# Chapter 5

# Conclusions and Future Directions

This chapter presents a summary of the research performed for this thesis. A review of the results presented in Chapter 4 is also presented. Topics for future areas of research are suggested in this chapter.

### 5.1 Summary of Research

In 2001, there were 13 million devices shipped with integrated Bluetooth and this is predicted by Gartner Dataquest to reach 36m units this year and 186m in 2003. There are approximately 500 qualified Bluetooth products ranging from the Compaq 3870 iPaq and Sony Handycam camcorder -- both with embedded Bluetooth -- to accessories for the Gameboy and other consumer electronic devices. The dominant interferer for Bluetooth will be Bluetooth on Bluetooth.

From the Bluetooth piconet simulations performed with DH1 packet interferers, it is observed that the probability of colliding with 1 adjacent piconet is .70%. The effect of cochannel interference from DH1 packets initially appears to be minimal, however the data throughput performance degrades as adjacent piconets become active. Nine active piconets significantly impact the data rate to an unacceptable level. Under the conditions of 9 interfering piconets with a collision probability of a 7.2%, the data rate decreases by 10.8% from 1.7kb/s to 1.61kb/s as seen in Figure 4.6. Twenty adjacent piconets returns a 14% probability of frequency collision. This results in an 11.3% decrease in performance, yielding a 1.5kb/s transfer rate as seen in Table 5.1.

Interfering DH5 multi slot packets results in even more interference and increased degradation. One interfering DH5 piconet has a 1.1 % probability of colliding with a DH1 packet as seen in Figure 4.8. Under the conditions of 9 interfering piconets with a collision probability of a 10%, the data rate decreases by 11.3% from 1.7kb/s to 1.55kb/s as seen in Figure 4.11. Twenty adjacent DH5 piconets return a 21% probability of collision that results in a 1.37kb/s data rate. This equates to a 12.4% decrease in the expected 1.7kb/s data rate.

In an environment with the same number of interfering piconets, Bluetooth will perform better when DH1 packets are transmitted. In Table 5.1, we observe an 11% reduction in data throughput when in the presence of 20 DH5 interfering piconets when compared to the same environment using DH1 packet interferers. The probability of frequency collision is the same in both scenarios, however DH5 packets have a much higher probability for a collision in the packet's slot. The higher payload in DH5 accounts for the increased magnitude of cochannel interference.

It should also be noted that large office and large rooms present very different channel conditions for Bluetooth piconets. Naturally a large room environment presents an opportunity for more frequency collisions do to the large area of space for bluetooth users to operate. However, given the C/I threshold discussion outlined in chapter 4, it is unlikely that a device from a range beyond 10 meters will impact a bluetooth piconet under study. Further, in projected bluethooth personal area networking usage scenarios, it is unlikely that more than 20 active piconets will operate in a given area as seen in the Figure 3.3 bluetooth topology. Large open areas are not unrealistic environments, for example during Bluetooth Unplug fest, in which many bluetooth developers converge in a large conference room and perform interoperability test. In an open area, Unplug fest environment Figure 4.5 and 4.10 provide insight to the type of data rates one might expect.

Table 5.1. Packet types and Data rate based on probability of collision

| Interfering Packet Type | Number of Interfering Piconets | Prob. of Frequency Collision % | DH1 Data Rate kb/s |
|---|---|---|---|
| | 1 | 0.7 | 1.71 |
| DH1 | 5 | 3.8 | 1.67 |
| | 7 | 4.8 | 1.65 |
| | 10 | 7 | 1.61 |
| | 15 | 10 | 1.55 |
| | 20 | 14 | 1.5 |
| | 40 | 24 | 1.31 |
| | 60 | 32 | 1.19 |
| | 80 | 37 | 1.09 |
| | | | |
| | 1 | 1.1 | 1.7 |
| DH5 | 5 | 5.7 | 1.63 |
| | 7 | 7 | 1.6 |
| | 10 | 11 | 1.54 |
| | 15 | 16 | 1.45 |
| | 20 | 20 | 1.37 |
| | 40 | 37 | 1.15 |
| | 60 | 50 | 0.9 |
| | 80 | 60 | 0.71 |

