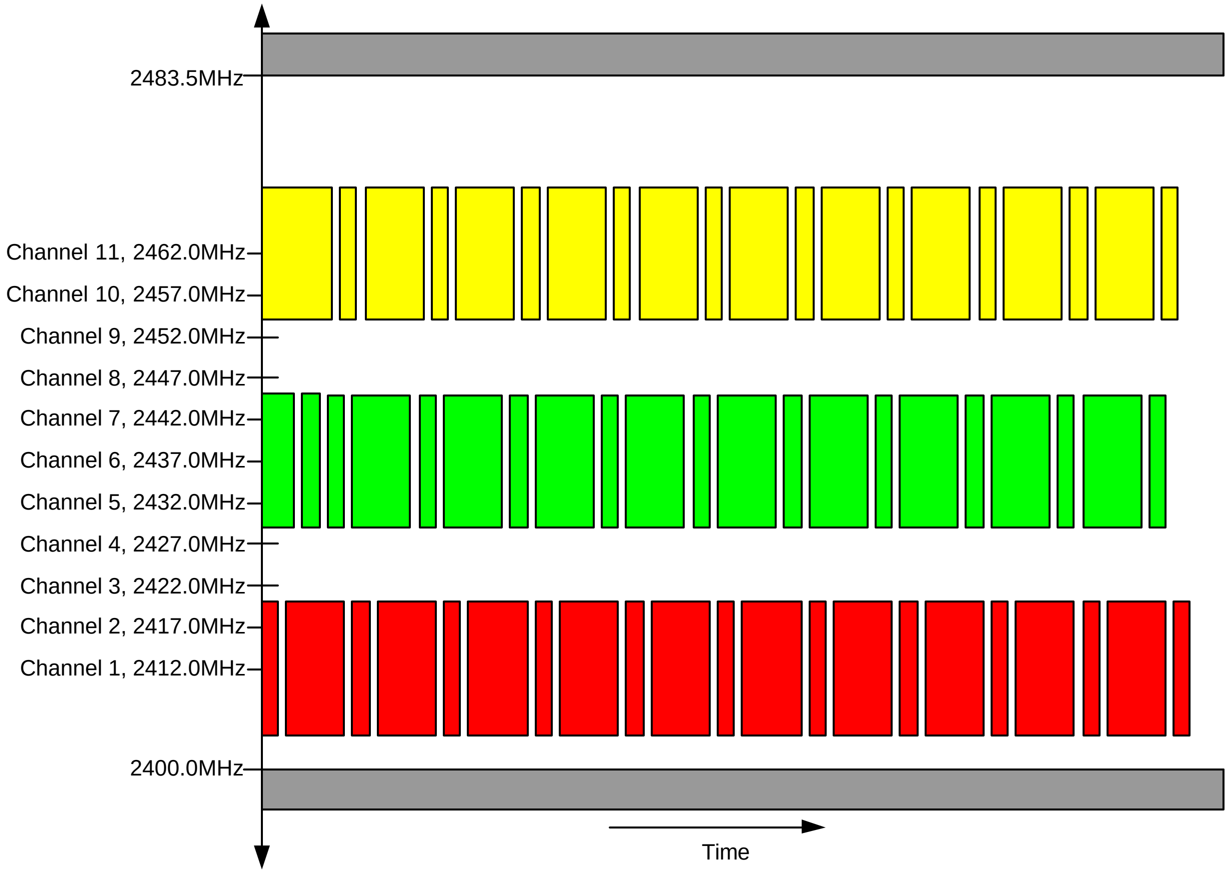

Figure 3-2 Frequency Occupancy of Three Wi-Fi networks

Figure 3-2 shows a typical frequency occupancy for three Wi-Fi networks. Each Wi-Fi network operates exclusively on one channel. The figure shows networks operating on channels 1, 6 and 11. The transmissions of each channel are distinguished by the color of each packet. The duration of each Wi-Fi packet varies based on the amount of data in the packet. There is typically a short acknowledgement packet after each data packet on the network.

