Enhancing ISM Band Performance Using Adaptive Frequency Hopping

Application Note

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Abstract and Contents

Bluetooth ™ is a low-cost, low-power wireless connectivity technology operating in the 2.4 GHz unlicensed ISM band. One of the most important challenges to Bluetooth adopters is coexistence with other devices within the shared spectrum. These devices range from cordless telephones to microwave ovens to wireless LANs such as 802.11b. This document describes a coexistence technique known as Adaptive Frequency Hopping (AFH). Motorola is at the forefront with regard to adopting AFH techniques, thereby providing a solution that improves the Bluetooth environment as well as aids other occupants of the ISM band such as 802.11b.

1 Introduction

Bluetooth is a short-range wireless technology that operates in the 2.4 GHz unlicensed ISM band. It may be used as a cable replacement technology or as an advanced personal area network. Bluetooth has a 1 Mbit/s raw data rate and its low-cost, low-power nature makes it appealing to a wide range of applications. Because of the unrestricted access to the ISM band, Bluetooth devices are exposed to a high level of interference from unknown proprietary products, such as microwave ovens, cordless phones, and so on. Interference is also possible from wireless LAN products, such as 802.11b. Bluetooth uses a frequency-hopping scheme to overcome fading and some of this interference. The scheme pseudo-randomly selects one of 79 possible Bluetooth channels (1 MHz wide) within the ISM band. In Bluetooth Version 1.1, this selection process happens without consideration for current occupants of the spectrum. Adaptive Frequency Hopping (AFH) addresses these concerns by actively modifying the hopping scheme and thereby avoiding collisions.

2 The Problem

Figure 1 shows how a Bluetooth device operates in the ISM band over time.

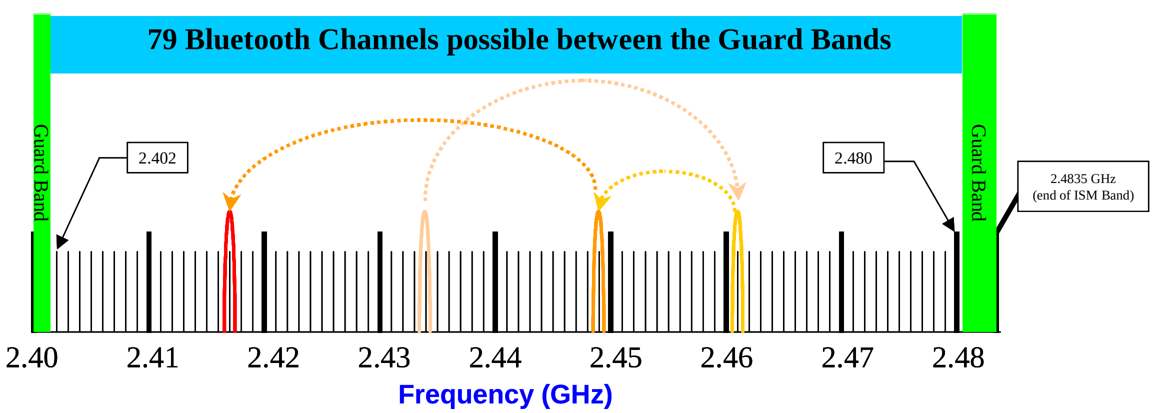

Figure 1. Spectrum Occupancy - Bluetooth Ver.1.1 Frequency Hopping Spread Spectrum (FHSS)

The Bluetooth device hops at a rate of 1600[1] hops per second, pseudo-randomly selecting a single 1 MHz channel for operation. The channel selection is made regardless of other occupants in the band. Viewed over time, the Bluetooth power is *spread*, making the entire ISM band experience the same average interference power from the Bluetooth device. This spreading allows Bluetooth to mitigate the effects of fading as well as interference.

Other technologies also occupy the ISM band. Figure 2 shows a typical dense deployment of 802.11b systems.

1. Using single slot packet types

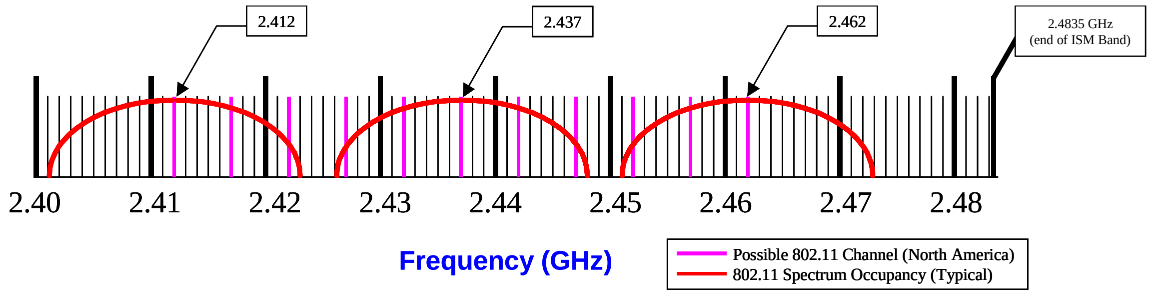

Figure 2. Spectrum Occupancy – 802.11b Direct Sequence Spread Spectrum (DSSS)

It is obvious that in an uncoordinated fashion, the technologies in Figures 1 and 2 would overlap in frequency and collide if operated in close proximity to each other. Since 802.11b is fixed in frequency and Bluetooth hops after each channel selection, it is up to the Bluetooth device to incorporate any frequency avoidance schemes.

