Chapter 3 Analysis

3.1 Introduction

Users of the Bluetooth wireless communication system can experience interference from various sources including Wireless LANs, microwave ovens, baby monitors and cordless phones. Adjacent channel bluetooth interference can also contribute to the degradation in performance in the bluetooth network. One of the biggest challenges in sending information via a wireless channel is to maximize efficient use of the limited available bandwidth and avoiding interference. Frequency reuse is a popular technique for increasing the number of users in a given area who can be supported by a particular band of frequencies. However, the downside of frequency reuse in the bluetooth network is the introduction of co-channel interference, which degrades performance resulting in an adverse affect on the achievable BER and data rate of each user. Co-channel interference results when two or more piconets hop on the same frequency of the desired signal.

Although bluetooth can experience interference from the aforementioned sources, the focus of this thesis study is the Co-Channel interference analysis from adjacent bluetooth piconets. Bluetooth-to-Bluetooth interference increases due to a smaller spectrum that is shared. Assuming 900 million Bluetooth-enabled devices are in existence 5 years from now, the dominant cause of Bluetooth interference will be from other Bluetooth devices.

In this chapter Co-Channel interference analysis on the physical layer in the presence of multiple interfering bluetooth piconets is explored. The present work focuses on the probability that this interference between adjacent piconets will occur. Assuming
a uniform distribution of Bluetooth devices in a room or office space, an analysis is provided to determine the probability of collision. In order to predict Bluetooth performance we explore what constitutes interference using an analytical and simulation methodology. First several metrics are identified; probability of frequency collision - interfering signal hops on the same frequency of a desired signal, C/I threshold, power received, transmitter – receiver distance, data throughput, data packet link load, single or multiple packets, additional Bluetooth devices connecting to unsynchronized networks within a ten-meter range, and distance to the interfering transmitter. Next to predict Bluetooth performance we also need to define what constitutes interference, for example C/I threshold and probability of frequency collision. Finally using the attributes of the Bluetooth wireless communication system provided in the previous chapter a MATLAB simulation model is developed. This model is used to illustrate co-channel interference, a major limiting factor in the performance of the Bluetooth radio. The simulation evaluates Bluetooth performance based on the data degradation as a result of the metrics aforementioned. The analysis described above is different from what previous researchers have done because the focus is Bluetooth on Bluetooth co-channel interference on single and multi-slot packets, which have gone unexamined up to this point.
3.2 Co-Channel Interference

Wireless communication systems use one or more carrier frequencies to communicate. Bluetooth uses the 2.4 GHz band, which under US FCC regulations, extends from 2.4 to 2.4835 GHz. The ISM band rules defined in FCC Part 15.247 state this band is License free, however, bluetooth devices must operate under certain constraints that are supposed to enable multiple systems to coexist in time and place. Systems can use one of two spread spectrum (SS) techniques to transmit in this band. Frequency-hopping spread spectrum (FHSS) allows a device to transmit high energy in a narrow band for a limited time. The second method is direct-sequence spread spectrum (DSSS) utilized by Wireless LANs. DSSS allows a device to occupy a wider bandwidth with relatively low energy in a specified segment of the band without hopping [8]. Bluetooth uses FHSS, employing channels of 1 MHz in width and a hop rate of 1600 times per second across 79 channels in the United States. As ad-hoc networks are formed in a 10m interchanged proximity of adjacent piconets, sharing the band is inevitable. Spread-spectrum techniques, which spread a signal across a larger band of frequencies than is required for normal transmission, can reduce the effect of non-bluetooth interference such as 802.11 Wireless LANs. However, the implementation of the FHSS technique in bluetooth network introduces frequency reuse, a popular technique that increases the number of users in a given region who can be supported by a particular set of frequencies. Piconets using the same frequency band have a high propensity to interfere with each other.
When receiving, the slave in the piconet is impacted by interference from slaves in other co-located piconets that are transmitting data or ACK. This interference is known as Cochannel interference when two users (the desired signal and the interfering signal are
assigned the same frequency for communication. This ratio is known as C/I, carrier to interference ratio in dB. The Bluetooth co-channel interference ratio is 11dB, which means specification performance is expected when the desired signal is 11 dB higher than another signal at the same frequency. Power received is a function of distance thus; co-channel interference depends on the distance between the transmitter and receiver under study and the distance of the interfering transmitter. The C/I will also depend on the transmit powers applied in the bluetooth transmitters. Transmit powers are fixed at 0dBm for the range of 10m. The performance is determined by the intended power received and the interfering power received, or the total C/I. The impairments caused by co-channel 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.