# 4 Wi-Fi and Bluetooth Coexistence Testing

Since Bluetooth devices hop over 79 MHz of the ISM band and IEEE 802.11b devices require approximately 16MHz of bandwidth to operate, it is not possible to have both Wi-Fi and Bluetooth products in the same area without the chance of interference. Due to the potential for interference, a series of coexistence tests have been run with actual Bluetooth and Wi-Fi products to determine their level of coexistence. The full details of the testing are available in [8]. A summary of the testing is provided in the following sections.

## 4.1 Testing Setup

The throughput testing was performed with a Wi-Fi certified access point (AP) and station. The Wi-Fi station consisted of a laptop computer with a Wi-Fi PCMCIA card. The icons used to represent each of these devices in later sections are shown in Figure 4-1.

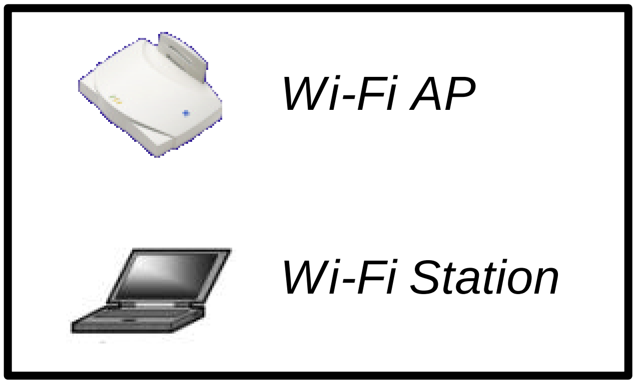

Figure 4-1 Wi-Fi AP and Station Icons

The Bluetooth devices that were used in the testing were also PCMCIA cards. Two laptops were used to enable one Bluetooth master and one Bluetooth slave. The icons used to represent the Bluetooth devices are shown below in Figure 4-2.

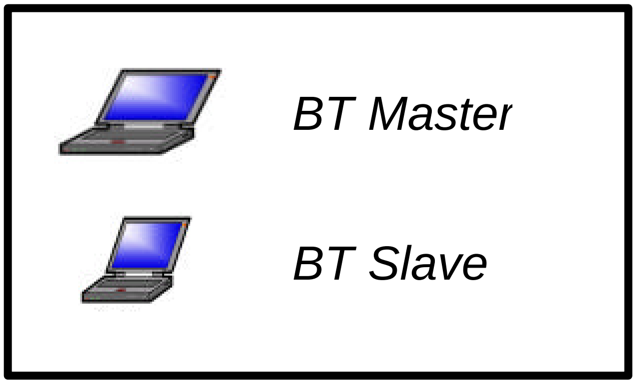

Figure 4-2 Bluetooth Master and Slave Icons

## 4.2 Baseline Performance

To obtain the maximum throughput for both the Bluetooth and Wi-Fi networks when there is no interference, baseline tests were performed. In each baseline test, the Chariot software package from NetIQ was used to transfer data as quickly as possible from one device to another.

### 4.2.1 Wi-Fi Throughput

To obtain a baseline for Wi-Fi, the setup in Figure 4-3 was used. Data was transferred from the access point to the station. Thus during the test, the majority of the packets going from the access point to the station were large payload data packets, while the majority of packets going from the station to the access point were short acknowledgment packets.

Figure 4-3 Wi-Fi Baseline Test Set-up

The distance between the Wi-Fi access point and the Wi-Fi station was varied while the two devices had a line of sight between one another. The resulting throughput as a function of distance is shown in Figure 4-4. The result is that the devices maintain a connection speed in excess of 5.5Mbps up to the maximum distance at which the test was performed of 250 feet.

