Performance Analysis Of 802.11b Networks

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Performance Analysis Of 802.11b Networks

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THESIS ABSTRACT

PERFORMANCE ANALYSIS OF 802.11B NETWORKS

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Wireless local area networks (WLANs), especially those incorporating the 802.11b standard, have experienced rapid evolution and unprecedented widespread deployment during the past few years. Increasing research led to the advent of new technologies and standards in WLANs enabling them to achieve higher data rates (e.g., from 2 Mbps to 11Mbps) and wider coverage. Since 802.11b networks operate in the unlicensed ISM (Industrial, Scientific and Medical) band of the frequency spectrum, they experience interference from other devices operating in the same band. Therefore, it is important to understand the performance of 802.11b networks, in terms of throughput and quality (packet error rate), for both TCP and UDP data transmissions over these networks, under interference. This thesis presents a detailed experimental study of the impact of self interference (other 802.11b access points and terminals), Bluetooth interference and microwave interference from household appliances on 802.11b networks. A mathematical model for predicting the throughput of 802.11b networks in the presence of self interference is developed. Such a model is extremely useful in planning WLAN network deployments in indoor environments and in proactive performance management.

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Finally, I am greatly indebted to my parents, sister and my grand father whose love and encouragement provided me the strength to achieve my goals and I humbly dedicate this work to them.

Style manual or journal used Journal of Approximation Theory (together with the style known as "aums"). Bibliograpy follows van Leunen's *A Handbook for Scholars.*

Computer software used The document preparation package TeX (specifically LaTeX) together with the departmental style-file `aums.sty`.

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Chapter 1

Introduction

Phenomenal growth and rapid advancements in the field of wireless communications enable us to transmit not only data but also voice and video through a variety of wireless communication systems. These systems can be wireless cellular systems, wireless local area networks (WLANs), wireless personal area networks (WPANs) and satellite communication systems [7]. Among them, wireless local area networks, especially 802.11b, have experienced rapid evolution and unprecedented widespread deployment during the past few years. It is economical to send data through WLANs as they work in unlicensed band where the radio spectrum does not incur any expense to the user or to the service provider. Hence, 802.11b networks are becoming increasingly popular, both indoor and outdoor at universities, offices and other public areas. Increasing research in this field led to the advent of new technologies and standards in WLANs enabling them to provide higher data rates and increased coverage.

Since 802.11b networks work in an unlicensed frequency spectrum, it experiences interference from other devices working in the same band. Therefore, it is very important to study the performance, in terms of capacity and quality, of both Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) over these networks, with and without interference. Since TCP is the most widely used data networking protocol, its performance is analyzed in this thesis.

1.1 Objective and Motivation

The objective and motivation of the research presented in this thesis is to

1. Evaluate and capture the effects of parameters like signal strength, propagation distance, packet size, Request to send/ Clear to send (RTS/CTS), transmission power and medium access control (MAC) retransmissions on the network performance.

2. Analyze the effect of interference of other 802.11b networks (self interference) in detail on 802.11b networks.

3. Evaluate the performance of 802.11b networks under Bluetooth interference for different network scenarios.

4. Develop an analytical model for predicting the throughput of 802.11b networks in the presence of self interference. Co-channel and adjacent channel interference was modeled to estimate the TCP throughput on all overlapping channels.

1.2 Overview of Results

The main contributions of the thesis are summarized as follows :

1. A mathematical model for predicting the throughput of 802.11b networks under self interference was developed. The model uses empirical data and piece wise spectral analysis. Most of the models consider the 802.11b stations to be on the same channel but in the present model the interfering stations can be on any of the overlapping channels. It is extremely difficult to model the behavior of a wireless link in the presence of interfering 802.11b stations. This is due to the time varying nature of the wireless channel. The model takes the distance between interfering wireless transmitter and receiver and the variation of transmission rate with the number of contending stations into consideration. Such dependencies are also not accounted for in other models [42-45].

2. Interesting results has been obtained for the 802.11b networks in the presence of self interference. It was noticed that when two 802.11b stations are close to each other and are on adjacent channels, one of the stations captures the channel and hence gives much higher throughput than the other.

3. Interference of Bluetooth devices on 802.11b networks have been studied for various network scenarios. The measured results of 802.11b throughput under Bluetooth interference have been compared with the theoretical results.

1.3 Thesis Structure

Chapter 2 discusses the existing literature in signal strength and throughput measurements of 802.11b WLAN networks without interference. Measured results obtained by varying the parameters like distance, transmission power, fragmentation threshold etc., are shown.

Chapter 3 focuses on throughput measurements of 802.11b networks in the presence of interference. Such interference may be due to other 802.11b stations or Bluetooth stations or household appliances like a microwave or a cordless phone. The results obtained are presented in an intuitive fashion.

Chapter 4 discusses the throughput prediction model which estimates the throughput in the presence of self interference on overlapping channels. Results validating the model were also presented.

Chapter 5 summarizes the main contributions and directions for future work.

Chapter 2

Prior Work and Interference-Free Measurements

In this chapter, a brief review of the existing literature on the performance of 802.11b wireless networks (without interference) is presented. Measurements showing the variation of the throughput of WLAN networks as a function of signal strength, distance between transmitter and receiver, power level of the transmitter , antenna orientation, request to send / clear to send (RTS/CTS) etc., are described

2.1 Literature Review

The performance and signal strength variation (with distance) of 802.11a and 802.11b networks are compared in [9]. It is concluded that the two networks have the same coverage but 802.11a exhibits higher data rates. A different AP-card pair for both 802.11a and 'b' networks is taken and the throughput variation with distance among different hardware is observed. It was shown experimentally that the throughput depends on vendor specific equipment. Similar variation has also been observed by our measurements.

The effects of path loss and building loss measurements due to residences for outdoor networks are described in [10]. Effects of various shadowing objects like trees and houses and receiver positions are measured and quantified.

Zahur et.al.,in [11] measure the performance of 802.11b networks. The effect of various parameters including distance, power, and RTS/CTS on throughput is measured with varied packet sizes using simulation. Hidden node problem is also considered to analyze the effect of RTS/CTS. In [12], net throughput is assessed by modeling the physical, medium access control (MAC) and TCP overhead. The throughput drop because of collisions and slot times is calculated. The modeled results match well with the measured throughput values at all bit rates for 802.11b networks. By modeling, a net throughput of 80 percent at 6 Mbps and 55 percent at 54 Mbps was predicted for 802.11a LAN, which was still in a draft stage then.

Performance of wireless LAN is evaluated with respect to signal to noise ratio (SNR), file size, number of simultaneous users and the direction of file transfer in [13]. The following are the observations made ; the throughput per user is quite low when there is more than one user in a LAN, but the overall or net throughput increases giving an impression that the lower layers of the 802.11b protocol stack reserves some resources for future users. It is also observed that fairness is preserved by the underlying mechanism of 802.11b protocol. The results show that the number of simultaneous users has a high impact on the throughput compared to that due to SNR while file size has little or no impact. Similarity of our experimental results to these observations will be discussed in a later chapter.

2.2 TCP and UDP

TCP is a connection oriented reliable protocol. Reliability is ensured by acknowledgements from the receiver and retransmissions of the lost packets at the sender. Congestion control and flow control mechanisms in TCP make sure that the fast sender does not swamp too many packets on to the slow receiver. Whenever a packet is lost, TCP reduces its congestion window size (a sender can only send a maximum bytes indicated by the window size) to reduce congestion [49]. TCP is traditionally designed for wired networks wherein the packet losses are mostly due to congestion. But in wireless networks (in 802.11 (a,b and g) networks) the packet loss due to collisions and corruption (because of poor signal strength) is very high. In such cases, TCP reduces its congestion window when a packet

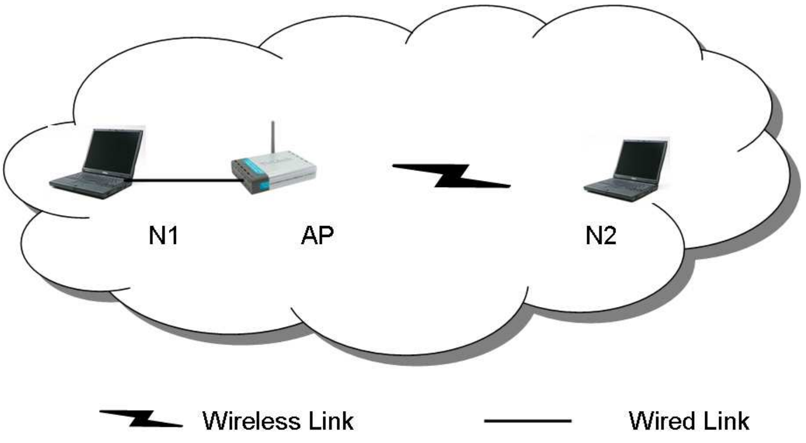


Figure 2.1: Test setup

loss is reported and eventually the throughput becomes zero. The 802.11 MAC employs MAC level retransmissions to hide these errors from TCP layer [6].

UDP, on the other hand, is a connection less unreliable protocol because there will be no acknowledgement from the receiver of a correct packet reception and hence no retransmissions. Please note that these retransmissions (transport layer) are different from MAC layer retransmissions.

2.3 Measurement setup and tools used

2.3.1 Experiment setup

Our setup for evaluating the effect of parameters like signal strength, distance, RTS/CTS etc., on throughput is shown in figure 2.1. The client (or transmitter) N2 is associated with the access point (AP) through a wireless connection while the server (or receiver) is connected to AP through a wired connection.

Client Specifications -

Operating System: Linux

Processor:1.6 GHz Intel Pentium M

Wireless cards: Linksys and Cisco AP 200

Server Specifications -

Operating system : Windows XP

Processor: 1.6 GHz Intel Pentium M

Wireless cards: Inbuilt Dell Wireless card

Access Point - Orinoco AP 2000

Tools Used -

Iperf [15] for calculating TCP bandwidth. A brief introduction to Iperf is given is next section.

RSSI value is measured by the Network Interface Card (NIC) and 'Wavemon' for signal strength. 'Wavemon' is an open source tool used for signal strength measurement.

Measurements are taken for 60 seconds at each data point to get an average value.

2.3.2 Received Signal Strength Indicator (RSSI)

The IEEE 802.11 standard defines a mechanism by which RF energy is to be measured by the circuitry on a wireless network interface card (NIC). "RSSI, abbreviated for Received Signal Strength Indicator, is an arbitrary integer value, intended for use, internally, by the microcode on the adapter and by the device driver" [49]. RSSI value can be treated as replacement for signal to noise ratio. RSSI value of 256 correspond to 100 db SNR (or 0 db signal value) and RSSI value of 156 correspond to 0 db SNR (or -100db signal value). The terms RSSI, signal to noise ratio and signal strength are all similar and hence are interchangeably used in this thesis.

2.3.3 Iperf

Iperf is a free software copyrighted by the University of Illinois [15]. It measures the TCP and UDP bandwidth, packet error rate, jitter and delay of a wireless connection. It is a sophisticated version of NETPERF [16]. In Iperf, there will only be a unidirectional traffic (like FTP) from the client to the server [15]. Hence, this reports the maximum throughput (bandwidth) of the link. In this thesis, throughput is the maximum throughput or bandwidth reported.

2.4 Measurements

This section gives a quick overview of how TCP throughput of a wireless LAN varies with parameters like signal strength, RTS/CTS, etc., TCP packets are transmitted by N2 in all the experiments unless specified.

2.4.1 Signal strength variation with distance

Figure 2.2 [obtained from [51]] shows the variation of signal strength with distance. We can see that the signal strength decreases exponentially as the distance increases. This is because the path loss is a logarithmic function of the distance.

2.4.2 Throughput variation with RSSI

Throughput is measured as the number of information bits transferred in unit time. The throughput variation with RSSI values (in dBm) is shown in figure 2.3 (Result obtained from [51]). Throughput increases exponentially with signal strengths and reaches saturation condition (max throughput) even at low signal strengths values. Throughput measured using Iperf is averaged over a time of 60 seconds. Hence, we consider average maximum throughput (or bandwidth) achieved and not the instantaneous value.

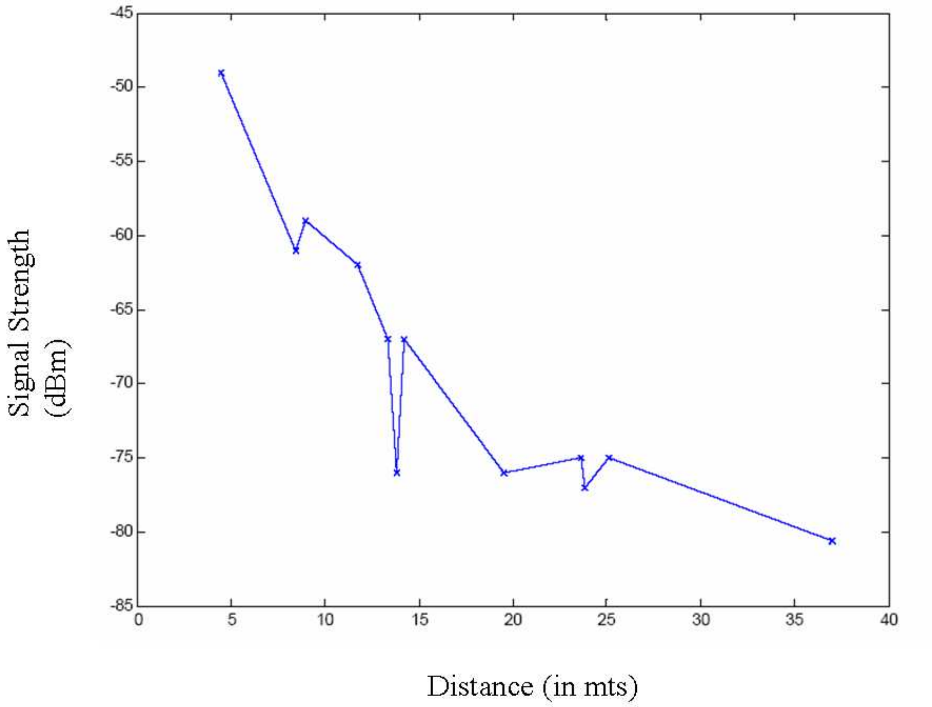


Figure 2.2: Signal strength variation with distance (Result from [51])

2.4.3 Effect of RTS/CTS signals on throughput

The 802.11 distributed coordination function (DCF) employs an optional feature called RTS/CTS, a hand shaking mechanism, to avoid collisions due to the hidden node problem. This mechanism reserves the channel for packet transmissions as less bandwidth is wasted in the event of collisions. In a collision free environment, the additional over head attached because of the RTS/CTS decreases the overall throughput and can be seen in the figure 2.4.

Hidden node problem is briefly explained here. Consider three stations A, B and C wherein station A can hear station B and station B can hear station C but stations A and C cannot hear each other. In such a case, CSMA/CA will not work (between A and C) and when stations A and C simultaneously transmit a frame to B, the frames will collide resulting in a packet loss [4].

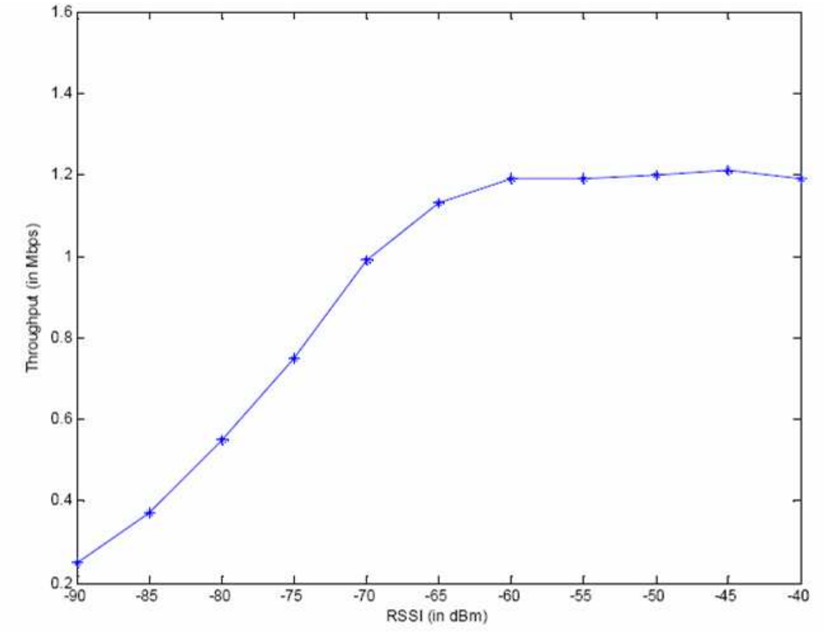


Figure 2.3: Throughput variation with signal strength

2.4.4 Effect of antenna orientation on signal strength

The orientation of the receiver(Rx)/transmitter(Tx) is important in measuring the signal strengths and throughput. The wireless card of the transmitter (AP) is kept facing the receiver (laptop). The orientation of the receiver is changed and RSSI values are measured. Figure 2.5 illustrates the effect.

