Evaluating the Adaptive Frequency Hopping Mechanism to Enable Bluetooth – WLAN Coexistence

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ABSTRACT: Both Bluetooth and IEEE 802.11b are the dominant wireless standards for cable replacement and WLANs respectively. They both operate in the 2.4 GHz ISM band and co-located devices cause mutual interference and hence performance degradation. A non-collaborative method to reduce interference is Adaptive Frequency Hopping. This paper presents experimental results of interference measurements with and without AFH in a typical office environment for both data and voice transmissions.

I. Introduction

Bluetooth [1] is rapidly emerging as the leading technology in the formation of low-power, short-range, wireless *ad hoc* networks. Operating in the globally available, unlicensed, 2.4 GHz Industrial, Scientific and Medical (ISM) band, Bluetooth has to share the available frequency spectrum with IEEE 802.11b, the leading standard in the establishment of Wireless Local Area Networks (WLAN).

Bluetooth supports an aggregate data rate of 1 Mbps through the modulation scheme of Gaussian Frequency Shift Keying (GFSK). The devices use Frequency Hopping Spread Spectrum (FHSS), where each device transmits on a single frequency for 625 µs, before hopping to a different frequency. This scheme is employed on a packet-by-packet basis, permitting devices to use the entire of the available ISM band by hopping over 79 different channels each with a 1 MHz separation.

The IEEE 802.11b standard provides a maximum bit rate of 11 Mbps through a transmission mode based on 8-chip Complementary Code Keying (CCK) modulation at a chip rate of 11 Mchip/s. Since IEEE 802.11b employs the Direct Sequence Spread Spectrum (DSSS) technique, thereby occupying a dedicated bandwidth of approximately 22 MHz within the ISM band.

The quantification of Bluetooth and IEEE 802.11b coexistence has received much attention lately. A number of simulation studies [2, 3] have been performed in analysing the effects of coexistence, while empirical studies [4, 5] have been used in evaluating system performance degradation due to mutual interference. In retrospect, a number of coexistence mechanisms have been proposed to mitigate the effects of interference when the two systems are collocated. These fall into one of two categories: collaborative or non-collaborative. A collaborative coexistence mechanism permits the exchange of information between the Bluetooth network and the WLAN in reducing mutual interference, whereas a non-collaborative technique accounts for each system operating independently.

This paper focuses on Adaptive Frequency Hopping (AFH), a non-collaborative mechanism, in enabling Bluetooth – IEEE 802.11b coexistence. It presents experimental results of the benefits offered by AFH in view of justifying its selection as a compulsory feature by in the Bluetooth specification Version 1.2 due to be released in late 2003. Hereafter, the terms IEEE 802.11b and WLAN will be used interchangeably.

II. The AFH Coexistence Mechanism

Adaptive Frequency Hopping is a non-collaborative technique implemented by Bluetooth radios in order to avoid interference. The AFH algorithm dynamically changes the frequency hopping sequence of the device, thereby restricting the number of channels the Bluetooth node hops across. This allows certain frequency channels to be left open for use by other systems, such as WLAN.

The AFH mechanism for Bluetooth can be divided into four main components [6, 7], namely:

- **Channel Classification**, this component classifies frequency channels as either *good* or *bad* in accordance to the level of interference present on that channel,
- **Link Management (LM)**, the primary role of the LM is to coordinate and distribute the AFH information to all Bluetooth nodes in the network,
- **Hop Sequence Modification**, the function of this component is to selectively reduce the number of hopping channels within the sequence in order for the Bluetooth node to avoid *bad* channels, and
- **Channel Maintenance**, due to the unpredictability of the wireless medium, this method is used to periodically re-evaluate the quality of the channels.

Having established the *good* frequency channels, each Bluetooth node modifies it frequency hopping sequence through the Sequence Modification method, thereby avoiding the interference limited *bad* channels. An example of AFH implementation can be seen in Figure 1.