It is an optimal wireless network design when users that share the same channel are placed at a separation distance such that the co-channel interference is just below the maximum tolerable level for the required BER and data rate. However the nature of the bluetooth technology provides usage scenarios that allow many piconets in close proximity. This scenario makes bluetooth subject to Co-Channel interference. In the diagram below the desired packets (blue) are operating in piconet one. The interfering packets (red) are in an adjacent piconet within the ten- meter range of the desired receiver. The FHSS scheme introduces interference as illustrated in Figure 3.1. As the bluetooth devices hop across the 2.4GHz spectrum eventually a collision will occur which degrades the performance of the system.
The foregoing analysis is helpful, but does not describe the Bluetooth performance analysis completely. Accurate estimates of network throughput in the presence of interfering piconets must account for the probability of collision as the number of adjacent piconet grow. This is described in section 3.6.
3.3 Received Power and Path Loss

The present interference model is intended to predict co-channel interference trends corresponding to T-R distance in desired piconets and distance from interfering transmitters. Propagation measurements in a mobile radio channel show the average received signal strength decays as the transmitter separation distance is increased from the receiver. [5] Propagation models predict the average received signal strength as distance varies from the transmitter. To simulate a typical office environment, this analysis employs the free space propagation model, used to predict received signal strength in clear, unobstructed line-of-sight path between the transmitter and receiver.

When power is radiated from an antenna, only a small portion of the signal reaches the receiver, a phenomenon known as path loss. Path loss is the received power divided by the transmitted power, and this loss is a function of the transmitter-receiver separation distance. The nominal link range is 10 centimeters to 10 meters, but can be extended to more than 100 meters by increasing the transmit power. With 0dBm power, the communication range may be up to 10 meters (30 feet) while 20dBm transmit power increases the range to100 meters (328 feet). The analysis is limited to devices that transmit at 0dBm. (1mW) The received power level as distance varies from the transmitter allows one to predict interference based on the C/I 11dB threshold. Received signal power is proportional to the transmit power and inversely proportional to the square of the transmission frequency and the transmitter-receiver distance raised to the power of the path loss exponent, n. The indoor radio channel differs from the traditional mobile radio channel in terms of the distances covered, which are much smaller and the various propagation characteristics over a manifold of building environments. [5]
Using the following formula the bluetooth received power for the desired signal and the interfering signal strength was calculated as a function of the ten-meter range of both the desired and the interfering signals [9].

**For T-R Distance >8 meters**

Received Power = Power TX – Path Loss = 0 - \( \left( 58.3 + 33 \times \log_{10}(D/8) \right) \) \[6\]  
\( D = \text{Tx-Rx distance} \)  

\( \text{Received Power} = \text{Power TX} – \text{Path Loss} = 0 - \left( 20 \times \log_{10}(4 \times \pi \times D / .1224) \right) \) \[6\]  