The explanation of the legend in the figure is as follows -

0 - Both the wireless cards (of Tx and Rx) are facing each other

90 - Wireless cards with a 90 degree angular variation between each other

180 - Wireless cards with a 180 degree angular variation between each other

270 - Wireless cards with a 270 degree angular variation.

In future chapters, we can see that the antenna orientation plays a major role in determining the throughput especially under self interference.

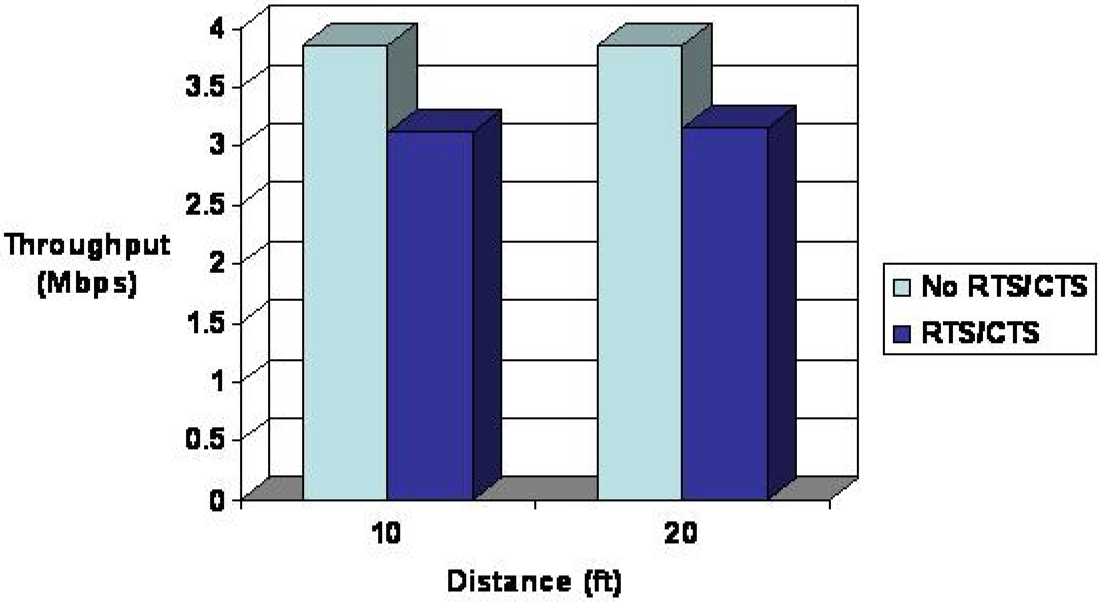


Figure 2.4: Effect of RTS and CTS on Throughput

2.4.5 Fragmentation threshold on throughput

802.11b wireless stations can use the optional feature of fragmentation to divide a large data frame into smaller fragments, which are then sent independently to the destination. Fragmentation threshold can be set for a wireless card, which then fragments all frames more than the set value. If the fragmentation value is set to a lower value, it adds additional overhead for each packet and hence the throughput decreases [11]. But setting it to a low value can be very useful in environments where the losses are high. In our experimental setup, the signal conditions were quite good. Hence we could only see a degradation in throughput as shown in figure 2.6

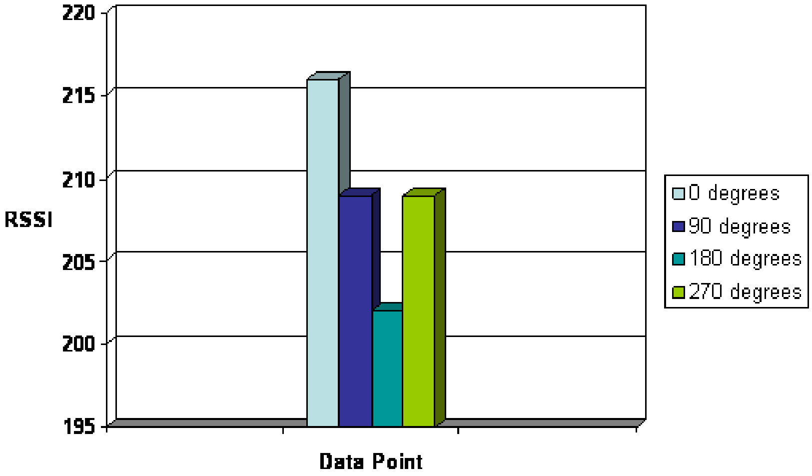


Figure 2.5: Change in RSSI values because of change in the orientation.

2.4.6 Impact of Transmission power of wireless card

The transmission power of a wireless card also plays a very crucial role in the performance of a wireless LAN. Figure 2.7 shows the variation of throughput at different transmission powers and at different signal strengths. We can see that at higher RSSI values the transmission power has negligible effect on throughput. However as RSSI value decreases the effect becomes more evident. The throughput almost reaches zero for lower power values even at decent signal strengths. The values shown in the legend are the transmission power levels of the wireless card while the values shown on the x-axis indicate the signal strength of the AP perceived by the wireless station.

2.4.7 MAC retransmission values

Wireless medium is prone to high error rate when compared to the wired medium. Hence, 802.11 MAC employs MAC level retransmissions to hide these errors from TCP layer. This is because the TCP layer takes stringent action thinking that the loss is because of congestion. The common MAC protocol employed is a 'Stop and Go' protocol, where

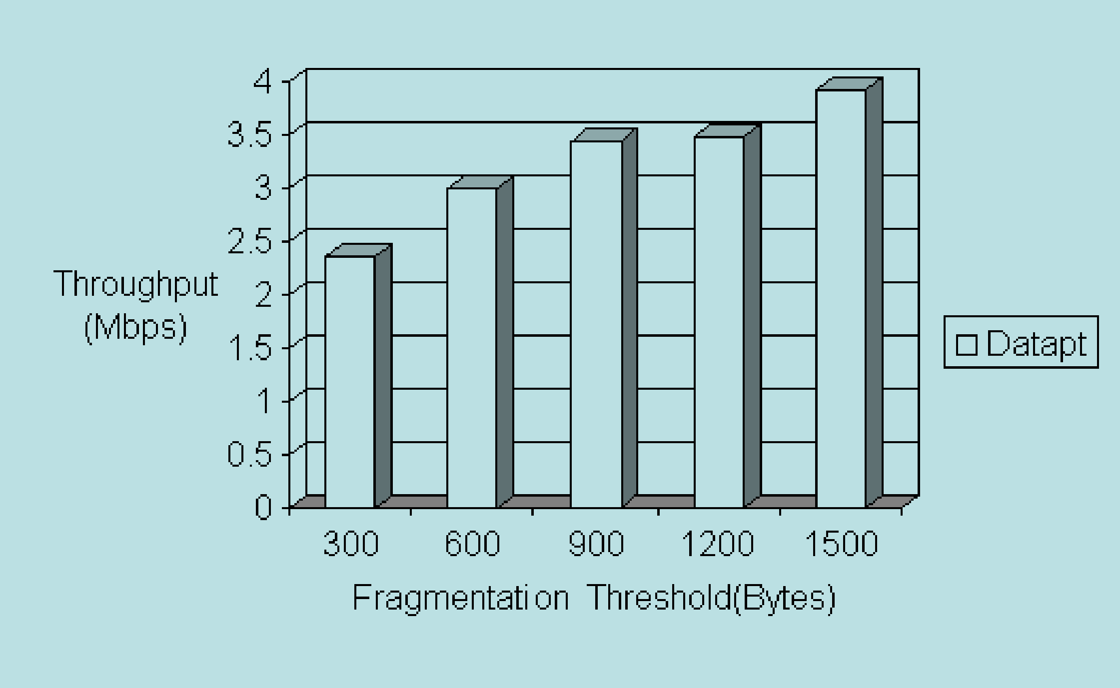


Figure 2.6: Effect of Fragmentation threshold on Throughput

in the next MAC frame is sent only when it receives the acknowledgement (ACK) for the previous frame [21]. Please note that this ACK is different from the TCP ACKs which work at a different layer (transport layer). Figure 2.8 shows the performance of TCP throughout at different MAC retransmission values.

2.5 Summary

In this chapter we have discussed the the impact of parameters like signal strength , distance fragmentation threshold, MAC retransmission values, RTS/CTS and transmission power level on TCP throughput in detail.

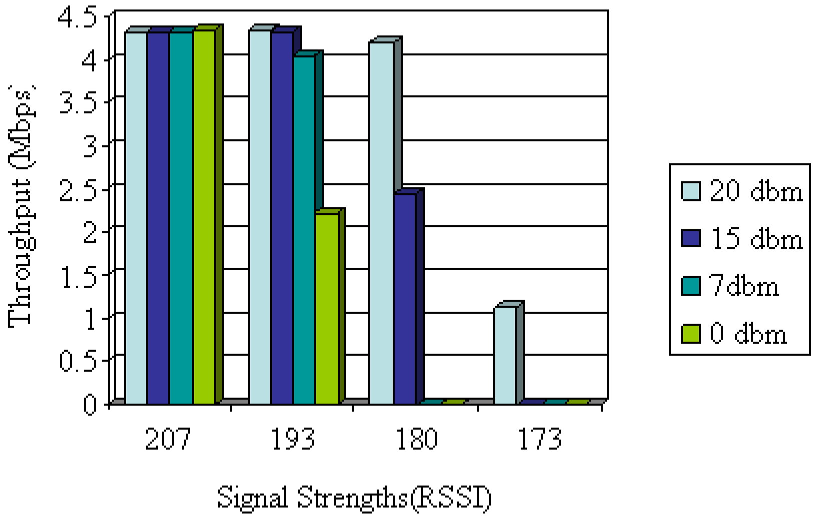


Figure 2.7: Throughput variation with transmission power at different RSSI values

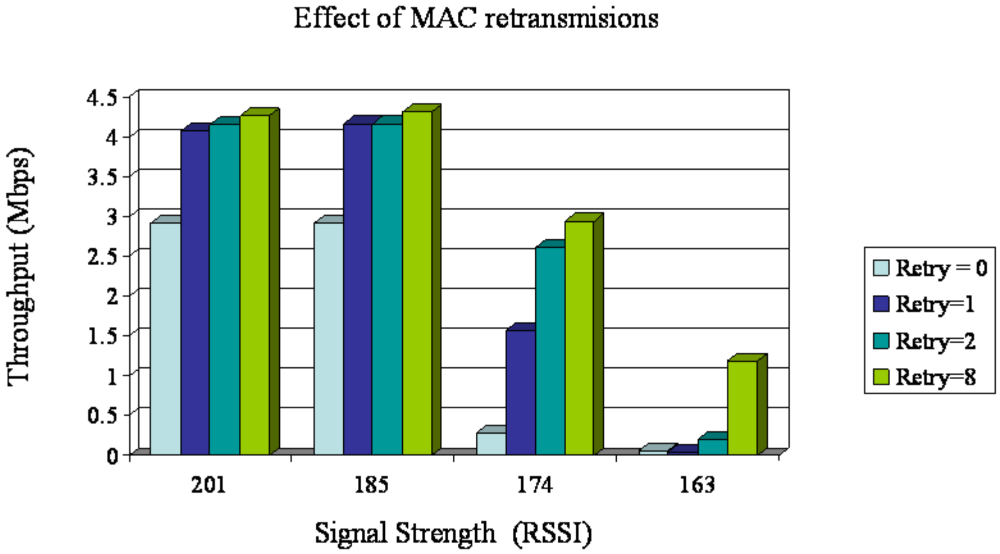


Figure 2.8: Impact of MAC retransmission values on TCP throughput

CHAPTER 3

INTERFERENCE STUDY OF 802.11B NETWORKS

Wireless LANs are commonly deployed today in homes, offices and in public spaces such as airports and shopping malls. Hence, many devices operate in the same frequency band and in close proximity to the 802.11b networks such as Bluetooth, other 802.11b and 802.11g networks, microwave ovens, cordless phones etc., to name a few. In the present work we study the performance degradation, in terms of throughput and packet error rate, of 802.11b networks in the presence of interference. Experiments are carried out in an anechoic chamber so as to reduce the effects of multi path, fading and other radio interferences. An 802.11b network is setup in an anechoic chamber, so as to capture and understand the true effect of the interference introduced without the presence of other radio related interference. The results show that there is a significant degradation of performance if two 802.11b networks work in the same or adjacent channels. Interesting phenomenon is observed while analyzing the self interference. Performance in the presence of Bluetooth technologies, both v1.1 and v1.2 (differences between the versions are described later in the chapter) was also investigated under various scenarios.

3.1 Introduction

802.11b WLANs operate in the 2.4 GHz ISM band. Many technologies such as Bluetooth, 802.11g and devices like microwave ovens and cordless phones work in the same band. In many instances, these devices have to work in the presence of each other. In such cases, there is bound to be interference and hence performance degradation in terms of higher packet error rates, higher delays and lower throughput. Due to the large increase in the number of wireless users, more 802.11b access points have to be deployed to cater to the increasing demand. In this case, efficient assignment of channels is difficult and hence 802.11b networks may be operating in overlapping channels that are closely spaced.

Bluetooth devices also operate in the same frequency band as 802.11b networks. Bluetooth is considered to be a low power communication system and is identified as IEEE 802.15, a standard for personal area networks (PANs). IEEE 802.15 WPANs are designed for short range, low data rate communication (typically a few meters) unlike 802.11b networks that are designed to operate at a maximum range of about 300 meters. Bluetooth (BT) devices often work in close proximity to WLAN networks. Performance of 802.11b networks in the presence of above mentioned interference sources is experimentally measured.

3.2 Previous work

Self interference occurs when several 802.11b networks work in close proximity to each other on interfering channels. Self Interference of 802.11b networks was not studied in detail until now. There are a few papers that discuss the interference among 802.11b devices [25], [26]. Since 802.11b access points have longer range (approximately 300 meters) and were provided with 11 channels in the standard, two access points working together on the same channel or on adjacent channels is considered to be a rare possibility. But, because of the reasons mentioned in section 3.1, the co-existence of access points on interfering channels is a common phenomenon. In [25] and [26], adjacent channel interference was studied, but the emphasis was on frequency planning and analysis of channel assignment.

Performance analysis under interference between 802.11b and Bluetooth is not new; many publications in the past have assessed the interference effects in detail using either simulations or experimental test beds considering various scenarios [27] - [33]. Mathematical and analytical models have also been proposed to analyze the effect [34]. But most of the studies were conducted in indoor or outdoor environments where unwanted external interference sources may exist which may influence the measurements. Our experiments were conducted in an anechoic chamber, so as to filter out the effect of unwanted interference sources. The anechoic chamber experiments permitted the introduction of controlled and intentional interference.

3.3 Anechoic chamber

Computer simulations do not really give us true picture of the scenarios considered. Accurate models to address the behavior of various wireless network protocols under realistic radio environments are very difficult and complex. Approximate models, however, do not accurately predict the network performance. So it is imperative to have a fully functional test bed to capture and obtain the true performance of a wireless network [23].

A functional test bed too has its limitations in analyzing the wireless protocols accurately. Repeatability and control over the unwanted parameters are the biggest challenges of the test beds created. Experiments conducted in realistic environments are affected by interference from devices operating at the same frequency. Interference caused by reflections and multi path also have considerable effect on the accuracy of the results. Unpredictability and time varying nature of the wireless channel often render experimental results to be not reproducible [23].