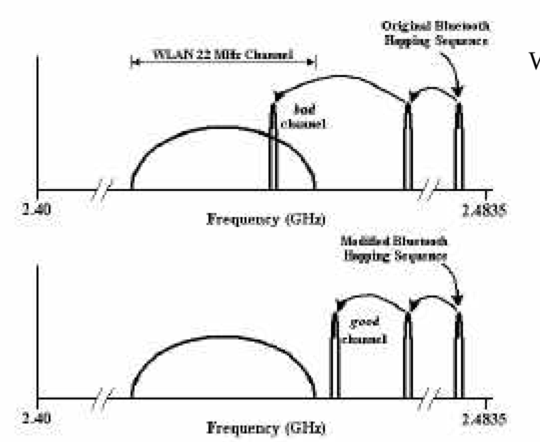

Figure 1. Example of AFH implementation.

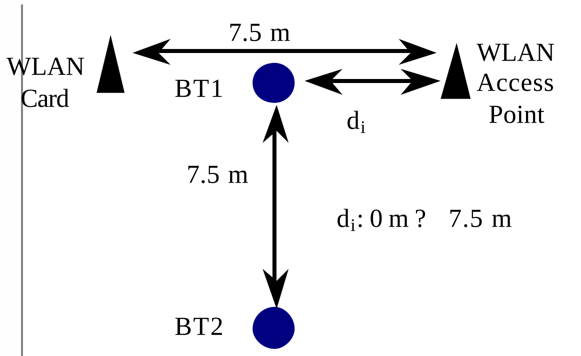

Figure 2. Experimental Setup used to measure the interference between Bluetooth and WLAN systems.

III. Implementation

The experimental setup for measurements of the 802.11b network with Bluetooth interference consisted of a Draytek ADSL Wireless modem, an ORiNOCO Wireless Card and two Bluetooth USB devices using CSR's BlueCore modules [8]. The testing was carried out in an open office environment; there were no objects nearby that could be a significant source of multi-path interference. The experimental setup is shown in Figure 2.

CSR BlueCore firmware implements Channel Quality Driven Data Rate (CQDDR) where the choice of data packet rate is influenced by the prevailing RF conditions. This means that the packet type used in the Bluetooth link varied depending on the RF conditions. The WLAN modem uses Automatic Rate Selection; this is where if packets are being lost the transmission rate will be decreased in an attempt to reduce congestion. The specified transmission rate is 11Mbps with a fallback to 5.5, 2 and 1Mbps.

A file transfer was started from the WLAN laptop through the access point to a PC and also between the two Bluetooth devices. The distance between the access point and the Bluetooth device, d_i, was increased for each test and the data was recorded. The aim of this experiment was to quantify the interference at different distances between the Bluetooth and WLAN systems. This experiment was repeated using a beta-version of the AFH algorithm being developed at CSR [8]. This version did not include automatic channel classification; instead the channels had to be classified manually.

In the third experiment a HV3 audio connection was setup between the Bluetooth devices to provide a steady traffic stream. The voice packets are sent once every third slot pair and are commonly used between a Bluetooth headset and mobile phone. This would show the effect on voice transmission when in the close proximity of a WLAN. Again, this was repeated using the AFH algorithm.

IV. Results

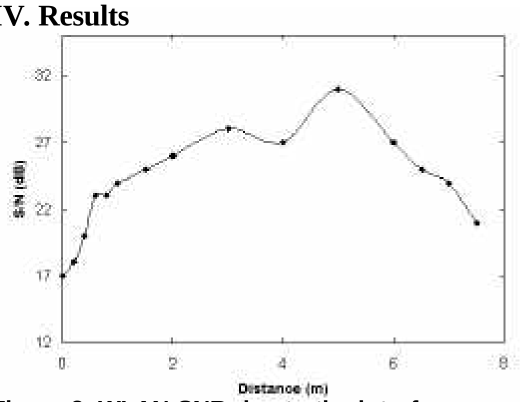

Figure 3. WLAN SNR due to the interference from the Bluetooth devices at different distances, d_i.

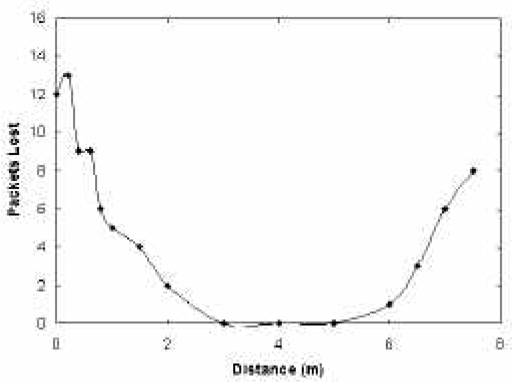

Figure 4. WLAN packets lost due to the interference from the Bluetooth devices at different distances, d_i.