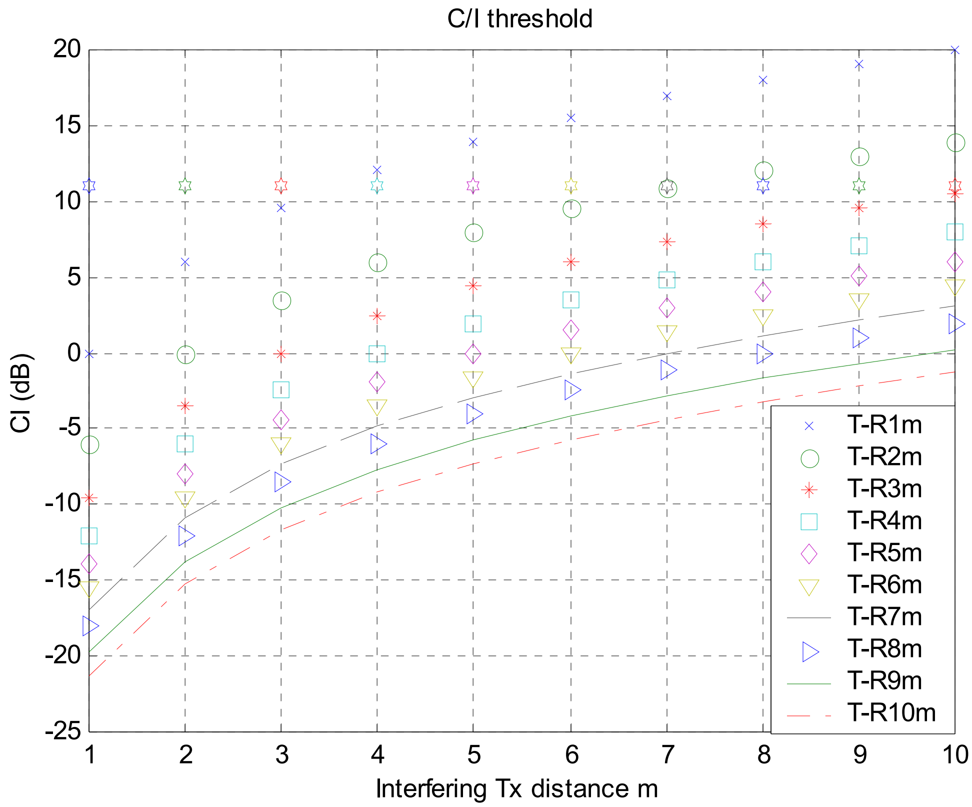


*Figure 5.1 C/I Performance Threshold*

The analysis illustrates the degree to which the desired bluetooth receiver is susceptible to interference from nearby bluetooth transmitters is clearly dependent upon the range. This relationship is shown in Figure 5.1, which captures the interference threshold when two bluetooth transmitters from independent piconets (the desired signal and the interfering signal) are assigned to the same frequency for communication. This ratio is known as C/I, carrier to interference ratio in dB. The Bluetooth C/I "C/I (co-channel) = 11dB" in the radio specification which means that specification performance is expected when the desired signal is 11 dB higher than another signal @ the same frequency. The impairments caused by cochannel interference on system performance will depend on the distance between the desired bluetooth receiver and bluetooth transmitter and the distance between the bluetooth receiver and the interfering transmitter.

From the graph in Figure 5.1, we observe when the desired receiver is 1 meter from the transmitter; the C/I threshold is met when an interfering transmitter is approximately 3.5 meters away from the desired receiver. Transmitters that are approximately 3.5 –10 meters away do not meet the C/I threshold to cause harmful interference to a receiver that is 1 meter away from its transmitter. When a desired receiver has a Tx-Rx separation distance of approximately 3.5 -10 meters, Bluetooth transmitters hopping in an independent piconet anywhere within a 10 meter range will break the C/I threshold. As seen in Table 4.1, for the Tx-Rx separation distance of 10 meters, the received signal is -62 dBm. An interfering signal would have a transmit power of -51 dBm which corresponds to a device 3.5 meters away or a greater distance.

In conclusion from the simulation results, it is seen that Bluetooth on Bluetooth cochannel interference can degrade the throughput performance in a piconet. Further DH5 multislot packets have a greater impact when compared to DH1 single slot interference. Probability of collision is also highly dependent on the bluetooth environment such as Large offices or Large open areas with a high density of active bluetooth devices, where the C/I ratio will vary dependent on distances between the desired and interfering transmitter.

### 5.2 Future Work

Research has been done to investigate the performance in bluetooth piconets as a result of Cochannel interference. The Cochannel interference was simulated and evaluated with DH1 single slot packet and DH5 multi slot packet interferers. These earlier publications investigated the effects of multiple Bluetooth devices in projected Bluetooth usage scenarios. The work in this thesis could lay the foundation for developing adaptive frequency hopping algorithms. Possible future directions include the study of adaptive frequency hopping algorithms, reduced hop frequencies and an automatic power control feature. Intelligence is required to recognize other users hop sequences within the spectrum band so that it individually and independently chooses and adapts its hop sets to avoid hopping on occupied channels. For Bluetooth to combat the Cochannel interference problem from surrounding piconets it is imperative that potential interfering piconet's frequency hopping sequences and distances are known. Before a bluetooth-enabled device connects to any piconet, part of the inquiry should be to record the hop sequence of surrounding piconets. Once this device connects to the desired piconet, the potential interfering piconet's hop sequence would be reported to the Master. In this case the master would adjust its own hop sequence to avoid a collision. Automatic power control based on transmitter to receiver distance would also mitigate interference. Good power control will mitigate the interference issue where the C/I threshold is broken as devices move in the 10-meter proximity. A device that is 1 meter away from the desired receiver should not transmit at the full 0dBm specification. Accompanied by a reduction in transmit power the coordination of frequency hopping systems can potentially mitigate the Bluetooth Cochannel interference analyzed in this thesis.

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## VITA

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