So, we have conducted our experiments in the anechoic chamber, which minimizes the influence of external interference sources. Anechoic chambers enable us to perform experiments in an interference-free and reflection-free environment. The apparent disadvantage of using anechoic chamber is the physical space limitation. Hence power variability in the devices becomes an important parameter to emulate real-life situations [23]. The results of measurements taken in anechoic chamber can be treated as a benchmark for ideal behavior of scenarios considered. Table 3.1 emphasizes the need for considering anechoic chambers. In case I, the transmitter is located in an office room and in case II, the transmitter is located in an anechoic chamber. In both cases, a microwave oven is operated in an adjacent room about 10 ft away from the transmitter. The receiver is about 20 ft from transmitter. Throughput degradation is high in office environments while it is negligible in an anechoic chamber. This shows that the anechoic chamber successfully prevents external interference.

	Office Environment	Anechoic Chamber
	(Case I)	(Case II)
Throughput With Interference (Mbps)	2.63	4.9
Throughput Without Interference (Mbps)	5.06	5.06

Table 3.1: Effect of anechoic chamber in mitigating unwanted interference

3.4 Self Interference with other 802.11b networks

3.4.1 IEEE 802.11b

IEEE 802.11b wireless local area networks are the most popular wireless systems that have experienced rapid evolution and widespread deployment. They can use either a Frequency Hopping Spread Spectrum (FHSS) or a Direct Sequence Spread Spectrum (DSSS) technique, the latter being the most widely used. The 802.11b standard defines a total of 14 frequency channels, of them; channels 1 through 11 are used in the United States. Figure 3.1 shows the frequency channel assignment in 802.11b networks [22]. The 802.11b signal usually occupies about 30 MHz of frequency. Since the frequency difference between two adjacent channels is 5MHz, a signal destined to a channel will also occupy (or overlaps with) adjacent channels. Due to this, channel 1, 6 and 11, are the only non-overlapping channels among the available 11 channels. WLANs are generally deployed and are operated by assigning these channels to physically adjacent access points.

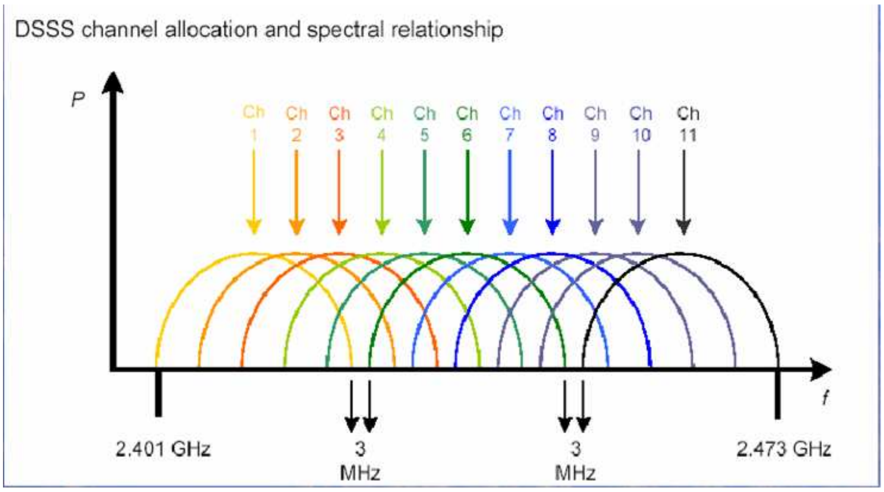


Figure 3.1: 802.11b Channel Assignment

802.11b standard specifies MAC layer, which co-ordinates the communication over the wireless medium. This uses CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). In CSMA/CA, collision happens when two or more stations send their packets in the same slot. The performance of wireless links in the presence of self interference from 802.11b networks is analyzed in the next section.

3.4.2 802.11b self interference

Experimental Test Bed

The test bed architecture consists of three laptops and two access points-

N1, a Pentium M 1.6 GHz Windows XP machine acting as a server

N2, a Pentium M 1.6 GHz RedHat linux 9.0 laptop equipped with 802.11b interface acting as a client

N3, a Pentium Windows 2000 laptop equipped with 802.11b interface acting as an interfering node

AP1, a Dlink -2100 802.11b/g access point

AP2, a Dlink -514 router acting as an interfering router

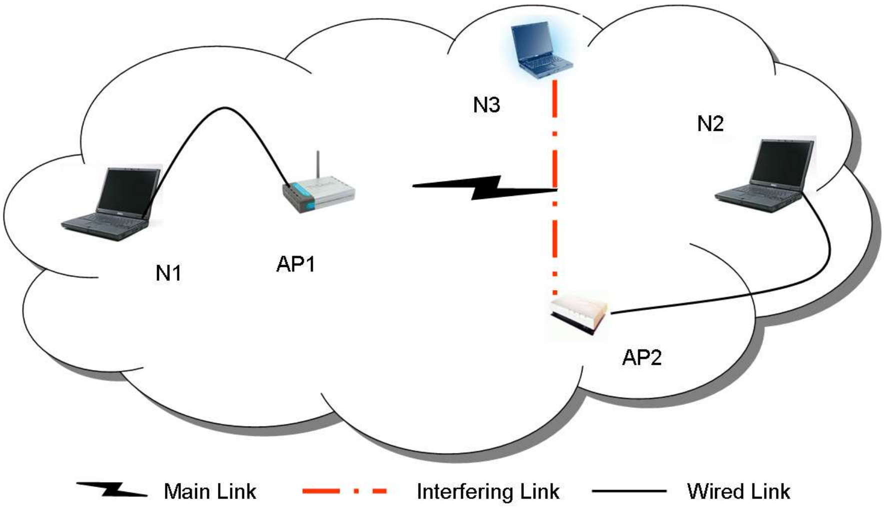


Figure 3.2: Experimental Test bed

The dimensions of the anechoic chamber are about 36 ft x 18 ft. All laptops run Iperf, a bandwidth estimation tool [15]. The power level of the DLink-2100 access point can be varied from 15 dbm to 3 dbm. Signal to noise ratio (SNR) is further decreased by adjusting the detachable antenna of the access point. The orientation of the antenna is also carefully adjusted to obtain the desirable SNR. The power level of AP2 can also be varied from 17dbm to 10dbm. Both access points will be transmitting at their peak power levels unless specified.

Experimental scenario and results

Figure 3.2 shows the experimental test bed to measure the self-interference of WLAN 802.11b networks. The distance between AP1 and N2 is about 20ft. The channels of both the access points are set to 11. The interfering access point, AP2 is set to transmit at its maximum possible rate. Note that N2 is directly connected to AP2 and wirelessly connected to AP1. N2 will be transmitting packets to N1 and N3 from both the available interfaces (WLAN and Ethernet respectively). Main link (or measuring link) is AP1-N2 and interfering link is AP2-N3.

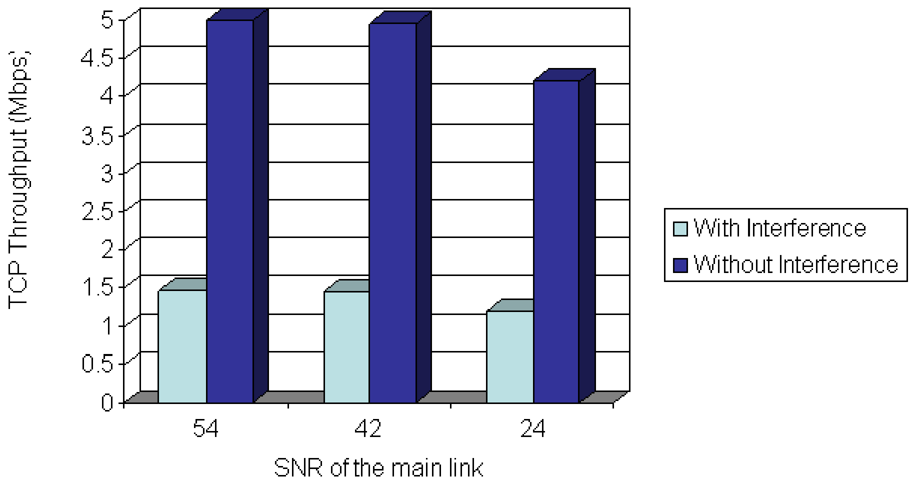


Figure 3.3: Throughput variation with and without interference

The results obtained in this case represent the worst case of the throughput degradation, as both the access points are set to same channel and the interfering access point is set to transmit at its peak data rate (about 5 Mbps). Figure 3.3 shows the experimental results at different SNR values of the main link. We can see that the throughput dropped from around 5 Mbps to around 1.47 Mbps even at good SNR (SNR of AP1 is higher than AP2). The SNR from AP2 is about 45 db. The throughput starts to degrade once the SNR crosses a threshold value and we would see a steep decrease in throughput. Throughput in the graphs shown is the throughput of the main link.

3.4.3 Co-channel and adjacent channel interference

Co-channel interference occurs when two access points working close to each other are on the same channel (e.g., Ch11- Ch11 on both access points) and adjacent channel interference occurs when they are on interfering channels (e.g., Ch11-Ch10, Ch11-Ch9, Ch11- Ch8).

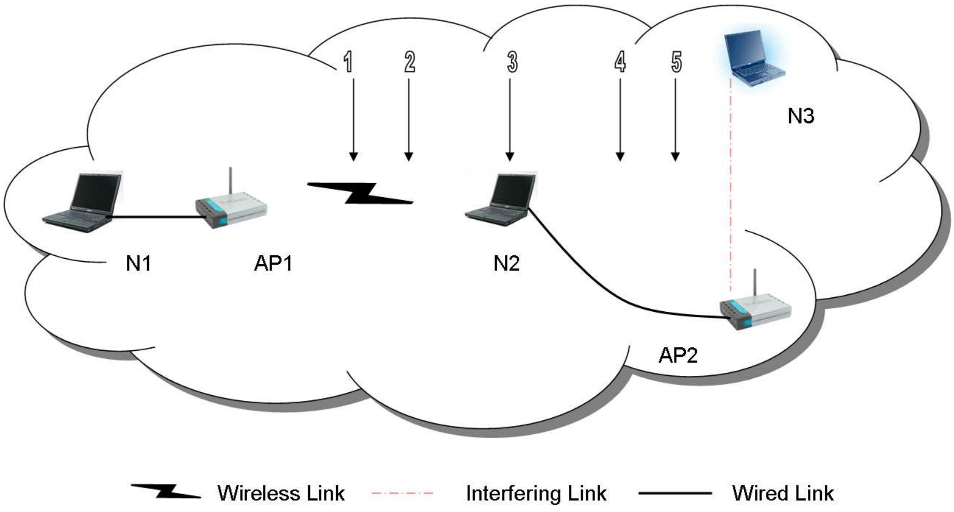


Figure 3.4: Experimental test bed for evaluation of co-channel and adjacent channel interference

Experimental test bed

The experimental test bed to see the effect of co-channel and adjacent channel interference on 802.11b network is shown in figure 3.4. The distance between AP1 and AP2 is 20 ft while the distance between AP2 and N3 is 4 ft. Measurements are taken while moving N2 from positions 1 through 5. Positions 1 through 5 are at a distance of 5 ft, 7 ft, 11 ft, 15 ft and 17 ft. respectively from AP1. AP2 will be on channel 11 throughout the experiment while the channels of AP1 are changed from 11 to 1. The wireless card of N3 is associated with AP2 and that of N2 is associated with AP1. Let SS1 and SS2 be the signal to noise ratios of AP1 and AP2 observed by N2. No RTS/CTS was used throughout the experiment. SNR of the interfering link is about 60 db.

Results

Figure 3.5 shows the throughput variation of the main link at different channels of AP1, the other access point being at Channel 11. The difference in the signal strengths measured at each position is also listed in the figure. From the results, Channels 6 through

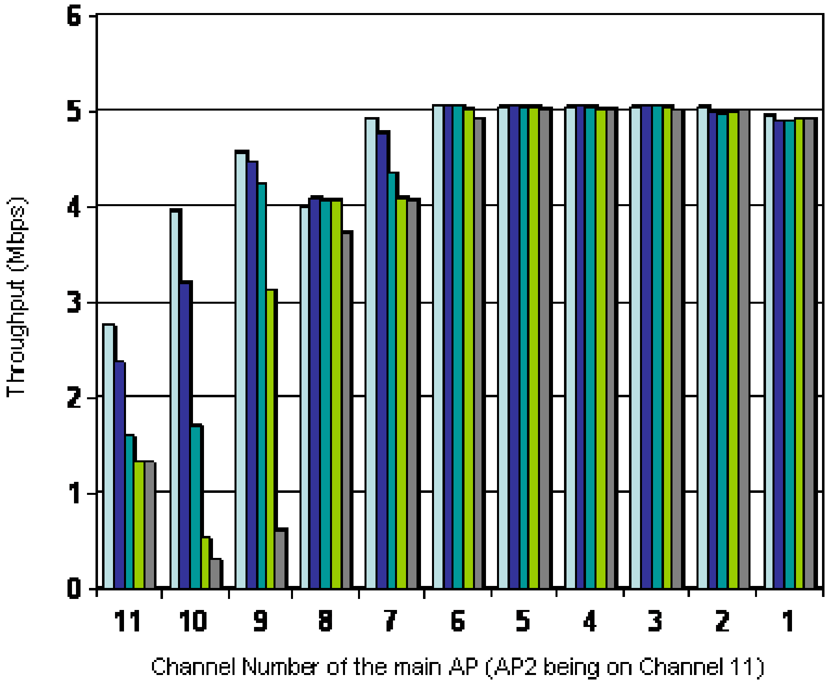
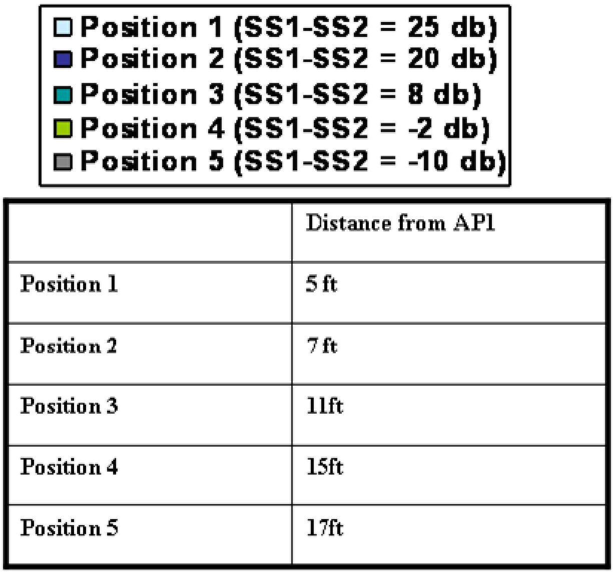


Figure 3.5: Behavior of co-channel and adjacent channel interference at different distances from main AP

1 were unaffected by interference while a decrease in throughput was observed on channels 11 through 7. Measured data shows that at positions 1, 2 and 3, throughput increases as the channel distance increases which is quite expected except on channel 8. Individual channel throughputs decrease as N2 moves closer to AP2. This is due to the fact that as the signal level of AP2 starts dominating the wireless link, the number of packets lost due to collisions increases resulting in the decrease in throughput. Figure 3.6 gives the location along with the signal to noise ratios at different positions.

Anomaly observed

Careful observation of the results in figure 3.5 leads to a very interesting phenomenon when N2 is close to AP2. At position 4, throughput on channel 10 is observed to be less



□ Position 1 (SS1-SS2 = 25 db)
■ Position 2 (SS1-SS2 = 20 db)
■ Position 3 (SS1-SS2 = 8 db)
■ Position 4 (SS1-SS2 = -2 db)
■ Position 5 (SS1-SS2 = -10 db)

	Distance from AP1
Position 1	5 ft
Position 2	7 ft
Position 3	11ft
Position 4	15ft
Position 5	17ft

Figure 3.6: Signal Strength difference of access points and distance of N2 from AP1 at different locations

than channel that on 11. A similar observation was seen on channel 9 at position 5 where the throughput on channel 9 is far below than that on channel 11. We observed a decent throughput of 1.33 Mbps at position 5 while the same on channels 10 and 9 are 0.310 Mbps and 0.61 Mbps, respectively. In short, lower throughput was observed on adjacent channels than on co-channel when node (N2) is close to the interfering access point. Percentage of throughput degradation was also more on adjacent channels than on co-channel. This kind of behavior is also true when AP1 is transmitting instead of N2.