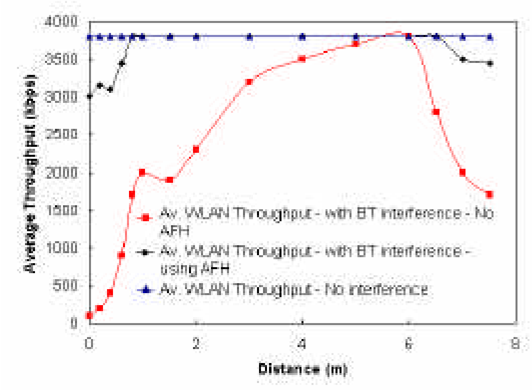

Figure 5. Average WLAN data throughput with no interference, Bluetooth interference and Bluetooth interference using AFH.

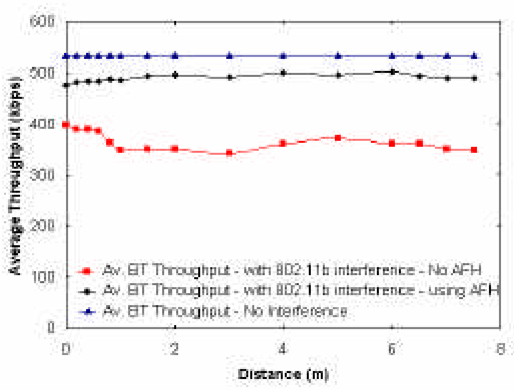

Figure 6. Average data throughput between the Bluetooth devices with no interference, WLAN interference and WLAN interference using AFH.

The results gathered during this experimental setup were averaged from 5 attempts at each distance. This was to decrease the effects of the CQDDR and the Automatic Rate Selection mechanisms.

Figure 3 shows the performance of the automatic rate selection 802.11b devices in the presence of Bluetooth interference. At a smaller value of d_i the interference is greater i.e. the SNR is lower. Figure 4 shows there is greater packet loss at smaller values of d_i. The packet loss corresponds to the decrease in SNR and as the SNR increases, i.e. there is less noise, the number of packets lost decreases. As expected the greatest number of packets lost is when the interferer is closer to the receiver i.e. $d_i = 0$. As the interferer (Bluetooth) is moved further away from the (802.11b) receiver, the SNR increases, i.e. the noise level decreases, but as it approaches the (802.11b) transmitter the interference increases again.

The average throughput of the WLAN system, without the Bluetooth devices using AFH, follows the same pattern, as shown in Figure 5. When the interferer (Bluetooth) is as close as possible to the (802.11b) receiver the throughput is barely significant – 100 kbps. Slowly, as the interferer is moved further from the (802.11b) receiver the throughput increases. Until the distance is 0.8 m the throughput does not drastically improve – 800 kbps. Again at approximately 3 m the throughput is at almost maximum 3200 kbps, or 3.2 Mbps, and at 6 m the throughput is measured to be at a maximum, 3800 kbps (3.8 Mbps). As the interferer (Bluetooth) approaches the (802.11b) transmitter the SNR decreases, packet loss increases and the throughput falls, but not as severely as before. This is due to the higher power signals leaving the WLAN transmitter. When the Bluetooth devices are using AFH the average 802.11b throughput is 3800 kbps (3.8 Mbps) for most distances and does not drop below 3 Mbps even when directly on the WLAN transmitter.

Figure 6 illustrates the fact that Bluetooth is more robust to interference and its average throughput does not vary significantly with distance. The throughput without using AFH is approximately 365 kbps and by using AFH this increases on average by 125 kbps.

The problem with using automatic rate selection is that the time taken to transmit a single packet using 2 Mbps is 5.5 times longer than using 11 Mbps. Hence, the transmit duration time increases, thereby increasing the vulnerable period for a Bluetooth-WLAN packet collision. Since the loss of any part of the WLAN packet causes the loss of the entire packet, the packet loss rate is higher at 2 Mbps. In such cases, the built-in mechanism of automatic rate selection used by the WLAN system, which is supposed to decrease the effects of noise and interference, actually causes increased degradation.