What is needed is a technique for the Bluetooth device to detect and classify the interference; modify the hopping algorithm to avoid this interference; distribute the modifications to the other members of the network; and periodically maintain the hopset to handle changing channel conditions.

3 What is Adaptive Frequency Hopping?

Put simply, adaptive frequency hopping is a method for avoidance of fixed frequency interferers. AFH for Bluetooth can be broken down into four main components:

- **Channel Classification** – A method of detecting an interfering source on a channel-by-channel basis (each channel equals 1 MHz)
- **Link Management** – Coordination and distribution of the AFH information to the rest of the members of the Bluetooth network (accomplished via LMP commands)
- **Hop Sequence Modification** – Avoiding the interferer by selectively reducing the number of hopping channels
- **Channel Maintenance** – A method for periodically re-evaluating the channels

Channel classification involves the detection of the interfering network. There are various methods to accomplish this, such as RSSI measurements, consecutive packet errors, packet error averages, etc. There are pros and cons for each method. For instance, RSSI allows the device to passively evaluate each channel and even allows for the evaluation of multiple ISM channels per 625 μs time slot. Techniques requiring the delivery of a packet give a better indication of the ability to send packets via the specific point-to-point link, however, these techniques can be slow, vary based on packet type sent, and require lost packets before adaptation can take place.

Regardless of the classification technique, metrics of channel quality are stored on a channel-by-channel basis (each channel equals 1 MHz). These metrics are used to classify each channel as either *good* or *bad*. The piconet then uses **link management** for coordination and distribution of the channel information. Whereas the channel measurements may be taken by any device within the network, the master acts as the ultimate distributor of any updated channel information. The master accomplishes this by sending link manager protocol (LMP) commands to the devices indicating which frequencies have been added or removed from the acceptable channel list. This means that for a piconet to operate using adaptive frequency hopping, the master device must be AFH-capable.

Once the new pool of good channels has been determined and distributed, each device needs to modify their hopset so that the bad channels are avoided (**hop sequence modification**). This modification of the hopping kernel needs to be synchronized (in time and frequency) between any devices wishing to carry on communications within the piconet.

Now that the Bluetooth piconet is operating using a smaller subset of frequencies, the process of channel classification, management, and modification, needs to be performed periodically (**channel maintenance**). This procedure needs to be performed regularly enough to accommodate changing channel conditions. Interference conditions can change due to a mobile interfering device entering the proximity of the Bluetooth network or a low-duty cycle interferer suddenly increasing its transmission activity. The regularity of channel maintenance also needs to be balanced with the sleep and power consumption modes of various devices as well as the additional traffic burden placed on the piconet (to coordinate and distribute the AFH information).

4 An Example

The following example shows a situation where Bluetooth is operating in close proximity to a single 802.11b system. The devices within the Bluetooth piconet will collect metrics on each 1 MHz channel. Channels will be deemed either good or bad and this information will be distributed to all devices within the piconet. Due to the presence of the 802.11b WLAN, the bad channels most likely include the 22 MHz occupied by the 802.11b system. The bad channels are replaced with good channels making the system operate in a manner shown in Figure 3.

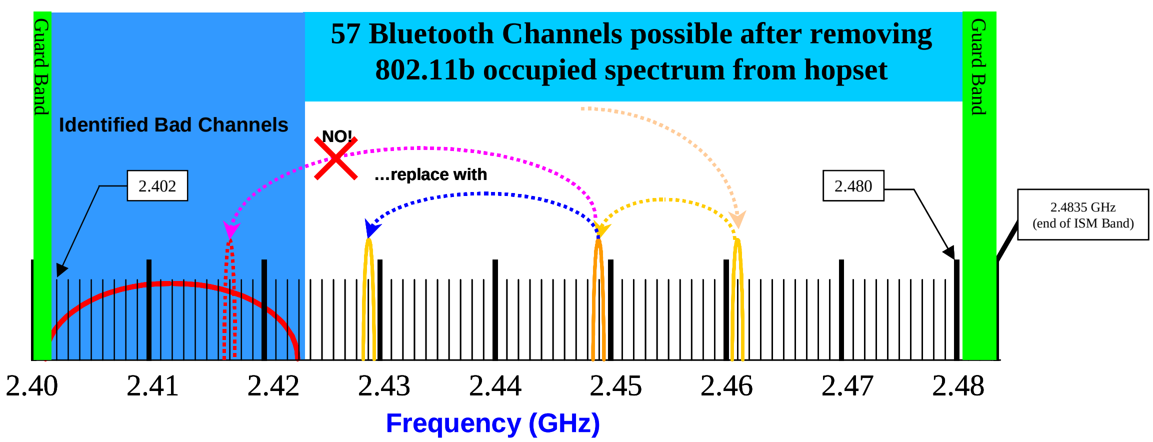

Figure 3. Bluetooth with AFH Coexisting with a Single 802.11b System

Figure 3 illustrates that when a bad channel is selected, the hopping kernel replaces this selection with a channel from the good pool. Figure 4 shows the decision tree inside the AFH-capable Bluetooth unit.