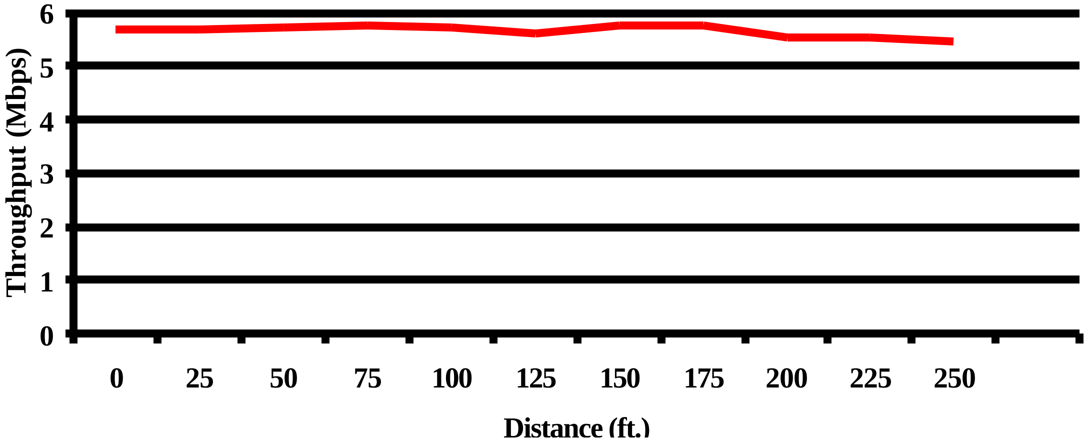

Figure 4-4 Wi-Fi Baseline Throughput

### 4.2.2 Bluetooth Throughput

In analogous fashion to the Wi-Fi baseline throughput testing, two Bluetooth devices were configured as shown in Figure 4-5.

Figure 4-5 Bluetooth Baseline Test Set-up

Data was transferred from the Bluetooth master to the Bluetooth slave with no interference in the area. The resulting throughput was approximately 550 kbps at all distances up to 250 feet. Again all testing was performed with a line of sight between the devices under test. A plot of the throughput achieve on the Bluetooth network is shown in Figure 4-6.

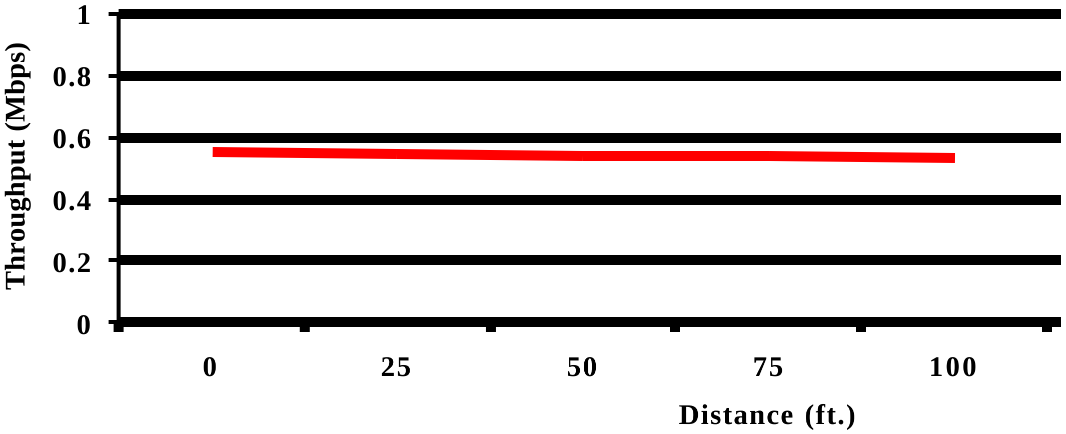

Figure 4-6 Bluetooth Baseline Throughput

## 4.3 Wi-Fi Performance with Bluetooth Interferer

In this section the results of two key tests will be shown. The first test is the same as the baseline throughput test in Section 4.2.1 except that a Bluetooth master and slave are both placed within 10cm of the Wi-Fi station. This test is a worst case for Wi-Fi networks. The Bluetooth devices used a transmit power of 100mW, and the Wi-Fi devices used a transmit power of 30mW. Both Bluetooth devices were located within 10cm of the Wi-Fi device that was attempting to receive data. This set-up is shown in Figure 4-7.