Similar result was observed on overlapping channels of AP1, when AP2 was set to channel 6, where in the main link on channels 5 and 7 at position 3 record lower throughputs than on channel 6. Results are shown in figure 3.7.

The throughput on overlapping channels, under interference, not only depends on the signal strength (or distance) of the interfering access point but also on the signal level of the link between the interfering access point (AP2) and the receiver (N3). As the SNR of

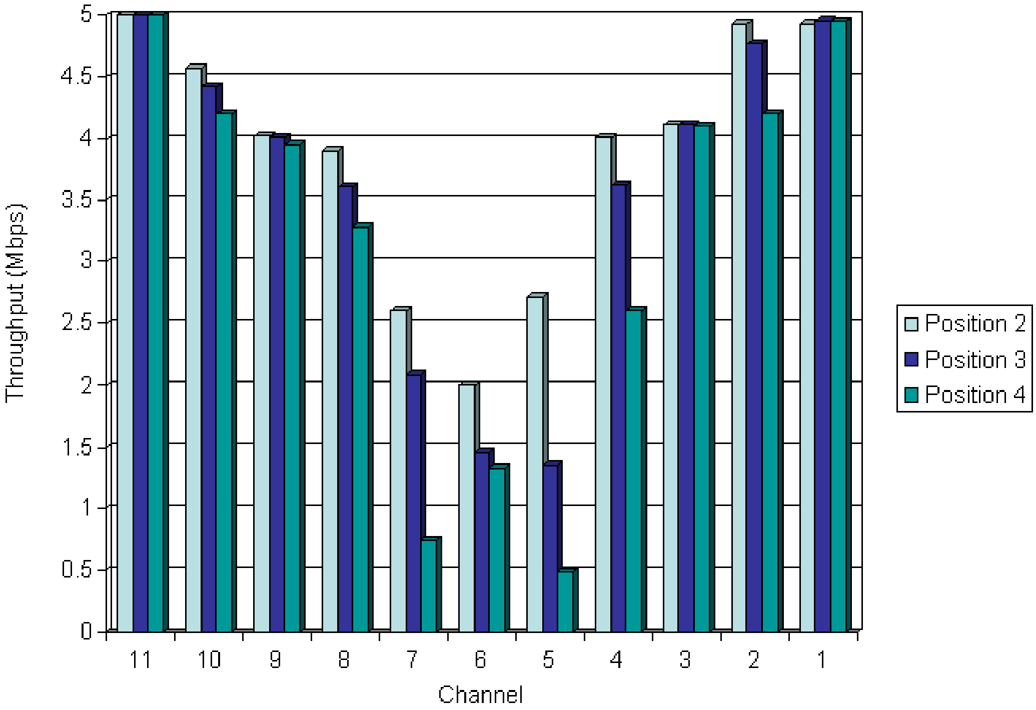


Figure 3.7: Co-channel and adjacent channel interference (when AP2 is on Channel 6)

the link between AP2 and N3 is decreased, an increase in throughput is observed on the overlapping channels of main link (AP1 and N2).

A decrease in SNR on interfering link is achieved by either changing the distance between AP2 and N3 or by decreasing the power level on AP2. In the present scenario, since physical distance is a limitation due to the size of anechoic chamber, the transmitting power of AP2 is set to 12.5 percent of the maximum available power. The distance between AP2 and N3 was set at 8 ft. Figure 3.8 gives the comparison of the throughput change. Let SNR1 and SNR2 be the signal strengths observed by N3 before and after the change in transmission power. The measurements are taken at position 3.

We can see from figure 3.8 that after the transmission power of interfering access point AP2 is reduced, there is an increase in the throughput on all channels. A significant increase

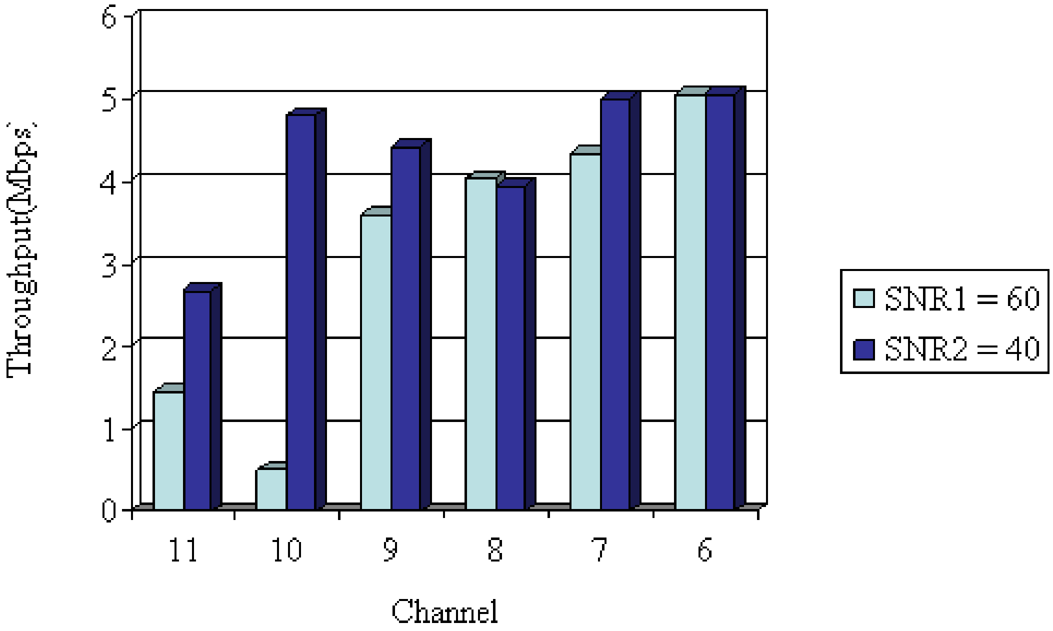


Figure 3.8: Throughput variation with the change in the distance (or SNR) between AP2 and N3

in throughput on channel 10 before and after the adjustment of power level (or SNR) re-emphasizes the point that the link with better SNR captures the channel when the links are on different channels. After the adjustment, the main link on Channel 10 has a better SNR than the interfering link and hence there is a significant increase in the measured throughput. The interfering link suffers in this case. When both links are close to each other, one link capturing the channel is also observed in [25], but the paper does not describe the adjacent channel link behavior.

Discussion

Ideally, we would like to have both the interfering access points on orthogonal channels which is not always possible. The other alternative is to assign the access points on overlapping channels. But from figures 3.5 and 3.7 it can be concluded that it is better to have both the APs on the same channel rather on adjacent channels at lower SNR values. This is because when N1 nears AP2, the throughput degradation is more on adjacent channels. The threshold level of performance is drawn depending on the application in use. Depending on the acceptable baseline for performance, the appropriate channel is chosen. The percentage of throughput drop was also observed to be higher on adjacent channels when compared to that on co-channel.

3.4.4 Impact of interfering access point (AP2) data rate

Test bed and results

The location of AP2 being so close to AP1 (about 20 ft away) is not a realistic situation. AP2 would be a good 50-100 ft away in real-life situations. Since physical space is a limitation in our case, the data rate at which AP2 is transmitting is varied to emulate larger distances (or lower signal strengths). This is done considering the fact that at different signal strengths, the data rate would be different and the access point wont be transmitting at high data rate always. So, instead of varying the physical location of AP2, we changed its data rate to emulate different distances between AP2 and N3. Figure 3.9 shows the throughput variation of the main link at different transmitting data rates of interfering AP2. The measurements are taken at position 1.

From figure 3.9 we can see that the throughput level would become unacceptable when the data rate of the interfering access point is more than 1Mbps.

3.5 Bluetooth interference

3.5.1 Bluetooth

Bluetooth devices use frequency hopping where signal is hopped over 79, 1 -MHz channels at 1,600 hops per second. So, at each channel the packet transmission time will be

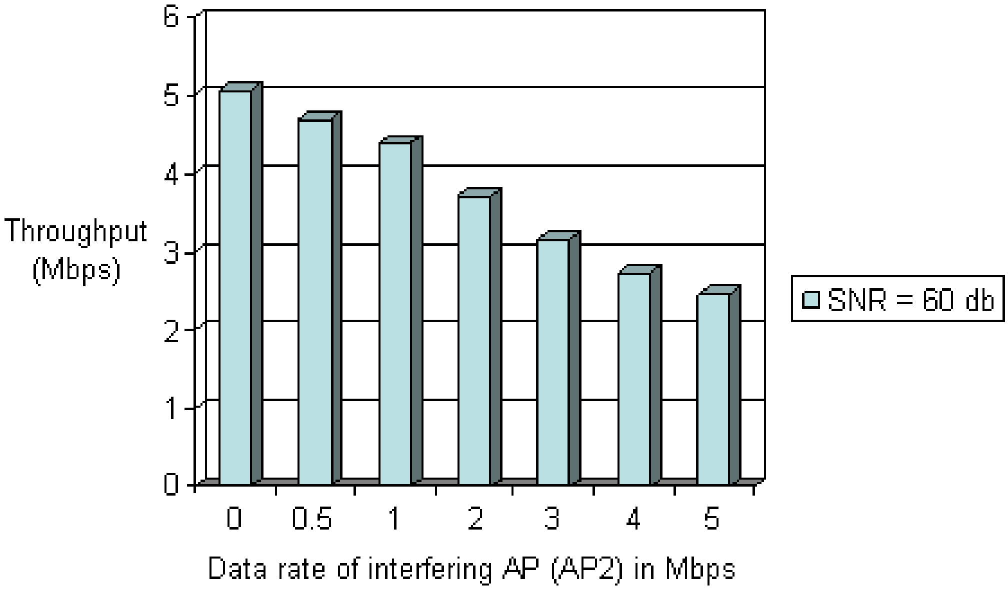


Figure 3.9: Effect of varying data rates of AP2 on the throughput of the main link

625 microseconds. The data rate is around 728 Kbps. Recent advances in Bluetooth technologies provide good range (up to 100m) for Bluetooth devices by increasing the power. Bluetooth uses a master-slave concept for communication. A group of Bluetooth devices communicating in master-slave fashion is called a piconet. The master chooses the frequency hopping sequence of the piconet. They use different links - Synchronous Connection Oriented (SCO) and Asynchronous Connection Less (ACL) for communication. SCO is used for voice while ACL is used for data [27]. Since a channel in a WLAN DSSS system occupies about 22 MHz of frequency, the probability that a Bluetooth device transmitting simultaneously in the same channel is roughly 28 percent (22/79). Because of this interference, there would be performance degradation in both WLAN and Bluetooth systems. The severity of degradation depends upon the power level of the devices operating and the proximity of Bluetooth devices to 802.11b devices [27].

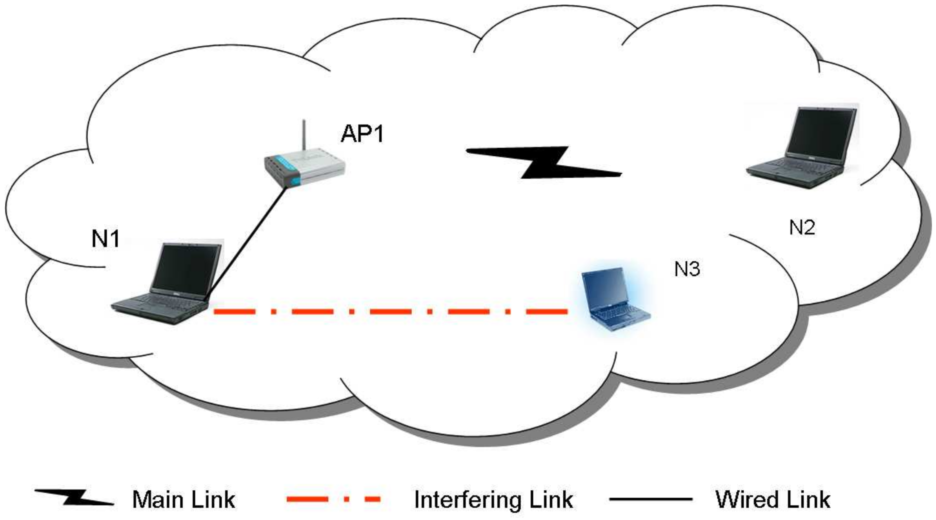


Figure 3.10: Experimental setup for Bluetooth interference on 802.11b

Bluetooth Version 1.1 and 1.2

The differences between Bluetooth v1.1 and v1.2 technology are enhanced data rate, addition of new profiles and services and better communication and co-existence with other devices in the ISM band. One of the features of v1.2 that is most striking is Adaptive frequency hopping (AFH). AFH improves the performance by identifying the busy channels and excluding them. This is done by collecting the statistics on metrics such as packet error-rate, bit-error rate or RSSI [35], [43].

3.5.2 Interference with v1.2 devices

Experimental test bed and Results

Our test bed consists of Anycom Bluetooth USB-240 adapters which are compliant with Bluetooth v1.2 technology with a range of 330 ft. They are placed on devices N3 and N1 and are made to communicate in an adhoc fashion as shown in figure 3.10. The rest of the set-up is same as in figure 3.3.

Due to AFH, we hardly see a difference in the throughput with and without interference. AFH technique usually takes some time to adapt and performance degradation was seen only for the first few seconds (10-20 seconds) after the transmission starts. So, the Bluetooth v1.2 effectively prevents throughput degradation.

3.5.3 Interference with v1.1 devices

Experimental test bed and results

Test bed for one test scenario is same as that in figure 3.10. N1 and N3 are equipped with Dlink DBT-120 Bluetooth v1.1 USB adapters. The power level of Bluetooth USB devices are 0 dbm and the range is about 33 ft peer to peer. Here, N3 is the transmitter and N1 is the receiver. Let d be the distance between N1 and N3. N3 is moved from N1 towards N2. Figure 3.11 shows the variation in throughput as a function of distance d. As d increases, the throughput decreases, because of increase in the distance between N3 and N1 and also because of N3 moving towards a stronger transmitter N2. Significant impact was felt only when Bluetooth devices are close to each other (approx. 5 ft). SNR mentioned in the figure is the SNR of the wireless link. Please note that in the figure, No Int. is the throughput without BT interference.

3.5.4 Bluetooth interference with 802.11b and BT embedded in the same device

Test Bed

This experiment was conducted with both 802.11b network interface card and Bluetooth adapter collocated in the same device. Figure 3.12 shows the experimental test bed of such a setup. The distance between N2 and N3 is 4 ft throughout the experiment. The

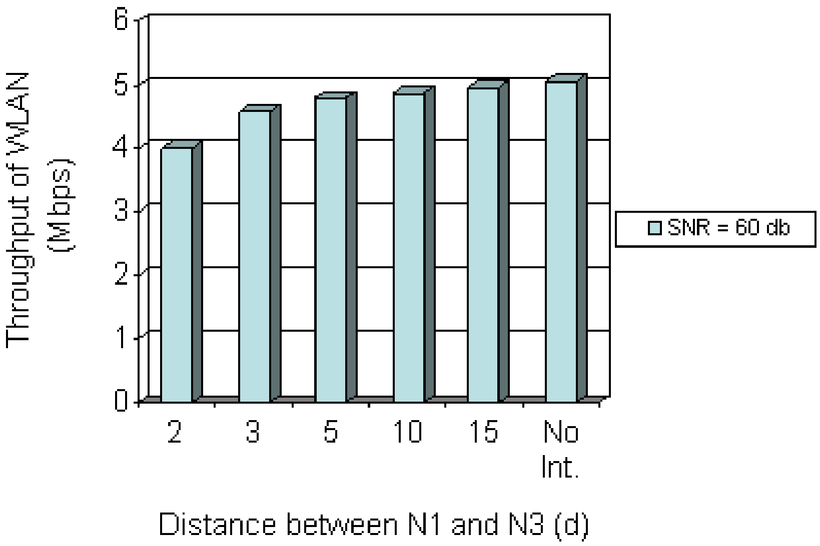


Figure 3.11: Throughput of WLAN vs distance between Bluetooth nodes

output power level of the wireless card is 15 db. Four scenarios are considered in this test bed -

Case 1: N2 transmitting on both the 802.11b and Bluetooth link

Case 2: N2 transmitting on 802.11b link and receiving on Bluetooth link

Case 3: N2 receiving on both the links

Case 4: N2 receiving on 802.11b link and transmitting on Bluetooth link

This work is an extension of the one in [27] where emphasis was to study the effect of WLAN interference on Bluetooth. Table 3.2 summarizes the measurement details.