**3.4 Multipath Fading**

Due to reflections, scattering and diffraction of the transmitted signal in a channel, multiple versions of the transmitted signal arrive at the receiver with different amplitudes and phases. Interference between two or more of these signals that arrive at slightly different times at the receiver result in fading [5]. An indoor wireless channel is often described by Rician fading. In addition to the multipath received from reflections, scattering, and diffraction, a non-obstructed line-of-sight (LOS) path exists between the transmitter and receiver. Thus the random multipath components are superimposed on the stationary dominant signal.
In order to model the received signal in a Ricean faded channel, the path loss equations are used in Figures 3.1 and 3.2. The first order multipath fade, results in a 6 dB drop in the received signal power after the component is summed at the receiver antenna. In an open environment all other order fading is negligible. This is illustrated in Figure 3.2. Using the path loss equations 3.1 and 3.2 we observe in Figure 3.2, the second order
fade signal that travels 24.14 meters results in a received power of -80dBm. This power is below the receiver sensitivity threshold -70dBm, therefore the receiver is unable to detect this faded signal. In worst case scenario where this faded signal is the exact reciprocal of the original signal, the received power is below the receiver sensitivity threshold and the signal is not detected by the receiver. The summation of the power received due to path loss and the Ricean fade results in the received signal. For the cochannel interferer fading is ignored as we assume worst-case interference.

Rayleigh fading statistics are not implemented in this study due to the nature of the environment. Rayleigh fading illustrates an environment that changes with time such as a mobile user riding in a moving vehicle where no LOS path exist between the transmitter and the receiver. The Bluetooth environment is fixed and does not generally change in time. The fading in a fixed environment is accounted for in the Ricean channel.

3.5 Bluetooth network topology

A single room office environment (LOS propagation) , with a number of piconets distributed in it is postulated to analyze the collision probability. Interference is expected to grow as a function of the number of overlapping piconets. Using a typical office environment the bluetooth cochannel interference performance is modeled for several network topologies. We explore the large offices with 28 interfering piconets (Figure 3.3) and large open rooms with potentially 110 interfering piconets (Figure 3.4). Figure 3.2 illustrates a receiver (desired signal) located in piconet 1 and interfering transmitters in an adjacent office in piconet 2. The bluetooth units are in two
unsynchronized piconets. It is assumed that there is one interfering piconet co-located with piconet 1. The analysis will build upon this model to include several interfering piconets within a ten-meter range. The piconets consists of two or more devices, which are capable of establishing at least a point-to-point link.

Several piconets can be established and linked together ad hoc, where each piconet is identified by a different frequency hopping sequence. All users participating in the

*Figure 3.3 Simulated desired and interfering bluetooth piconets. The bluetooth receiver can be located up to 10m away from the BT transmitter. Any transmitter in Piconet 2, in range, can potentially interfere with the desired receiver.*
same piconet are synchronized to one hopping sequence. The topology can best be described as a multiple piconet structure. Each Piconet includes one master and seven slaves.

**Large office**

Desired Piconet

Potential Interfering Piconets

![Figure 3.4 Simulated large office environments.](image)
**Large open room**

Desired Piconet

Potential Interfering Piconets

20 meters

Figure 3.5 Simulated large open room environments. (110 interfering piconets)

3.6 Probability of Interference

In order to analyze cochannel interference, a probability function is used to simulate the frequency collision probability of multiple piconets. Each channel is represented by a pseudo-random hopping sequence, unique to each piconet. In countries where 79 hopping frequencies are used (USA and parts of Europe) obviously there is a basic 1/79
chance that devices will collide with another device in one adjacent piconet. This probability increases as the number of piconets increase. Multi-slot packets, which span 5 times the normal slot size, increase the chances of this type of packet being involved in a collision. The probability that interference will occur is presented based on user scenarios for data links. A frequency collision will only occur if all of the following conditions are met: Data is transmitted at the same time in multiple piconets, both piconets hop on the same frequency, both piconets are within the ten meter distance and C/I is less than the 11dB