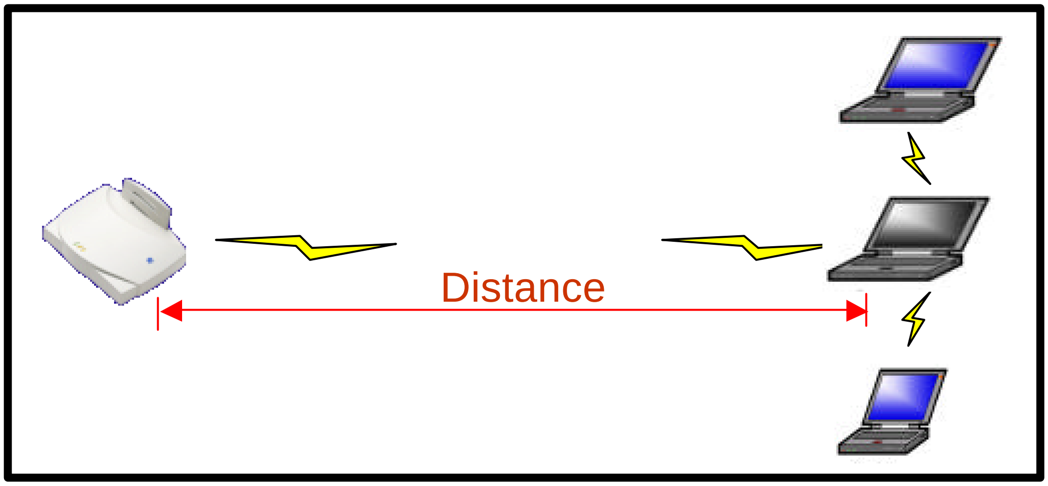

Figure 4-7 Wi-Fi Throughput with Bluetooth Interferer Test Setup

The second test is similar to the first test, except the Bluetooth interferers are moved 30 feet away from the Wi-Fi station. The set-up is shown in Figure 4-8.

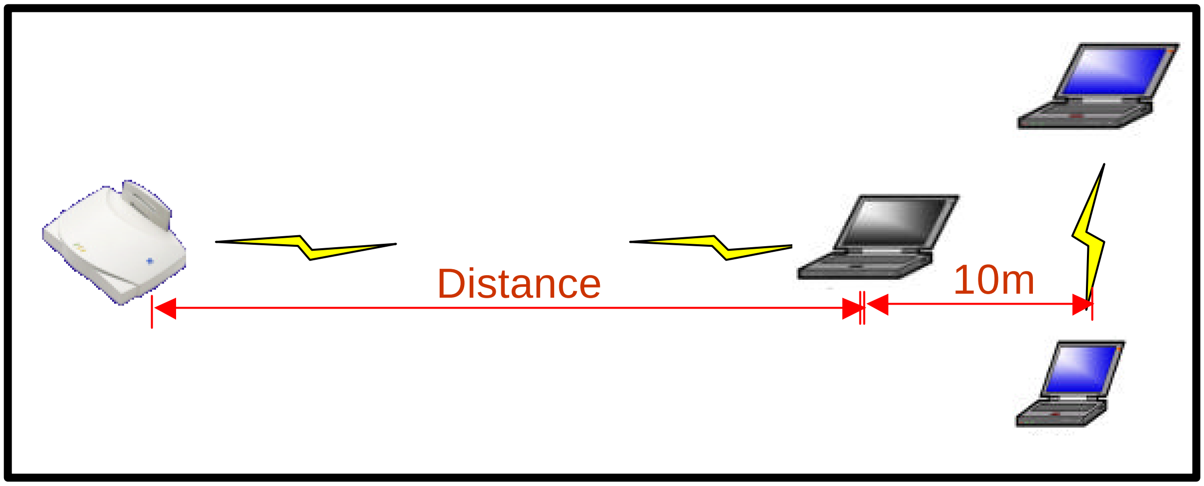

Figure 4-8 Wi-Fi Throughput with Bluetooth Interferer at Distance Test Set-up

The results of these two tests are shown along with the baseline Wi-Fi throughput in Figure 4-9. It is observed that when the Bluetooth interferers are very close to the Wi-Fi station, the impact on performance due to interference is substantial. However, when the Bluetooth interferes are moved as little as 10 meters away, the throughput is only minimally effected compared to the baseline.