Results and Discussion

Measurements for all test cases are taken at three different signal strengths. In case 1, at high SNR, the drop in throughput is not high as WLAN is transmitting. Since the output power level of the wireless card is much higher than that of Bluetooth, WLAN dominates the data transfer in cases 1 and 2. At lower SNR, since the Bluetooth is transmitting in case

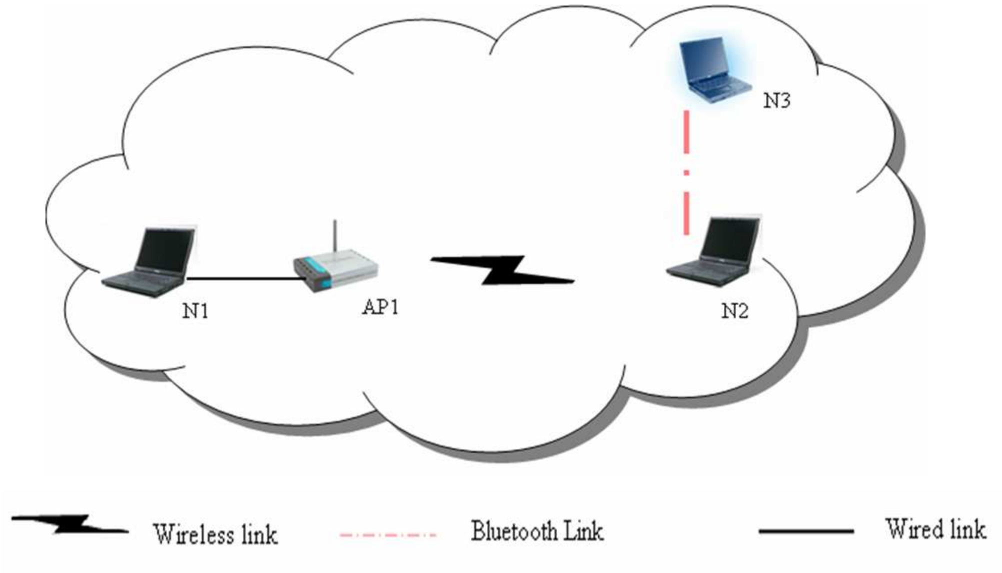


Figure 3.12: Test bed when BT and 802.11b are embedded in the same device

1, it has lower throughput than case 2. In case 3, a decrease in the throughput is observed compared to earlier cases as the WLAN card is in the receiving mode. The impact of the presence of Bluetooth interference on WLAN is very strongly felt in cases 3 and 4 especially at lower signal strengths.

	SNR=60 db	SNR=48db	SNR=21db
Case 1	4.71	4.7	3.2
Case 2	4.7	4.7	4.65
Case 3	4.31	3.77	0.565
Case 4	4.13	3.4	0.677

Table 3.2: Bluetooth Interference on WLAN for various test cases

3.6 Bluetooth interference - Comparison of mathematical and experimental results

Several papers [46], [47], [30] [48] and [60] discuss the mathematical analysis of the Bluetooth interference on 802.11b networks. In this section, we compare the mathematical

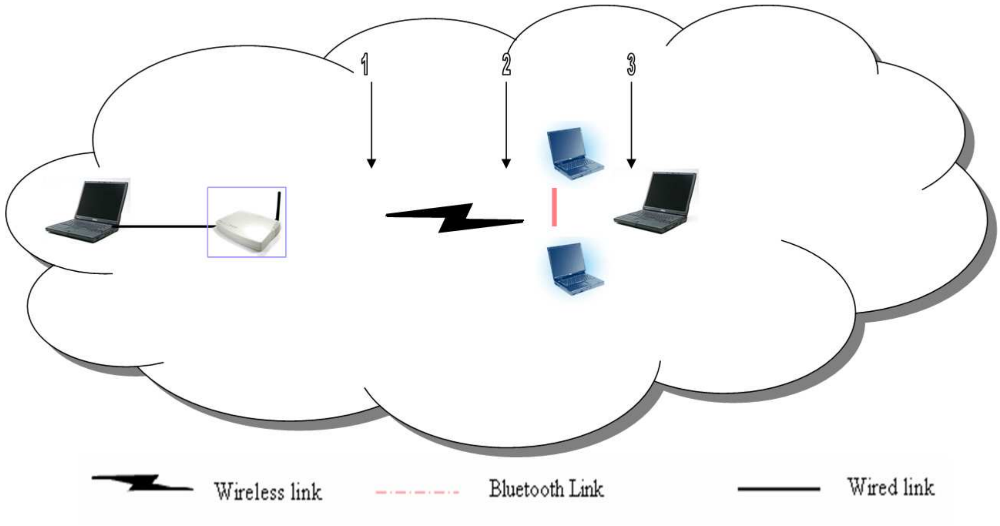


Figure 3.13: Test Bed to compare throughput values with and without interference

results obtained in [47] to that of our test bed results and present the same in an intuitive fashion.

3.6.1 Test bed and Results

Test bed for the present scenario is shown in figure 3.13. Laptops with Bluetooth devices are about 2 ft away from the main receiver, N2, and about 3 ft away from each other. The positions 1, 2 and 3 are at distances of about 4m, 10m and 14m away from AP1. FTP (file transfer protocol) file transfer takes place between N3 and N4 (Bluetooth nodes) and hence the BT load factor is 100 percent.

Case 1 : N2 at position 1

Figure 3.14 shows the throughput change with and without the Bluetooth interference at 4m away from the 802.11b transmitter. We can see that there is no throughput degradation. This is due to the fact that signal to interference ratio (SIR) is greater than 10 db.

Case 2 : N2 at position 2 and 3

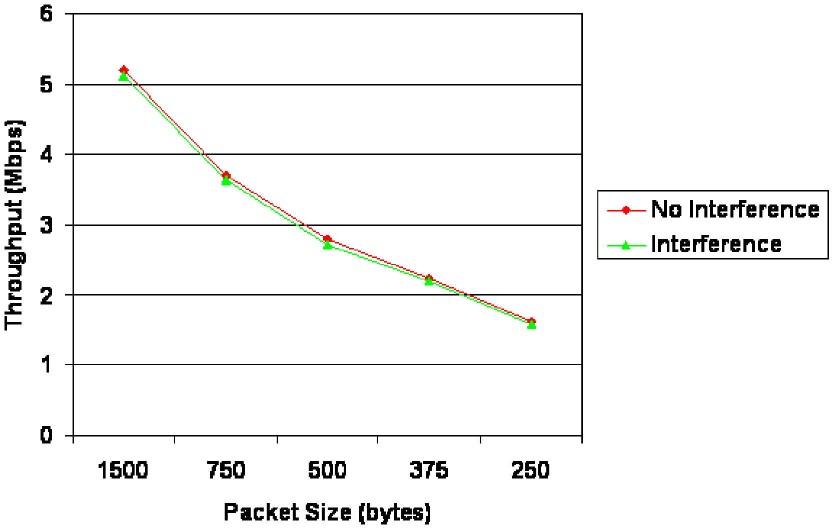


Figure 3.14: Theoretical and practical throughput comparison at 4m away from the transmitter

From figure 3.15, we can observe the decrease in the throughput because of the effect of interference at all packet sizes at positions 2 and 3, respectively. Understandably, the throughput degradation in both the cases is not the same even if the SIR is less than 10 db. This highlights the fact that even though involved in collision, not all Bluetooth packets involved in collision are lost. But most of the papers on mathematical analysis, do not take this aspect (variation of throughput with SIR) into account and assume that all packets involved in collision are lost. Hence the predicted throughput will be the same for both the distances. One interesting observation in figure 3.15 is that the throughput for 750 byte packet size is greater than 1500 byte packet size. Similar observation was also made in [47]. This is because smaller 802.11b packets take less time to transmit and hence have low probability to collide with Bluetooth packets. But, if the packet size decreases further, the over head increases (even though the probability of collision decreases) and hence we see a decrease in throughput.

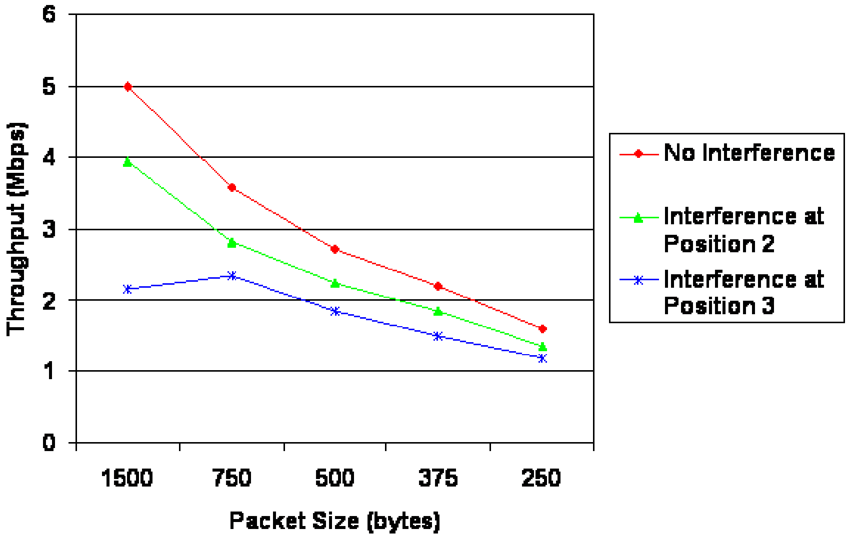


Figure 3.15: Throughput comparison with and without interference at 10m and 14m away from the transmitter

It would be more meaningful to compare the change in throughput because of interference than the absolute throughput. Figure 3.16 shows the comparison of percentage decrease in throughput due to interference for the test bed results and the results obtained in [47].

The reason for comparing the theoretical results to the practical values is to highlight the fact that most of the models neglect the signal to interference ratio (or the ratio of distance between main transmitter and receiver to the interfering transmitter and the main receiver) factor in determining the packet error rate and throughput and assume that the packet under collision is lost. Even in the model which consider this factor the throughput values predicted by the model are not compared to the practically observed ones to determine the error.

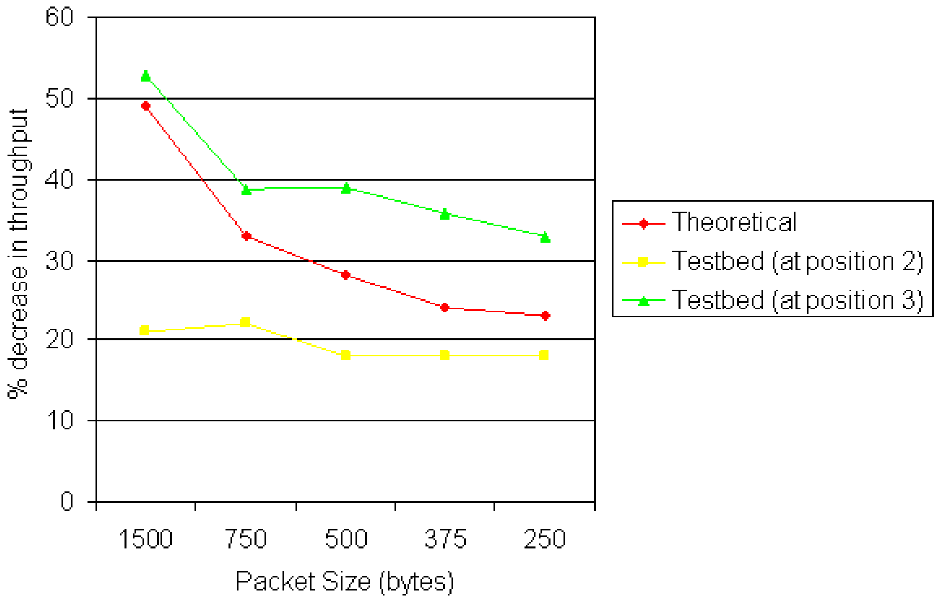


Figure 3.16: Percentage decrease in throughput comparison

3.7 Summary

In this chapter we have studied the interference effects of WLAN and Bluetooth on 802.11b networks. Though the emphasis was on performance measurement under interference, the results are very useful in interpreting how they can be used for proactive network management. In the presence of self interference, where 802.11b networks have to operate in proximity, the performance when the devices are on adjacent channel was worse than that when they are on co-channel at lower SNR.

Since the power level of Bluetooth devices are 0 dbm we can only see interference if the Bluetooth devices are close to each other. But the performance degradation is significant when the 802.11b device is in receiving mode instead of in transmitting mode, if they are embedded in the same device. Simultaneous usage of both technologies should be avoided for better performance. Safe distance must be maintained for efficient resource usage.

CHAPTER 4

THROUGHPUT PREDICTION MODEL IN THE PRESENCE OF SELF INTERFERENCE FOR TYPICAL OFFICE ENVIRONMENTS

This chapter describes a mathematical model for predicting the throughput of the 802.11b wireless LAN in the presence of self interference. The throughput prediction model is one of the key contributions of this thesis.

4.1 Introduction

Prediction models aid in estimating the performance, throughput in our case, or any other parameter of interest. Knowing the performance before hand via modeling, can be very useful for several reasons:

1) Reduces a lot of effort in actually setting up a test bed and measuring and

2) Helps in proper network planning and performance management

Modeling the behavior of throughput for different scenarios with an appropriate set of mathematical equations forms the basis of our prediction model. The present model can be viewed as a combination of empirical and analytical parts since it makes use of experimental measurements in the process of building a model.

4.2 Prior Work

Mathematical and analytical models have been proposed for the performance of 802.11b in the presence of Bluetooth interference. Many publications [53] - [60] have done an extensive analyses of the performance under such conditions. Few papers have actually compared the results (throughput or PER) obtained by the models to the measured ones. But very few papers have concentrated on the performance variation under self interference. We will discuss here a few empirical/analytical throughput prediction models that are already developed.

In [50], the performance of public wireless LANs in the presence of multiple users is experimentally evaluated through extensive measurements. A throughput prediction model is built based on the measurements. Single user and multi-user environments are considered. An AP is placed inside the building and measurements are taken outside at different signal strength locations - 11 for single user measurements and 3 for multi-user measurements at each of the 3 restaurant sites. The piece-wise linear model and exponential model are validated for throughput. The results show that the predicted throughput for a new environment is within the confidence intervals of the measured one. The authors also developed an empirical model which estimates the throughput with 'N' number of stations in a WLAN.

In [49], a measurement based approach is used to predict the throughput of rate adaptive 802.11a WLANs. Throughput and packet error rate (PER) variation with signal strengths and distance, the dependence of average RSSI with physical data rate rate is measured for different environments (Indoor line of sight (LOS), outdoor line of sight and indoor non line of sight (NLOS)). The physical layer simulation results and MAC layer analyses along with the measurements are used to predict the throughput. Reasonable assumptions are made depending upon the observations from measurements - 1) wireless card is adapting data rates so as to keep the PER constant and 2) The average RSSI is strongly related to the average physical data rate value. Results show that the predicted throughput closely matches the measured values. The measurements exhibited strong correlation with the environment being used.

While [50] is entirely empirical, [49] is a combination of simulation and analytical modeling. But the common key aspect of both research approaches is the conversion of signal to noise ratio into either PER or throughput. Piece-wise or exponential model is used in [50] where as simulations are used in [49]. The discussion here is to emphasize the fact that it is necessary to either use an empirical mathematical model or simulations to map the SNR to PER or throughput.