Figure 7 shows the spectrum analysis of the total Synchronous Connection-Oriented (SCO) data captured in the different scenarios. The audible frequency range for humans is 20 Hz – 20 kHz and generally speech ranges from 100 Hz – 8 kHz. The Figure shows that the WLAN interference caused more low frequency components and this accounts for the popping and gritty speech received. The SCO data captured using AFH is very similar to the SCO data with no interference in frequency range and signal level. The quality of the call itself is equal to before, with almost no distortion.

With no AFH specification currently available this work represents, to the best of the authors' knowledge, the first publicly available empirical study of the operational improvements offered by AFH in reducing Bluetooth – IEEE 802.11b system interference.

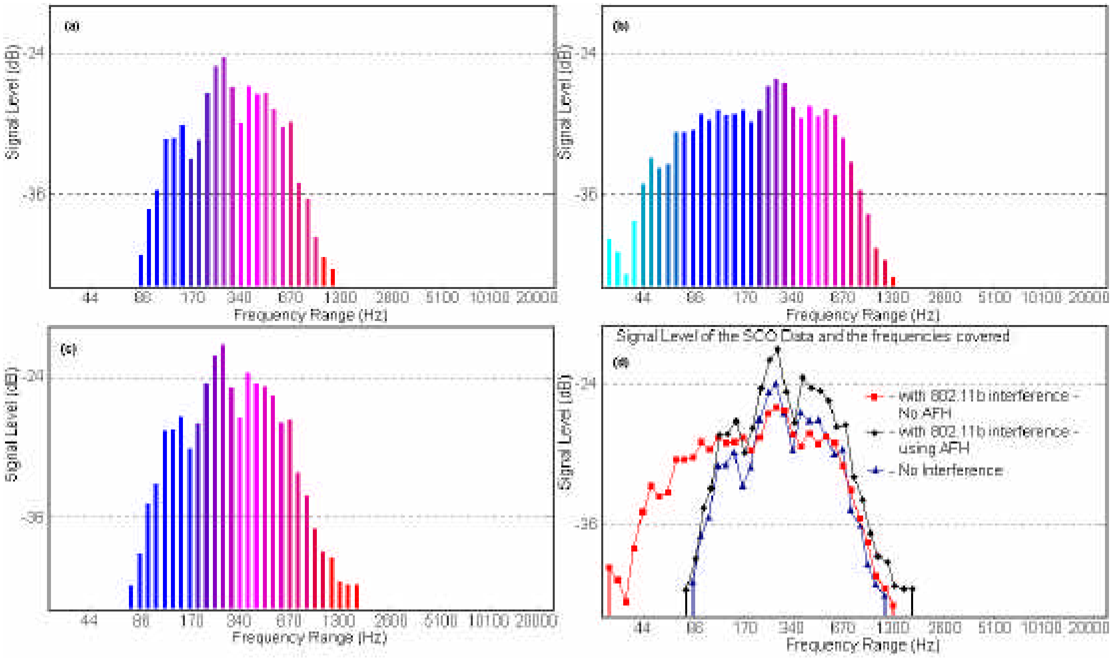

Figure 7. Spectrum analysis of the recorded SCO data (a) SCO link with no WLAN interference. (b) SCO link with WLAN interference, (c) SCO link with WLAN interference using AFH and (d) Comparison of a, b and c.

V. Summary

The interference quantification results indicated that when the two systems are collocated, the effect of Bluetooth on WLAN operation is more profound than the degradation of Bluetooth due to WLAN. According to the results obtained, at distances smaller than 2 m, the operational efficiency of WLAN drops off, with distance, by a factor of 2. The impact of interference on Bluetooth reduces throughput by roughly 35% and is most evident when dealing with SCO data, in which case speech was found to be largely unintelligible.

Empirical testing indicated that the AFH algorithm achieves a performance improvement of roughly 30% for Bluetooth and an increase of around 80% for WLAN. It also offers increased Bluetooth SCO voice quality, close to that achieved when no interference is present.

This paper has focused on the effect of a single point-to-point Bluetooth link on a single point-to-point WLAN connection. Further work on accounting for multiple devices should be carried out and the attained throughput would be significantly reduced. Quantifying the effects of multiple Bluetooth piconets and/or WLANs could result in a constraint having to be imposed on the number of devices that can operate at a given time instant within a certain area.

VI. Acknowledgements

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VII. References

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