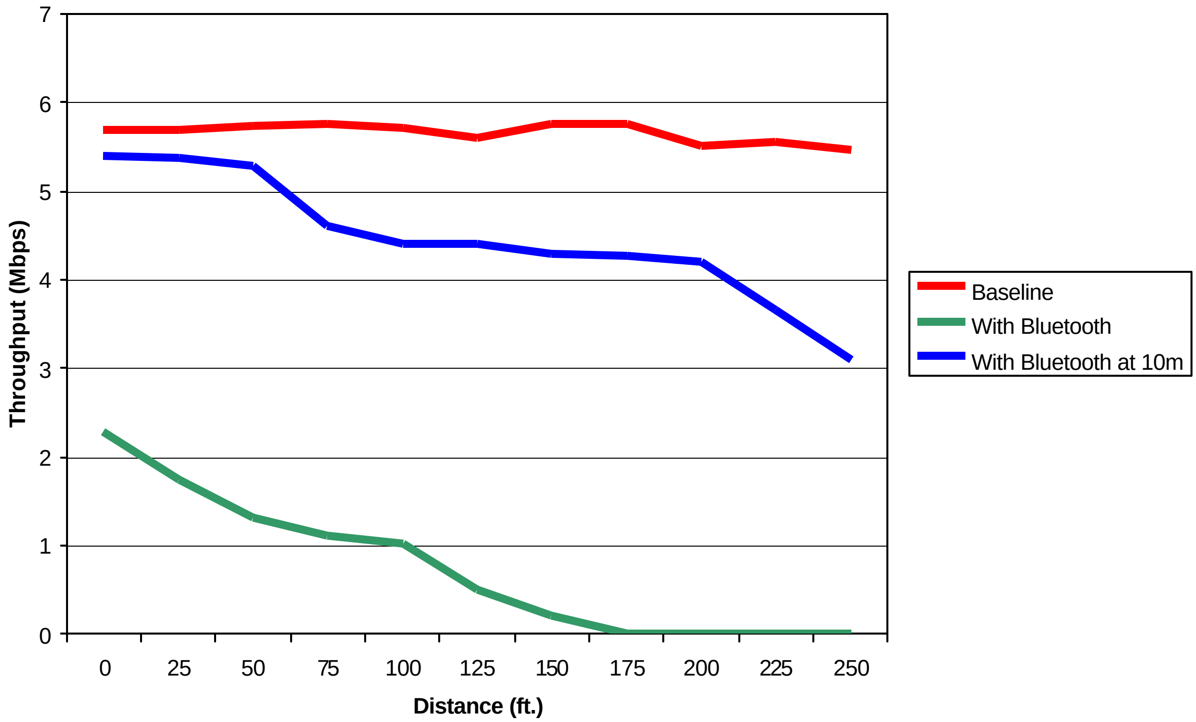

Figure 4-9 Wi-Fi Throughput with Bluetooth Interferer

## 4.4 Bluetooth Performance with IEEE 802.11b Interferer

To determine the effect of Wi-Fi as an interferer on a Bluetooth network, the same experiments that were carrier out in Section 4.3 where carried out again with the Bluetooth and Wi-Fi devices switching location. The results of the tests are shown in Figure 4-10. It can be seen from the results that Bluetooth throughput is impacted when a Wi-Fi device is very close. On the other hand, when the Wi-Fi device is moved away, the Bluetooth throughput significantly improves and is approximately ninety percent of the baseline throughput independent of range.

These experiments show that when Bluetooth and Wi-Fi devices are at a reasonable distance from one another, both types of devices obtain the large majority of the throughput that would have been obtained if there were no interference. However, these simulations also demonstrate that interference between the two does degrade performance of both Bluetooth and Wi-Fi devices. In the following sections, the causes of the interference are analyzed and several solutions are discussed.