In his highly acclaimed work [8], Bianchi proposed an analytical model which predicts the throughput of 802.11b DCF (distributed coordination function) networks. The performance of networks largely depends on parameters like number of stations and contention window size.

From [8], the probability that a transmission occurring in the channel is successful is the probability that exactly one station transmits given that at least one station transmits. This is given by,

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{4.1}$$

where τ is the probability that a station transmits in that slot time. Therefore, the probability that the transmitted packet is not successful i.e., it encountered a collision is,

$$P_c = 1 - P_s \tag{4.2}$$

Using Markov chain model, the probability with which a station transmits in a slot time, τ,is calculated. To achieve maximum throughput, the optimum τ value is given by the following equation.

$$\tau \approx \frac{1}{n\sqrt{T_c^*/2}} \tag{4.3}$$

Where $T_c^* = T_c/\text{slottime}$. T_c is the period of time sensed busy by other non colliding stations and n is the number of stations. The above shows that τ is inversely proportional to n. But, Bianchi's model does not relate throughput and PER variation with the change in SIR.

The models discussed in [50], [49]and [8] do not predict the throughput when the interfering stations are on other channels. Such a model is important because, in enterprise environments, the stations which act as interference sources will be on different channels. The complexity of predicting the throughput, when the stations are on different channels and at different distances from each other, is so high that some reasonable assumptions are to be made for multi-user, multi-channel environments.

4.3 Throughput prediction model - Inputs

The inputs to the throughput prediction model are

1) the distance between the transmitter and receiver of the measuring/main link i.e., measuring link distance (say dm)

2) distance between interfering transmitter (either an AP or a station) and main receiver (say d1)

3) distance between interfering transmitter and receiver (say d2)

4) channel distance between the main WLAN and interfering WLAN (channel distance is defined as the difference between the operating channels of the two WLANs)

We assume that the interfering stations are at the same distance from the main receiver. We also assume that every station had a packet to send at all times.

The model is based on DCF (distributed coordination function) access method of the 802.11b MAC. We first present the model which estimates the throughput when the interferer is on the same channel and extend the model further to 'n' stations all being on different channels. Main/measuring WLAN here mean the wireless transmitter- receiver (or client-server) pair for which the throughput is being measured.

Since indoor environment is considered for the model, SNR is calculated from the distance 'dm' according to the path loss equations given in [54]

$PL = 32.45 \ + \ 20\log(f.dm) \ldots\ldots \ if \ dm \ < \ 8m$

$= 58.3 \ + \ 33\log(dm/8) \ldots\ldots \ if \ dm \ \geq \ 8m$

where f is the frequency in GHz (2.4 GHz in our case) and dm is the distance between the main transmitter and receiver pair.

A brief derivation of the above path loss model is given below.

The basic log-distance path loss model for distance dm is given by the equation,

$PL(dm) = PL(d_o) \ + \ 10nlog(dm/d_o)$

where, d_o is the reference distance and n is the path loss exponent

The theoretical free space path loss, $PL(d_o)$ is given by

$PL(d_o) = 20log(4\Pi d_o/\lambda)$

substituting $\lambda = c/f$ in the above equation we get

$PL(dm) = 20log(4\Pi d_o/\lambda) + 20log(f) + 20log(dm/d_o)$

Line of sight is assumed for the first 8 meters and non-line of sight for distances greater than 8 meters. Hence, the path loss exponent in the above equation is chosen accordingly [54],

$n = 2 \ \ and \ \ d_o = 1m \ \ for \ dm < 8m$

$n = 3.3 \ \ and \ \ d_o = 8m \ \ for \ dm \geq 8m$

Substituting the above parameters and by rearranging we obtain the path loss equation defined.

The received power, P_R, in dbmW is calculated as [55] -

$P_R = P_T - PL$ where P_T is the transmitted power

SNR is obtained according to the equation

$$SNR = P_R - SR \tag{4.4}$$

where, SR is the receiver sensitivity in dbmW. Receiver sensitivity (a threshold value) indicates how low a signal can get before it cannot be detected. Receiver sensitivity is a very important feature of the receiver and it varies with the data rate employed. Typical receiver sensitivity values for a Linksys WPC11 wireless card is given in table below [56]. This model of the wireless card is used as the main transmitter for our measurements.

Data rate (Mbps)	Sensitivity dBm
11	-82
5.5	-85
2	-89
1	-91

Table 4.1: Receiver sensitivity values of Linksys WPC 11 wireless card

In order to determine the throughput, a model which maps the SNR to throughput is required. An empirical exponential throughput prediction model, proposed in [52], is used and is expressed as,

$$T = T_{max}(1 - e^{-A_e*(SNR - SNR_o)}) \tag{4.5}$$

Where, T_{max} is the maximum throughput that can be achieved using a wireless card. SNR_o is the signal where the throughput becomes zero. A_e is the rate at which the throughput decreases with respect to the change in SNR. T_{max}, SNR_o and A_e are constants.

The constants are calculated empirically for Iperf tool in [50] by taking extensive measurements at various data points and using a MATLAB curve fitting algorithms (for e.g., nlinfit and polyfit). The constants are reported as, For Orinoco card,

T_{max} = 5 Mbps, A_e= 0.069 and SNR_o= 6.9

For Cisco card,

T_{max} = 5.3 Mbps, A_e= 0.07 and SNR_o= 5.4

Equation 4.5 is a single-user (and no-interference) throughput prediction model which estimates the throughput from SNR. Please note that we also haven't considered the interference effect till this point. A_e and SNR_o for both cisco and orinoco cards have almost same values and hence we can assume them to be the values mentioned above for most of the wireless cards.

4.4 Effect of interference

Let us first consider the scenario when both the main and interfering stations are on the same channel. We would later extend this when the interfering stations are on overlapping channels. Please refer to figure 3.1 for channel allocation in 802.11b standard.

In the presence of interference, when both the main and interfering stations are on the same channel, (time) sharing of the channel takes place. So if there are two stations competing for the channel, the throughput achieved is approximately half of the single user throughput. This is with an assumption that all transmitting stations are at approximately the same signal strength from the associated receiver(when $dm \approx d1$). Similarly, when there are 'n' number of stations involved, the throughput gets divided among the 'n' stations.

Though 802.11 stations have CSMA/CA mechanism, when two stations sense the channel at the same time, they transmit the packets in the same slot time. This would result in collisions and hence packet loss. Assuming perfect channel sensing by the stations, the probability that the transmitted packet is not successfully received (due to collision), P_c, when 'n' stations are competing for the channel is given by equation 4.2

$$P_c = 1 - \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{4.6}$$

where τ is defined by the equation 4.3

When the interfering stations are close to each other then the packet error rate is same as P_c. P_c can also be interpreted as maximum packet error possible. In other words, when all the packets failed to reach the receiver due to collisions, the PER $\approx P_c$. The PER is calculated using UDP transmission since the Iperf tool reports PER only for UDP transmission. Hence, the reported error rate might be slightly more than the actual PER which is neglected.

4.4.1 Calculation of Practical τ

Earlier, it is assumed that all stations have perfect channel sensing. But, in practice it is proved that perfect channel sensing is not possible. Because of this, τ defined should be modified for practical purposes.

For this, we first measure the maximum PER in the presence of 'n' stations where 'n' is 2 , 3 and 4. Now, we calculate the empirical τ values from the PER using equation 4.6. The theoretical values of τ are obtained using equation 4.3. The theoretical and empirical values of τ and their variation with the number of stations is shown in figure 4.1. The figure in turn reflects the significant difference between the theoretical and practical PER.

From the empirical values, we derive a new equation for τ expressed as

$$\tau_{prac} = (k * n + c) * \tau \tag{4.7}$$

where k and c are constants and n is the number of stations. The constants show the variation τ_{prac}/τ with n. A linear curve fitting algorithm called 'polyfit' is used to calculate

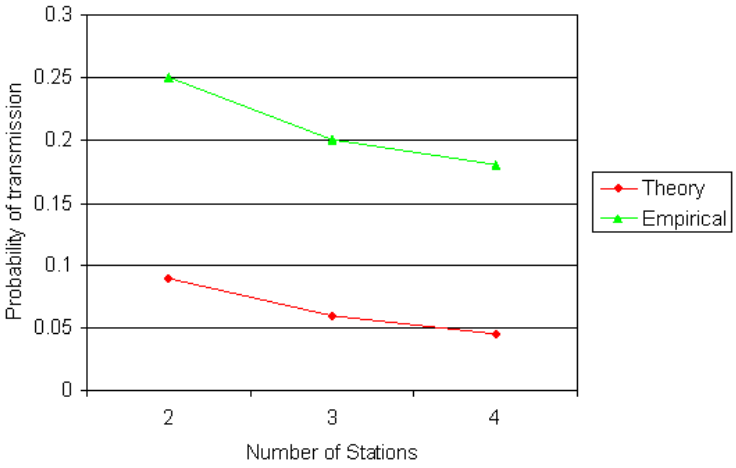


Figure 4.1: Variation of τ with n

the constants in MATLAB [58]. k and c values are calculated to be 0.6111 and 1.5377 respectively. From the above equation for τ_{prac} we can calculate PER values for any 'n'.

4.4.2 Packet Error Rate

It was observed from our experiments, that the PER values are high and almost constant for the first few meters. As d1 increases further, the PER almost varies linearly with d1 according to the figure 4.5(explanation of such variation is explained in section 4.4.4. Therefore,

$$PER \;=\; P_c ...when\ the\ interfering\ transmitter\ is\ close\ to\ main\ Rx$$

$$(when\ d1 < 3m)$$

$$PER = P_c(a * d1 + b + 1)....when\ the\ interfering\ station\ is\ away\ from\ the\ Rx$$

$$(when\ d1 \geq 3m) \quad (4.8)$$

where, d1 is the distance between the the interfering transmitter and main receiver and 'a' and 'b' are constants determining the variation of PER with d1.

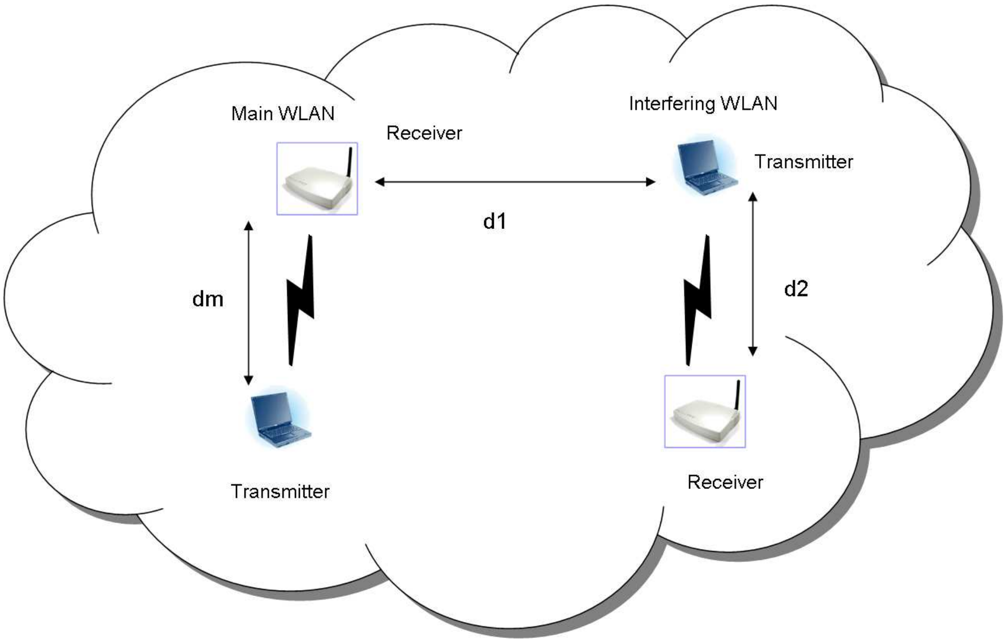


Figure 4.2: Experimental setup for studying the variation of PER and throughput with distances dm, d1 and d2

Throughput varies exponentially with SNR or SIR [50], [57]. It was shown in [48] that the throughput-distance relationship (variation of throughput with d) in a typical office building follows a linear relationship. Hence, from first order approximation we can say that the throughput varies linearly with d1. The relationship between throughput and PER is also linear [49]. Hence, the relation between PER and d1 follows a linear rule. Calculation of 'a' and 'b' values is explained in the next section.

The test bed for the mathematical model is shown in figure 4.2. One of the inputs (dm, d1 and d2) is changed keeping the other two constant and its effect on PER and throughput is studied. The aim is to analyze the variation of the inputs individually on PER and throughput and fit in an appropriate mathematical equation to capture the variation.

4.4.3 Variation of throughput and PER with distance 'dm'

In this section, dm is changed keeping the other distances constant. d1 and d2 $\approx$ 5ft.

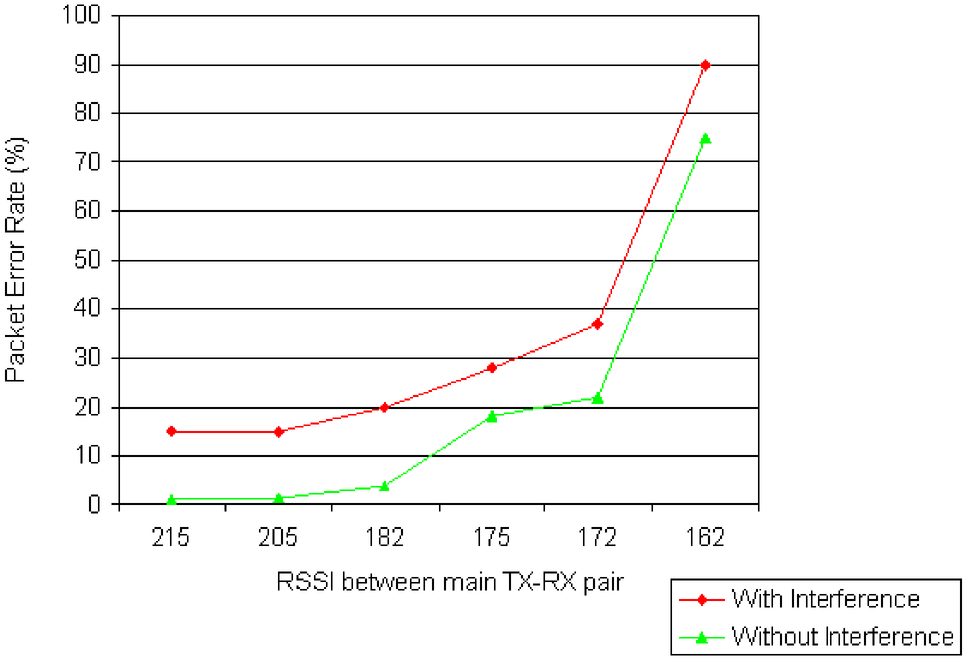


Figure 4.3: PER variation with dm

PER and throughput measurements are taken at each data point and are shown in figures 4.3 and 4.4 respectively. Since physical space is a limitation in our experiments, RSSI values are considered instead of dm. From figure 4.3 we can say that as dm increases (as RSSI decreases), a constant packet error rate difference is observed with and without interference. This shows that the PER, because of the interfering transmitter on the main wireless link at all dm values is constant. So in other words, the throughput of the main wireless link is determined primarily by the distance 'dm'. Hence the throughput would follow equation 4.5. Since two stations are contending for the channel, the channel is shared. Therefore, the throughput equation will be,

$$T_{dm} = [\frac{T}{2} * (1 - PER)] \tag{4.9}$$

where T is defined by equation 4.5 and PER is defined by equation 4.6

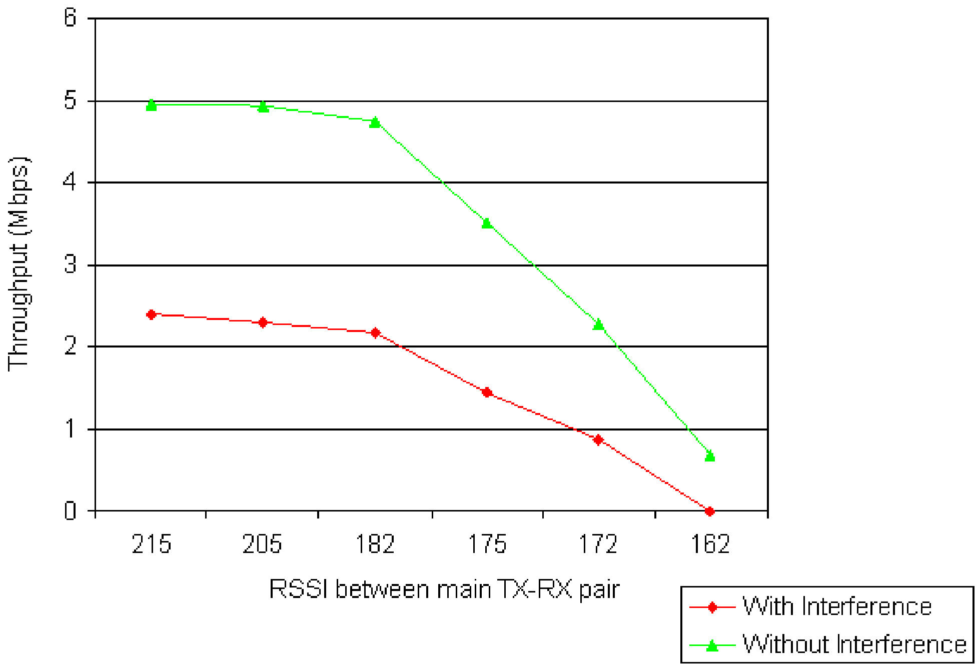


Figure 4.4: Throughput variation with dm

4.4.4 Variation of throughput and PER with distance d1

The test bed to see the effect of d1 on the throughput and PER of the main link is shown in figure 4.2. Note that the measurements are taken considering one antenna orientation for the entire experiment.