To determine the probability of interference, one must first determine if the received power from the interfering device is within the C/I. This is based on distance to the desired device as described in section 3.3. Next of the distances that are in range to interfere with the desired receiver the probability that the two signals collide on the same frequency is determined. Naturally as more piconets come in range the probability increases. A frequency collision occurs when signals from one or several piconets hop on the same frequency at the same time resulting in dropped packets. There are instances where hopping on the same frequency at the end of the packet transmit avoids interference. The slots are 625µs in length however, the packet has a duration of 366µs. Frequency overlapping analysis are based on the use of single time packets by the piconet resulting in a hop rate equal the transmit rate i.e. each transmission is at a different hop frequency resulting in a higher probability of collision. When transmitting the piconet system occupies a span of 1Mhz. Finally the number of dwell periods overlapped is a function of packet length and the Start-of-Transmission (SOT) time. SOT is a uniform random variable with a range of 0 to 625 usec. Based on these considerations and the
piconet load factor, the probability of collision for Bluetooth packets under consideration can be computed:

Assume interferer and desired signal transmit as the same time.

\[ N = \text{Number of Piconets} \]

Probability BT interferer hops onto desired Piconet’s frequency (Pcol): \( 1 - \left( \frac{78}{79^N} \right) \) [10] (3.3)

Probability BT interferer overlapping in slot (Pslot): \( 1 - \left( \frac{259 \mu \text{sec}}{625 \mu \text{sec}} \right) = 59\% \) (3.4)

Prob. single slot interferer collides in Multipacket slot: \( 1 - \left( \frac{2.866 u \text{sec}}{3.125 u \text{sec}} \right) = 92\% \) (3.5)

Total Probability of interference with Single slot packet piconets: \( 1 - \left( \frac{78}{79^N} \right)*0.59 \) (3.6)

Total Probability of interference with Multipacket slot piconets: \( 1 - \left( \frac{78}{79^N} \right)*0.92 \) (3.7)

\[ RX \ f(k) \quad f(k+1) \quad f(k+2) \]

625 µs Time slot

Desired Signal (Piconet1)

TX f(k)

Interfering Signal (Piconet2)

366 µs

Transmitter start period that will result in interference

259 µs

Transmitter start period that will not result in interference

*Figure 3.6 single slot*
Equation 3.3 provides the probability of piconets actually colliding in the Bluetooth spectrum. As seen in equation 3.4, there is a 59% chance of single slot packets colliding after hopping on the same frequency. The probability of frequency collision remains the same when we evaluate multi-slot packets however the chance that a single slot packet collides with a multi-slot packet increases to 93% as seen in equation 3.5.

Figure 3.7: Multi-slot packets [1]
3.7 Simulation model

As wireless communication systems become more complex coupled with a variety of channel environments, the result is typically a design or analysis problem that cannot be solved using traditional pencil and paper mathematical analysis. Computer-aided design and analysis is necessary to accurately predict system performance. Using numerical simulation can be a very valuable tool for analyzing these complex systems. The widespread availability of powerful computers provide tools that are currently within reach of most communication engineers making it possible to perform system-level simulations of complex systems at one’s desk. The video graphics capabilities of modern personal computers allow performance data to be generated in a usable form. [2]

The role of MATLAB simulation in the design and analysis process is to simulate the Bluetooth power received and the probability of frequency collision. MATLAB is a widely used tool developed to illustrate the operating characteristics of complex systems. Using the MATLAB simulation tool to design a Bluetooth network topology enables one to properly analyze the Bluetooth interference in a variety of network topologies. The system characteristics and interference metrics provide the basis to develop the simulation model, allowing one to move from the physical system to the software model. The model illustrates analytic and simulation methodologies, developed for measuring the metrics, given the occurrence of the co-channel interference...
within the Bluetooth network. These techniques are developed using Matlab simulation code to analyze and model the Bluetooth Co-Channel interference. First a simple piconet topology model is developed with two piconets in proximity to simulate possible interference. Using this model as a base, more complex network topologies can be developed such as channels that include multiple interfering piconets with multi-slot data packets. A simple indoor propagation model provides power received as a function of transmitter and receiver distance. The path loss simulation illustrates the distances that interference will occur assuming the worst-case scenario where the devices hop on the same frequency. Using the C/I threshold it is assumed an error occurs or a packet is lost if the C/I of the interfering transmitter is greater than the threshold. Based on the probability that the devices will hop on the same frequency multiplied by the packet link load accurate interference conclusions can be drawn.