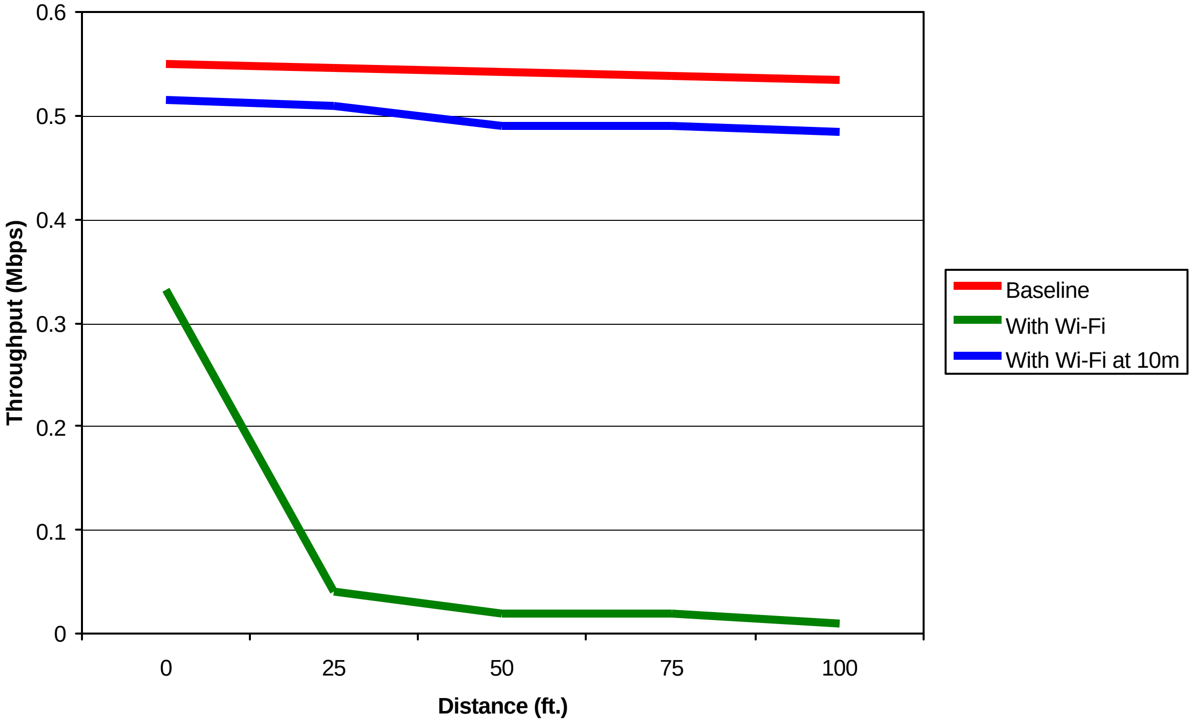

Figure 4-10 Bluetooth Throughput with Wi-Fi Interferer

# 5 Methods for Improved Coexistence

The need for coexistence of devices in an unlicensed band is not a new one. A good example of devices that required coexistence with other devices in an unlicensed band is cordless phones in the unlicensed 900 MHz ISM band. When cordless phones for the 900 MHz band were first introduced, they had limited ability to deal with interference in the band. However, over time they added often-simple changes that allowed them to operate in the presence of other 900 MHz devices and still maintain a quality connection.

Although there are some differences between the example above and the situation in the 2.4GHz ISM band, the premise remains the same. Due to the potential for other devices operating in the same band, it is necessary to imply features that allow for continued robust performance even in the presence of other devices. Fortunately, the regulations in the 2.4GHz band and most unlicensed bands prevent any device from using more than its fair share of the band. The following sections detail ways to improve coexistence and robustness of Bluetooth and Wi-Fi devices.

## *5.1 Dynamic Channel Selection for Wi-Fi Networks*

One of the best ways to coexist is to avoid using the frequencies in the 2.4GHz ISM band that are occupied by others. The example of coexisting Wi-Fi networks in Figure 3-2 is an example.

The three collocated networks use channels one, six and eleven to avoid interfering with one another. In current Wi-Fi products, the user or system administrator selects the channel. It is possible to dynamically select the channel on which a Wi-Fi network will operate.