At each of the five data points the PER and throughput are measured for '1' interferer. Similar measurements are also taken for '2' and '3' interferers. The results of which are shown in figure 4.5 and 4.6. The measurements are taken multiple times and the value indicated in the graph is the average value. even though the variation is not very linear we assume a linear relationship in order to fit an appropriate equation.

The measured PER values and the distances d1 are run through a MATLAB function called polyfit which fits the data to a linear function and gives the slope 'a' and intercept 'b' of the curve [50]. Parameters 'a' and 'b' signify the change in the PER with d1. The

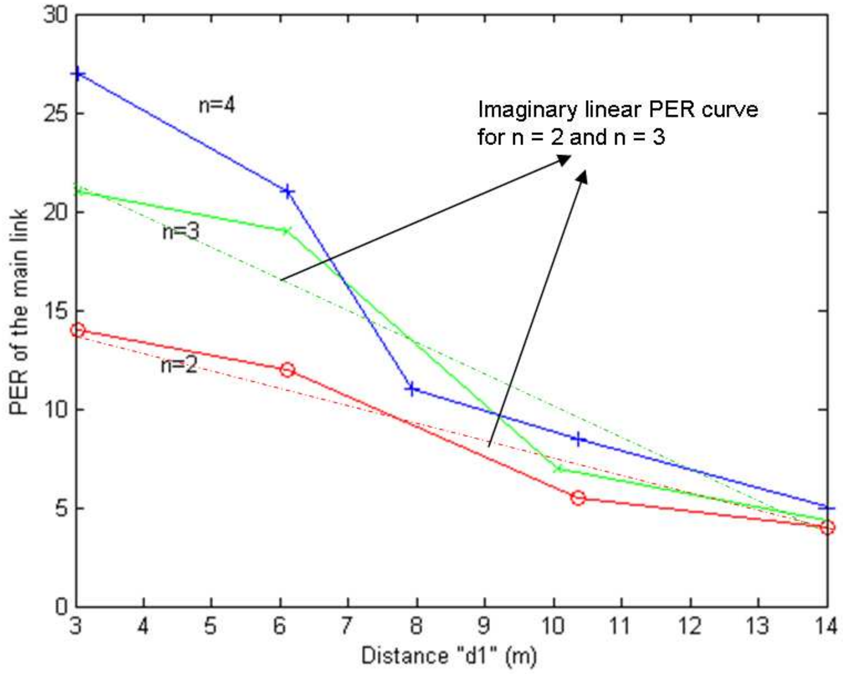


Figure 4.5: PER variation with d1

values of 'a' and 'b' for one interferer are 0.0158 and 0.0585, respectively. Similarly 'a' and 'b' parameters are calculated for n = 3 and n =4 (for 2 and 3 interferers, respectively).

From the measurements, we have observed that the percentage of throughput increase , as d1 increases, is greater than the percentage of PER decrease. To accommodate this we incorporate two other parameters α and β. The parameters α and β are calculated in similar fashion using polyfit function. These parameters are useful to closely match the theoretical values to the experimental values. These parameter values also change with d1.

While 'a' and 'b' shows the change in PER, α and β shows further change in throughput. The values of α and β for one interferer are 0.0145 and 0.0098 respectively.

All the parameters (a, b, α and β) are made as a function of the number of interferers (n-1) and are shown in table 4.2.

The net values of the parameters are obtained by taking the average value of each of the parameter.

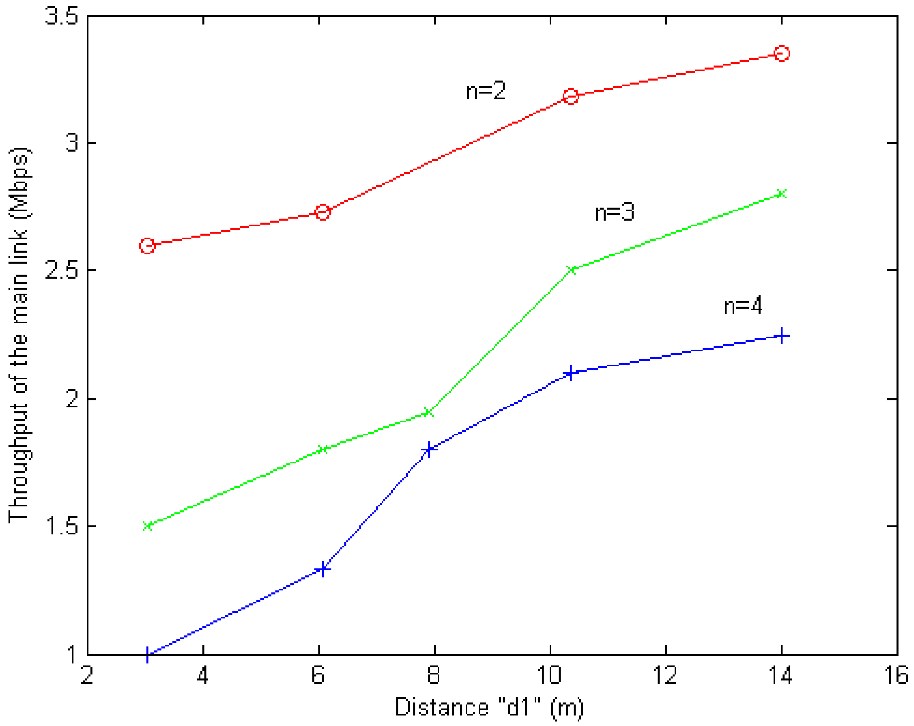


Figure 4.6: Throughput variation with d1

Hence, the throughput in the presence of one interferer (after incorporating the effect of d1 and d2) now would be,

$$T_{dm,d1} = [\frac{T}{2} * [\alpha * d1 + \beta + 1] * (1 - PER)] \tag{4.10}$$

where PER is defined by equation 4.8

4.4.5 Variation of throughput and PER with distance ’d2’

The distance between the interfering transmitter and interfering receiver is changed and its impact on the performance of the main link is analyzed in this section. It is extremely difficult to concretely conclude anything from such an analysis because of the complications involved in the test setup. But it can be inferred that as the interfering wireless link

n	a	b	α	β
2	-0.0634	0.1135	0.0145	0.0098
3	-0.0362	0.0836	0.0199	-0.1144
4	-0.0251	0.0580	0.0168	-0.1217

Table 4.2: Parameter values for different n

throughput decreases, because of the low SNR, the available throughput is being used by the main wireless link. Please note that the vice versa was also true i.e., when the main receiver moves away from main transmitter the lost throughput is used by the interfering link. The throughput of the interfering WLAN, without interference, will also follow equation 4.5.

Hence, the throughput in the presence of one interferer after incorporating the effect of d2 would be,

$$T_{dm,d1,d2} = [\frac{T}{2} * [\alpha * d1 + \beta + 1] * (1 - PER) + \frac{T_{maxi} - Ti}{2}] \tag{4.11}$$

4.4.6 Variation of transmission rate with number of stations

The individual transmission rate of each of the transmitter will decrease as the number of stations increases due to channel sharing. But the combined transmission rate of all the stations will increase with 'n' and is shown in Table 4.3. Similar observation in throughput is noticed in [13]. Hence the variation in the transmission rate because of the change in n has to be accounted.

It was also observed that when compared to other cards this particular card (Linksys WPC 11) with higher transmission rate gives more packet error rate and hence the transmission rate and PER are card - dependent. We have taken measurements, built and verified the model based on the measurements taken on this card. It was observed that some of the wireless cards have better transmission rate than others because of manufacturing variations.

number of stations	Individual Transmission rate of Linksys WPC 11 wireless card(Mbps)
1	6.03
2	3.4
3	2.6
4	2.2
5	1.9

Table 4.3: Individual transmission rate variation with n

Please note that to measure the PER and transmission rate we use UDP packets, with MAC retransmissions equal to zero.

The throughput equation now would be as follows -

$$\begin{aligned} T_{(dm,d1,d2,txrate)} = [\frac{T}{2} * [\alpha * d1 + \beta + 1] * (1 - PER) * \\ (change\ in\ transmission\ rate\ because\ of\ n) + \\ \frac{T_{maxi} - Ti}{2} \end{aligned} \tag{4.12}$$

4.5 Throughput prediction model in the presence of one interferer (two stations)

The factors affecting the throughput of the main link have been analyzed in the previous section. The net throughput in the presence of one interferer is expressed as

$$\begin{aligned} T_{interference(2)} = [\frac{T}{2} * [\alpha * d1 + \beta + 1] * (1 - PER) * \\ (\frac{txrate_2}{txrate_1})] + \frac{T_{maxi} - Ti}{2} \end{aligned} \tag{4.13}$$

T and PER are defined by the equations 4.5 and 4.8 respectively. $txrate_2$ and $txrate_1$ are the transmission rates when there are 'n' stations (2 in this case) and '1' station, respectively. The ratio signifies the change in the transmission rate and is necessary because we are calculating the throughput of the main link with just one station.

α, β, a and b parameters (introduced earlier) are estimated as explained in the previous section using a curve fitting algorithm called polyfit. The values of the parameters change as the number of interferers change.

The last fraction $\frac{T_{maxi}-T_i}{2}$ becomes significant when d2 is large. When d2 is small (as is the case in most of the experiments conducted to verify the model) this factor can be neglected.

Note that the number of interferers will be denoted as n'

where,

$n' = n - 1$

n is the number of stations contending for the channel.

4.6 Throughput prediction model in the presence of 'n' stations

When there are 'n' stations on the same channel, equation 4.13 is modified as shown below. We assume here that all interfering stations are at about the same distance from the main WLAN receiver.

$$T_{interference(n)} = [\frac{T}{n}[(\alpha d1 + \beta)n' + 1] * (1 - PER((ad1 + b)n' + 1)) * (\frac{txrate_n}{txrate_1})] + \frac{\sum_{i:1ton'}(T_{maxi} - T_i)}{n} \quad (4.14)$$

Where

T_i is the throughput of the interfering wireless station (without interference) defined by the equation 4.5. T_{maxi} is the maximum throughout achieved by that station.

The a , b , α and β values for the above equation can be obtained by taking the average of the values mentioned in table 4.2.

The fraction $\frac{\sum(T_{maxi}-T_i)}{n}$, as explained earlier accomodates the change in the throughput of the main wireless link when the interfering receiver is away from the interfering transmitter. But the equation is not entirely correct as the throughout division again depends upon the signal strength difference perceived by each of the wireless station. So, the signal strength weightage should also be included in the fraction. But this is extremely difficult to model. So, for this factor was not extended. The present model developed takes most of the factors that effect the throughput under interference into consideration.

We have experimentally measured the throughput and PER for 1 , 2 and 3 interferers and build the model. We have to check if this model works for 4 interferers. Figure 4.7 shows the comparison of experimental values to the predicted values. The percentage error is defined by the following equation.

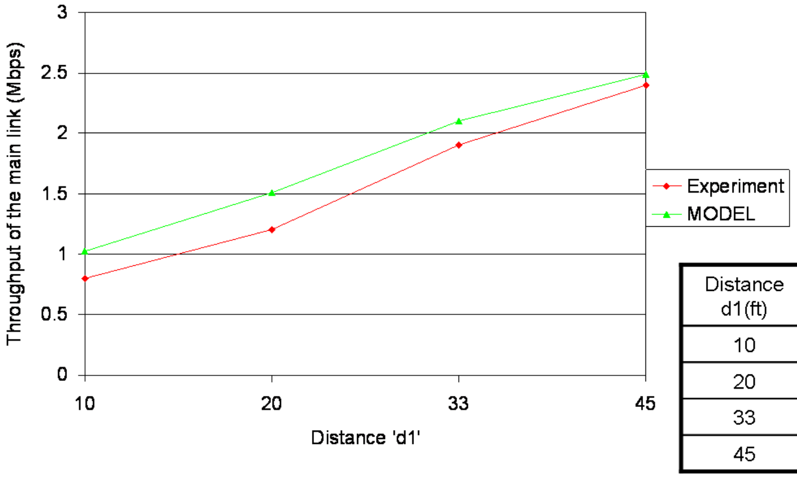
$$Error\ percentage = \frac{(Measured\ throughput - Predicted\ throughput)}{Measured\ throughput} * 100 \tag{4.15}$$

From the figure, we can say that the model predicts the throughput fairly accurately even in the presence of n stations.

4.7 Throughput prediction model for 'n' stations on different channels

Until now we have considered the scenario where in all the stations are on the same channel. But in practice, this assumption may not be realistic. We have different stations operating on different channels.

The hypothesis for the model is that the throughput can be studied by piece wise analyses of the spectrum. We verify our hypothesis from the measured results.



Distance d1(ft)	Error (%)
10	-27.5
20	-25
33	-10.5
45	-4.16

Figure 4.7: Throughput comparison when the number of interferers are 4

Also, to model such scenario the following assumptions are made

1) the frequency spectrum can be partitioned into non-overlapping sections.

2) the PER occurring in one part of the spectrum is independent of the PER occurring on the other part of the spectrum, if the spectrum is seen individually.

For better explanation of model behavior, we take an example where we have one station each on channel 11, 10 and 9. Let us say that we want to find the throughput of the station on channel 11. So the stations on channel 10 and 9 act as interferers. The spectrum division in such a case is shown in figure 4.8

Each channel is 22 MHz wide and the difference between the center frequencies of adjacent channels is 5 MHz [2].

We divide the spectrum into 3 pieces for analysis as shown. The first 5 MHz is used by only one station and hence experiences no interference. The next 5MHz is used by stations on channel 11 and channel 10. So two stations share this part of the channel frequency. The next 12 MHz is used by stations on channel 11, 10 and 9. Hence three stations share this part of the frequency on channel 11. The throughput of the station on channel 11 is therefore defined by the following equation.