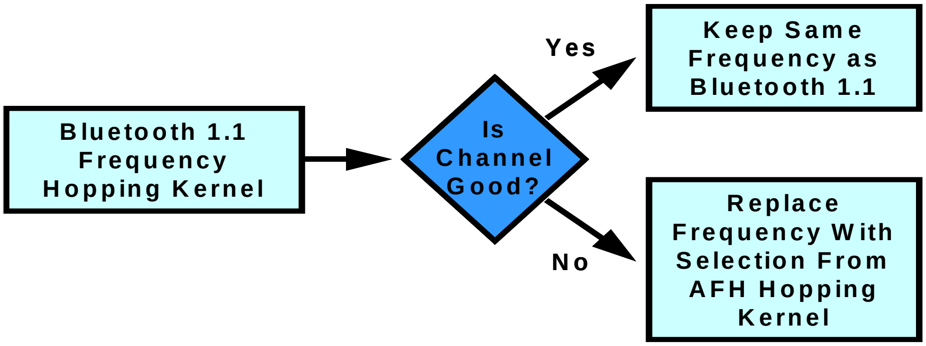

Figure 4. AFH Frequency Decision Flowchart

A replacement methodology such as this increases backwards-compatibility with non-AFH devices operating within the same piconet.

5 Benefits of AFH

AFH for Bluetooth is targeted toward easing the congestion of the rapidly crowding ISM band. AFH is specifically tailored to combat the interference of fixed frequency interfering devices such as 802.11b, some cordless telephones, microwave ovens, and others. Avoiding occupied spectrum enables the Bluetooth link to operate at a higher throughput and reliability translating directly into improved quality of service (QOS).

The benefits extend beyond that of just Bluetooth systems. The avoided system will experience higher throughput (e.g., 802.11b) or greater voice quality (e.g., cordless telephones). This is called Bluetooth's good neighbor policy and is due to the fact that (from their perspective) the interfering Bluetooth device is no longer hopping in their desired frequency band.

AFH allows for the coexistence between a Bluetooth system and another system (also occupying the ISM band) by having both systems avoid each other in frequency. Since both technologies will have less collisions, they will both experience lower latency due to a fewer number of retransmissions. The fewer retransmissions for both technologies also means there will be less overall interfering power generated within the ISM band.

6 Limitations of AFH

As the number of interferers increases for a given geographical environment, a greater number of bad channels are removed from the adapted hopping sequence. Without AFH, a legacy Bluetooth system would gradually experience a worse QOS with each additional channel lost to interference. AFH systems tend to hold steady the quality of the link up to the point where the minimum number of channels is reached. When Bluetooth systems operating at this minimum (15 FCC, 20 ETSI) experience further interference, throughput and reliability will begin to decrease due to the fact that known bad channels must be used in the hopping sequence.

7 Regulatory Environment

The fewer channels that a frequency hopping system hops over, the more interference that is generated over those channels. Therefore, the minimum number of channels an FHSS system is allowed to operate over is typically a specified parameter by regulatory agencies that govern shared usage spectrum. The Federal Communication Commission (FCC) has specified this minimum number of channels as 75, but is currently evaluating the response of a Notice of Proposed Rule Making (NPRM) that allows for the reduction of channels to 15. The NPRM proposal is a non-controversial issue and likely will not experience opposition. The European Telecommunications Standardization Institute (ETSI) already allows FHSS systems to intelligently reduce their number of hopping channels to a minimum of 20. The allowance of non-collaborative, intelligent, collision avoidance techniques such as adaptive frequency hopping is in the best interests of not only regulatory governing bodies, but also manufacturers, and ultimately end users.

8 Legacy Device Support

It is desirable, for obvious reasons, that Bluetooth Version 1.1 devices operate within a network that has Bluetooth devices performing AFH in it. This is achievable since the master of the network is aware which devices within the network implement the AFH feature and which do not. With this knowledge, the master is capable of switching between scheduling traffic to devices using the legacy hopping kernel and scheduling traffic to the enhanced AFH capable devices using the smaller subset of frequencies.

9 Summary

Adaptive frequency hopping is receiving support from regulatory bodies, Bluetooth manufacturers, 802.11b manufacturers, other ISM device manufacturers, and most importantly, end users. AFH’s ability to improve the interference environment for Bluetooth devices makes it an attractive feature to have for concerned Bluetooth users. AFH’s good neighbor policy also makes it an attractive feature for companies or users deploying diverse networks in close proximity to each other. The benefits of increased reliability, lower latency, and friendly compatibility ensure the widespread adoption of adaptive frequency hopping within Bluetooth products.