Dynamic channel selection allows the Wi-Fi access point itself to determine which channel is best to use depending on the current usage of the band. Determination of which channel is the best to operate on can be achieve by several methods:

- ☐ Packet Error Rate
  - o Communication with another Wi-Fi device allows packet error rate measurements on each channel. Channels with low packet error rates are desirable.
- ☐ Channel Noise
  - o Communication with another Wi-Fi device allows for measurement of the signal to noise ratio on each channel. Channels with high signal to noise ratios are desirable.
- ☐ Channel Multipath and Intersymbol Interference
  - o Communication with another Wi-Fi device allows for measurement of the amount of intersymbol interference and multipath that is experienced in the channel. Channels with low amounts of intersymbol interference and multipath are desirable.
- ☐ Received Signal Strength
  - o Independent of having other Wi-Fi devices in the area, an access point can determine which channel to operate on based on the signal strength of interferers in the band. For example, this can be determined by monitoring the setting of the automatic gain control on each channel.

Using the best channel available is not only good for the Wi-Fi network, but it is also good for other users of the 2.4GHz ISM band. It is likely that by choosing the best channel available, the Wi-Fi network has also avoided interfering with other devices using the band.

## *5.2 Adaptive Fragmentation for Wi-Fi Networks*

Wi-Fi networks have the ability to fragment packets to limit their length. When there is no interference on the network, fragmenting lowers the network throughput, because of the increased overhead of packet headers. However, in the presence of interference, it has been shown [8] that fragmentation can actually increase the throughput.

By decreasing the length of each packet, the probability of interference during a Wi-Fi packet can be reduced. There is a tradeoff that must be made between the lower packet error rate that can be achieved by using shorter packets and the increased overhead of more headers on the network. Finding the optimal fragmentation setting to maximize the network throughput on a Wi-Fi network has been addressed in [6].

One way to implement adaptive fragmentation is to monitor the packet error rate on the network and accordingly adjust the fragmentation level. The adjustment of the fragmentation level is also a function of on the amount of overhead associated with each packet. The optimal fragmentation level can be reached in approximately ten updates using an adaptive least mean squared algorithm.

## 5.3 Bluetooth Coexistence Enhancements

Various mechanisms can be used to improve the coexistence level of Bluetooth devices when interference is present. An assortment of mechanisms for this purpose is proposed in [3]. For data connections, Bluetooth devices can adaptively select the type of error control used and the length of each packet to transmit to maximize the throughput. In addition, flow control can be used to increase and decrease the rate of transmission. For example, when a contiguous block of bad channels is reached, the Bluetooth device may place traffic on hold until good channels are available.

## 5.4 Intelligent Frequency Hopping

Frequency hopping devices have an inherent level of robustness due to the fact that they do not continually transmit at the same frequency. The changing of the transmit center frequency or hopping means that the probability of colliding with the transmission of another device at any particular time is very small. This can be seen easily in Figure 3-1. Since the blue rectangles are very sparse in the time versus frequency plot, the probability of colliding with traffic in the band is small.

The level of robustness to interference that Bluetooth devices currently have is obtained blindly, since the transmitter uses no knowledge of the interference in the channel. If the hop sequence was designed to actively avoid other devices in the band, both the performance of Bluetooth devices and other devices in the band could be improved. For example, if a Wi-Fi device were active on Wi-Fi channel six, it would be advantageous for the Bluetooth device to never transmit in the frequency range 2.429 GHz to 2.445 GHz (see Figure 3-2), since any transmission in this range would likely result in a Bluetooth and Wi-Fi transmission errors.

Unfortunately, current FCC regulations require Bluetooth devices to hop over 75 MHz, so it is impossible to significantly change the frequency range over which Bluetooth devices hop. The FCC has been petitioned by Texas Instruments and other companies to allow Bluetooth and other frequency hopping devices to hop over as little as 15 MHz. Such a change would allow for the design of intelligent hopping schemes that improve Bluetooth performance in a multitude of situations.

Even without changes in regulations of the 2.4 GHz ISM band, there are intelligent frequency hopping schemes that will allow for improved throughput in the presence of interferers. Such hopping sequences can be design based on the fact that it is better to have several good hop frequencies in a row rather than alternating randomly between good and bad hop frequencies. Since acknowledgements are embedded Bluetooth packets, throughput can be improved by hopping through a sequence of good hop frequencies and thereby not losing any data due to lost acknowledgements. Designing hop sequences that have runs of good hop frequencies and runs of bad hop frequencies, e.g. due to a Wi-Fi device in the area, have been shown to significantly increase the performance of Bluetooth devices [1].