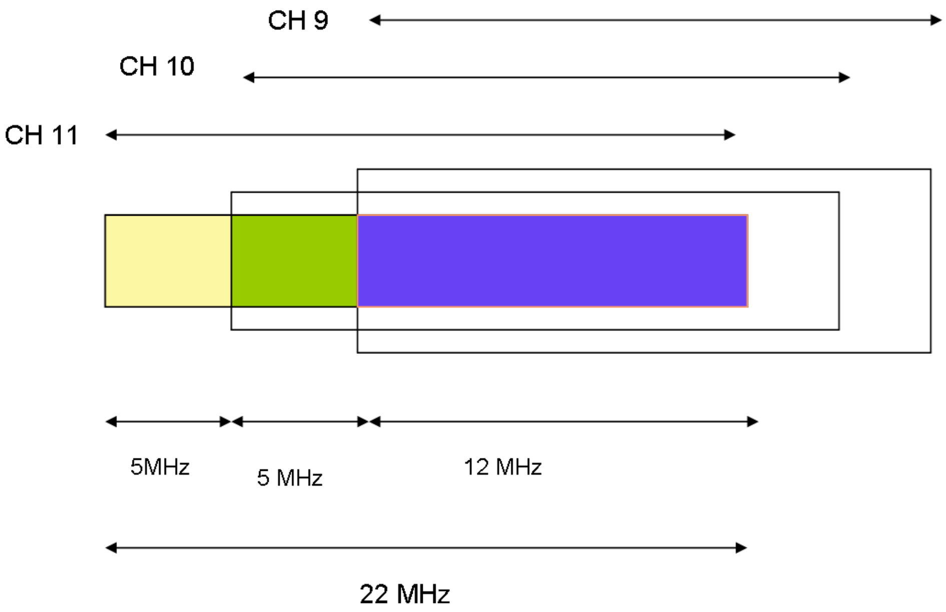


Figure 4.8: Piecewise Spectrum Analysis

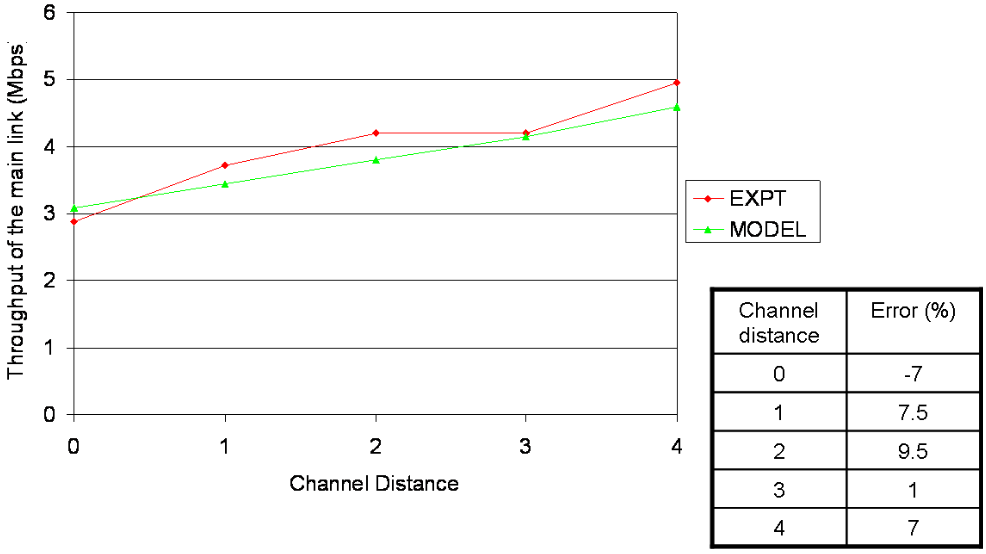
$$T_{totalinterference} = \frac{5}{22} * T + \frac{5}{22} * T_{interference(2)} + \frac{12}{22} * T_{interference(3)} \tag{4.16}$$

where,

T is defined by equation 4.5

$T_{interference(2)}$ and $T_{interference(3)}$ are defined by equation 4.16 when n = 2 and n = 3, respectively.

The first factor$(\frac{5}{22} * T)$ takes care of 5/22 th part of the channel frequency which is occupied by just one station with no interference. The second factor $(\frac{5}{22} * T_{interference(2)})$ takes care of 2 stations sharing the next 5/22 part of the channel. The third factor $(\frac{12}{22} * T_{interference(3)})$ takes care of the remaining channel spectrum occupied by all the three stations.



Channel distance	Error (%)
0	-7
1	7.5
2	9.5
3	1
4	7

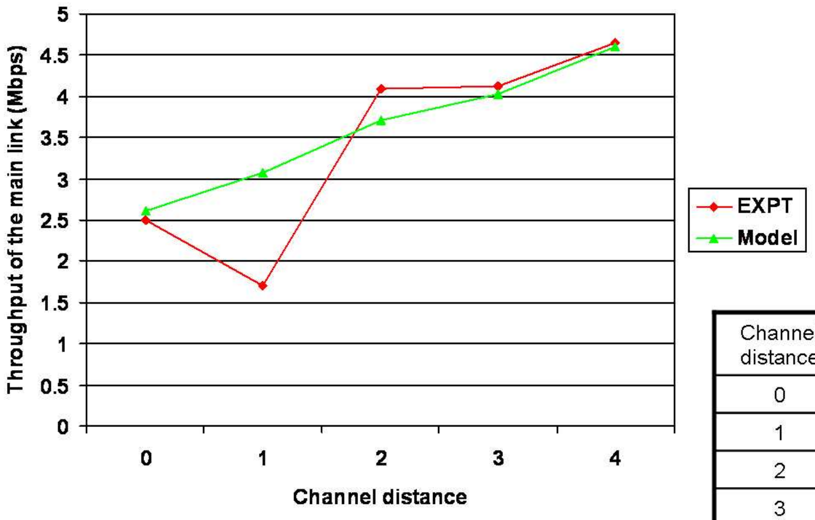
Figure 4.9: Throughput comparison for one interferer on all the overlapping channels at d1 = 10m

4.8 Experimental verification of throughput prediction model

Figure 4.9 shows the throughput comparison on all over lapping channels for one interferer for d1 = 10 m. The results show that the predicted throughput closely matches with experimental throughput. Therefore we can state that the throughput can be studied by piece-wise analyses of spectrum. The error percent is calculated and indicated for each measurement in the figure.

Figure 4.10 shows the same for d1 = 6 m. We can also observe the anomaly we had discussed in section 3.4.3 in the figure when channel distance is 1.

Figure 4.11 shows the throughput comparison between the measured results and the model at different dm values. The RSSI values indicated in the figure represent different dm values. Figure 4.12 shows the throughput comparison when 2 interfering stations are on the same channels other than the main station. Both the interfering stations are on the same channel indicated on the graph while the main station is on channel 11.



Channel distance	Error (%)
0	-4.5
1	-81
2	9.5
3	2.18
4	1

Figure 4.10: Throughput comparison for one interferer on all the overlapping channels at d1 = 6 m

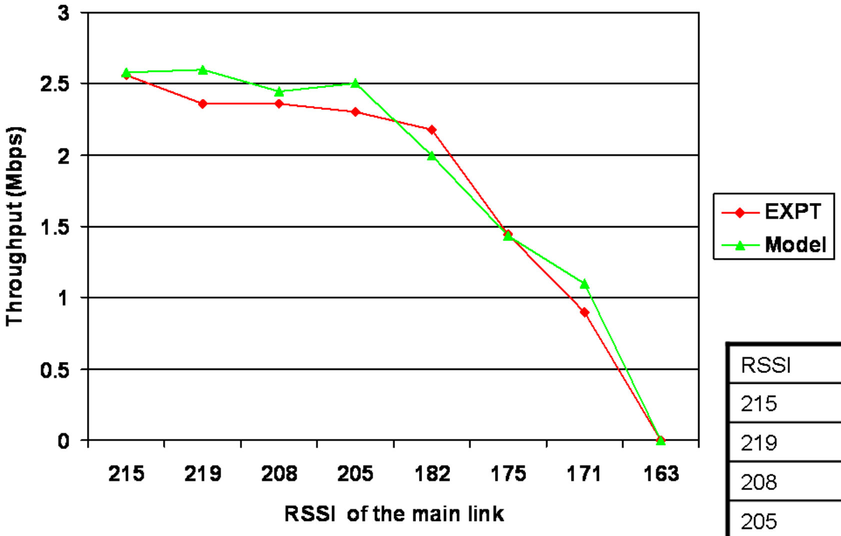
Figure 4.13 shows the throughput comparison for 2 interfering stations which are on different channels other than the main station. The main station, as in the previous case, is on channel 11.

We can see that as the number of stations increases the accuracy of the throughput prediction model decreases marginally.

4.9 Summary

A throughput prediction model combining empirical and analytical modeling is developed. The model is validated through experimentation.

The experimental results indicate that the throughput under interference is very much card dependent as no two cards give the same throughput values for a given setup. So it is extremely difficult to generalize the model for all card types.



RSSI	Error (%)
215	-2
219	-10
208	-4
205	-8.5
182	-8.25
175	0
171	-22
163	0
171	-22

Figure 4.11: Model validation for different d values

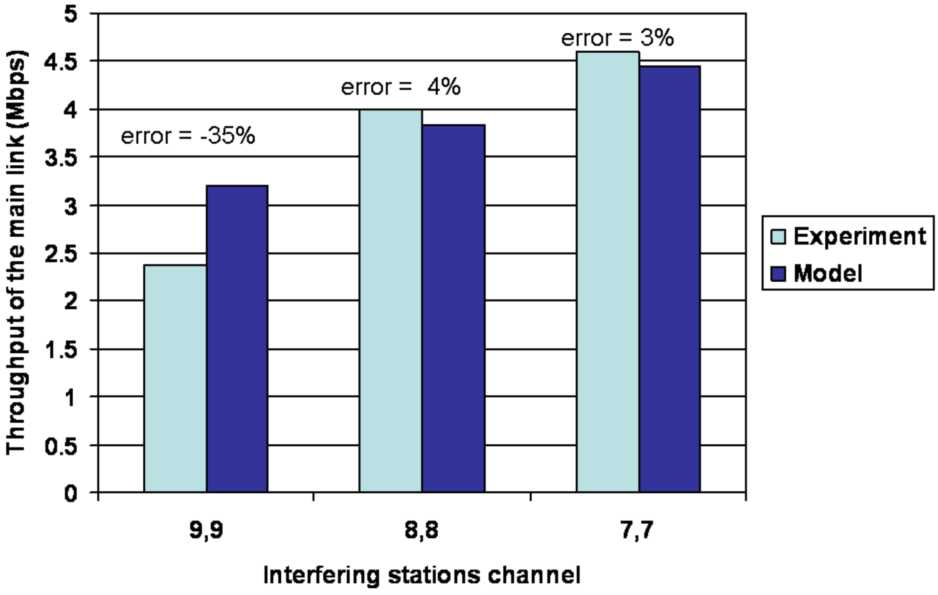


Figure 4.12: Model validation when two interferers are on the overlapping channels and the main station is on channel 11

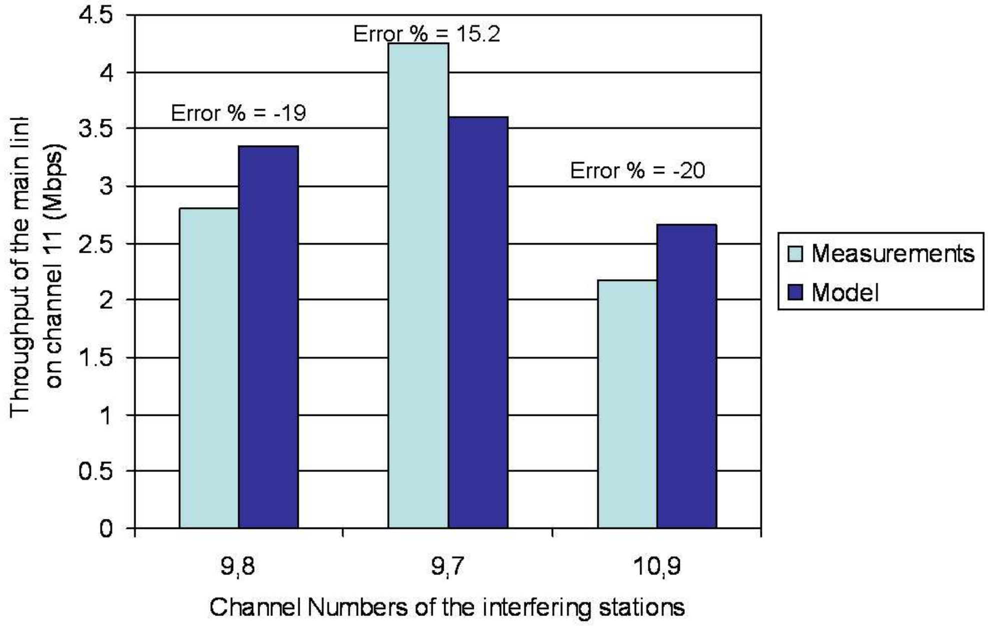


Figure 4.13: Model validation when interfering stations are on different channels and the main station is on channel 11

CHAPTER 5

CONCLUSION

A detailed study of the interference effects of 802.11b WLAN and Bluetooth on 802.11b networks are performed. The benefits of performing the experiments in the anechoic chamber is discussed and demonstrated experimentally. The performance of 802.11b networks in the presence of co-channel and adjacent channel interference is studied in detail. In the presence of self interference, the throughput of an 802.11b network is greater when the other 802.11b station (acting as interferer) is on the same channel than on adjacent channel when the devices are close to each other. Performance evaluation in the presence of both versions (with and without AFH) of Bluetooth standards is conducted. An extension to the already existing work in [27] is done. The theoretical results obtained from [47] are compared to our experimental results.

Since performance analysis is an important ingredient of network management, such an analysis of the wireless 802.11b networks under interference helps in drawing a base line for acceptable performance. This helps in proactive performance management which enables us to take necessary corrective measures for the imminent problem before hand and extract maximum performance in cases where interference is inevitable.

A mathematical model which estimates the performance of 802.11b network under self interference is developed. The factors which are neglected in the previous models have been taken into consideration. The model predicts the results fairly accurately within the error tolerance of less than 20 percent in most cases. We have observed that it is extremely difficult to model the behavior and predict the results under interference as different wireless cards gave different results. We have also learnt that the orientation of the wireless cards play an important role in the performance of a network under interference. So we have used only one particular antenna orientation throughout our experiments. Piece wise analysis of spectrum was employed when the interfering stations are on overlapping channels.

Knowing the throughput before hand using such models or tools will be extremely useful in network planning where the throughput prediction need not be very accurate. It saves a lot of effort in such cases in actually setting up a test bed and taking measurements considering various possible test scenarios into account.

5.1 Future Work

The model that we have developed has neglected certain factors like different antenna orientations which have to be considered. We have also assumed that the interferers are at about the same distance from the receiver. This may not be a realistic assumption. 802.11b networks are fast becoming obsolete with the emergence of 802.11g networks. Since 802.11g also operate in the same frequency band, our model can be used as a frame work for developing network planning tools for 802.11g networks. Such analyses can also be extended to WiMAX networks even though it is difficult because of their high range (around 2-3 miles).

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List of Definitions and Abbreviations

Self interference - Interference of other 802.11b stations on the 802.11b network of interest.

Bluetooth interference - Interference of Bluetooth devices on 802.11b network.

Co-channel interference - Co-channel interference occurs when two wireless stations working close to each other are on the same channel.

Adjacent channel interference - Adjacent channel interference occurs when two wireless stations working close to each other are on any of the overlapping channels.

SNR/RSSI - Signal strength of the access point perceived by the wireless station.

WLAN	Wireless Local Area Network
AP	Access Point
RSSI	Receive Signal Strength Indicator
MAC	Medium Access Control
PHY	Physical
LOS	Line Of Sight
NLOS	Non Line Of Sight
PER	Packet Error Rate
SNR	Signal-to-Noise Ratio
TCP	Transmission Control Protocol

UDP	User Datagram Protocol
RTS	Request to send
CTS	Clear to Send
FTS	Fragmentation Threshold Set
CSMA-CA	Carrier Sense Multiple Access-Collision Avoidance
CW	Contention Window
ACK	Acknowledgement
MS	Mobile Station
DCF	Distributed Coordination Function
PCF	Point Coordination Function
DIFS	DCF Inter Frame Space
SIFS	Short Inter Frame Space
NIC	Network Interface Card
IP	Internet Protocol
Tx	Transmitter
Rx	Receiver