## 5.5 Transmit Power Controls

When using a shared resource such as the 2.4GHz ISM band, it is important to not use more of the resource than is actually required. This can be thought of as a golden rule for using unlicensed bands. For example, if two devices in the band can communicate by transmitting at a power level of 4 dBm, it is an over usage of the band to transmit at 20 dBm. By transmitting too much power in the band, the overall capacity per area is reduced and the transmission of other users of the band may be needlessly interfered with.

Since the distance between devices does not change rapidly, the required transmit power does not tend to change rapidly either. This means that both Bluetooth and Wi-Fi devices can add dynamic power control without affecting the performance of either device. However, the fact that devices are no longer transmitting at their maximum power levels means that all devices in the area are more likely to be able to communicate with one another successfully.

A joint mechanism for rate shifting and power control of Wi-Fi devices is proposed in [5]. In addition, transmit power levels are suggested that can be used for Wi-Fi and Bluetooth devices as well as other users of the 2.4GHz ISM band. Power control is a mechanism that is relatively easy to understand and implement, yet can yield great performance improvements for all users of the band.

## 5.6 Methods for Collocated Wi-Fi and Bluetooth

When Bluetooth and Wi-Fi are located in the same device, the opportunity exists for an even greater level of robustness and coexistence. When Bluetooth and Wi-Fi devices are collocated, a simple signaling scheme with a coordination unit can be used to reserve transmit and receive slots in the channel access timing. A simple scheme for dealing with virtual contention, i.e. when Wi-Fi and Bluetooth devices attempt to make a conflicting reservation, is also desirable.

In such a situation it is important to maximize the throughput of both the Bluetooth network and the Wi-Fi networks. It is also important to maintain fairness between Bluetooth and Wi-Fi while avoiding long traffic delays. A scheme to do exactly this has been proposed in [4]. The scheme allows for flexibility in allocating throughput between Wi-Fi and Bluetooth networks. The proposed scheme uses a simple reservation protocol for Bluetooth and Wi-Fi transmissions. The scheme requires only a simple coordination unit to communicate reservations between the Bluetooth and Wi-Fi hardware. In addition, the coordination unit resolves conflicting reservations using a statistical method that also allows for adjustment of the maximum throughput on each network.

# 6 Standards Activity

Due to the importance of coexistence of Bluetooth and IEEE 802.11 devices, both the Bluetooth SIG and IEEE 802 are actively looking at methods for improved coexistence. Texas Instruments actively participates in the standardization of methods to improve coexistence in the 2.4 GHz band.

The IEEE 802.15.2 Task Group has been formed specifically to consider proposals for mechanisms to improve the level of coexistence between Bluetooth and IEEE 802.11 devices. Many of the solutions discussed in Section 5 have been proposed to the Task Group.

## 7 Results and Usages

Texas Instruments is committed to providing Bluetooth and Wi-Fi solutions that are the industry leader in their level of robustness to interference from other devices in the 2.4 GHz ISM band. As a result, both Bluetooth and Wi-Fi devices will be able to coexist in the same area and even within the same device without having a detrimental effect on one another.

For example users will be able to have a laptop that has Bluetooth and Wi-Fi in it. This will allow the laptop to communicate with a mobile phone or a PDA, while the Wi-Fi connection is communicating to a high-speed home gateway or to an access point in an enterprise environment. The usage combinations are endless, and due to products with enhanced coexistence capabilities, they will all be realizable.

## 8 References

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[2] Code of Federal Regulations, Title 47, Chapter 1, Part 15, Section 247.

[3] Jie Liang, *Proposal for Non-Collaborative BT Mechanisms for Enhanced Coexistence*, IEEE 802.15-01/026, January 2001.

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[6] Matthew B. Shoemake, *Proposal for Non-collaborative 802.11 MAC Mechanisms for Enhancing Coexistence: Adaptive Fragmentation*, IEEE 802.15-01/083, January 2001.

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[9] Std. IEEE 802.11b-1999, *Supplement to Information technology--Telecommunications and information exchange between systems--Local and metropolitan area networks--Specific requirements--Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher Speed Physical Layer (PHY) Extension in the 2.4 GHz band*, September 1999.