

**A PERFORMANCE ANALYSIS OF THE IEEE 802.11B
LOCAL AREA NETWORK IN THE PRESENCE OF BLUETOOTH
PERSONAL AREA NETWORK**

THESIS

**Submitted in Partial Fulfillment
of the REQUIREMENTS for the**

Degree of

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by

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Vita

I was born in St.Petersburg, Russia, in May 2, 1979. I spend my childhood there and in 1994 my family had moved to Brooklyn, NY, where we have been living for the past 7 years.

I have finished Fort Hamilton High School in Brooklyn, NY and was accepted into Polytechnic University. I was accepted into the Accelerated Honor Program after a successful completion of which I would be simultaneously awarded Bachelor of Science and Master of Science degrees. I have chosen Computer Engineering for the Bachelor of Science degree and Telecommunication Networks for the Mater of Science degree.

During my educational carrier at Polytechnic University I had a number of professional experiences. In my first summer at Polytechnic University, I undertook a volunteering work in the High Speed Networking Laboratory, where I was learning basics of networking technology such as Ethernet and ATM. During the following summer I was accepted into the Honor Junior Research Project, were I have studied the operation, analyzed and experimented with IEEE 802.11b wireless local area networks. During my last summer at Poly I was employed in Symbol Technologies, where I was involved in the research of interference between the IEEE 802.11b system and Bluetooth.

I was working on my Masters thesis for one and a half years, with substantial amount of work done during my time at Symbol Technologies. My research has been done under the advisement of Dr. David J. Goodman.

Acknowledgment

I would like to give my deep thanks to Dr. David J. Goodman for his constant and generous guidance, help and encouragement throughout my study at the Polytechnic University Graduate School. Working with him has been a great pleasure to me.

AN ABSTRACT

A Performance Analysis of the IEEE 802.11b Local Area Network in the Presence of Bluetooth Personal Area Network

by

Michael Fainberg

Advisor: Professor David J. Goodman

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The thesis presents analysis of the performance degradation in the IEEE 802.11b WLAN due to the presence of Bluetooth piconets. The IEEE 802.11b is a direct sequence spread spectrum (DSSS) system operating in the 2.4GHz band. It is designed to cover large areas, up to 100 meters in diameter, and connect hundreds of computers. The system operates at four different data rates of 1, 2, 5.5 and 11 megabits/second. Bluetooth is a frequency hopping spread spectrum (FHSS) system operating in the same frequency band as the IEEE 802.11b. The primary applications for Bluetooth are along the lines of a Wireless Personal Area Network (WPAN), involving relatively short distances, for communication between notebooks, palm units and similar personal computing and communication devices within a “piconet”.

In this thesis a model is developed that captures the performance impact of Bluetooth interference on the IEEE 802.11b packet reception, parameterized by the IEEE

802.11b data rate, packet size, a number of Bluetooth piconets and the piconet utilization, as well as distance between the collocating IEEE 802.11b and Bluetooth radios.

The analysis comprises interference at both physical and medium access control layers of the 802.11b systems. At the physical layer the key calculation is the probability of the bit error for the various IEEE 802.11b data rates. At the MAC layer the calculation of the probability of Bluetooth transmitter overlapping in both time and frequency with 802.11b Direct Spread packet is derived.

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Chapter 1

Introduction

1.1 Background

The 2.4GHz Industrial, Scientific, and Medical (ISM) band is poised for strong growth. Fueling this growth are two emerging wireless technologies: Wireless Local Area Networking (WLAN) and Wireless Personal Area Networking (WPAN). In the WLAN category the products based on the IEEE 802.11b technology are dominating. The IEEE 802.11b offers speeds of up to 11Mbps and covers a range of up to 100 meters. With WLANs, applications such as Internet access, e-mail and file sharing can now be done in the home or office environments with new levels of freedom and flexibility. It is predicted that there are going to be nearly 20 million WLAN systems installed in 2004.

The WPAN category is led by a short-range wireless technology called Bluetooth. Designed principally for cable replacement applications, most Bluetooth implementations support a range of up to roughly 10meters, and speeds of up to 700Kbps for data or isochronous voice transmission. Bluetooth is ideal for applications such as wireless headsets, wireless synchronization of PDAs with computers, and wireless peripherals such as printers or keyboards. It is predicted that market for Bluetooth devices will reach 800 million units by 2004.

Coexistence between these technologies has become a significant topic of analysis and discussion throughout the industry. WPAN and WLAN are complementary rather than competing technologies. Moreover, with both of them expecting rapid growth, collocation of the IEEE 802.11b and Bluetooth devices will become increasingly likely.

Because both technologies occupy the 2.4GHz frequency band, there is potential for interference between the two technologies. Due to the number of factors disclosed further, the IEEE 802.11b transmissions suffer much more severely from the presence of the Bluetooth radios, rather than the Bluetooth suffers from the 802.11b. Consequently, the emphasis of the work presented in this thesis is on the performance of the IEEE 802.11b system.

1.2 Previous Work and Problem Formulation

Analysis of interference between the IEEE 802.11b and Bluetooth is not new, as indicated by the publications of the Coexistence Task Group, formed under the IEEE 802.15 committee to address the problem of interference between the WLAN and WPAN, as well as industry leaders in the field of wireless networking such as Symbol Technologies. Early attempts to qualify interference effects have been based on simple mathematical models rather than actual usage models [1]. Some papers [2] focused on the calculating the probability of the overlap, in both time and frequency, of a continuous sequence of Bluetooth packet and an IEEE 802.11b packets. Relative power levels between Bluetooth packets and 802.11b packets were not considered. These prior efforts did not consider the details of the WLAN physical layer (PHY), for example different transmission rates, modulation and channel coding schemes, as well as nuances of medium access control layer (MAC) implementations. The signal propagation characteristics and the impact of a time and space varying wireless channel on the system performance were not studied either.

To understand fully the effect of interference of Bluetooth on the IEEE 802.11b system a fuller model has to be designed; a model that will combine all of the essential components pertinent to both systems.

1.3 Contribution of This Work

In this thesis a model is developed that captures the performance impact of Bluetooth interference on the IEEE 802.11b packet reception, parameterized by the IEEE 802.11b data rate, packet size, the number of Bluetooth piconets and the piconet utilization, as well as distance between the collocating IEEE 802.11b and Bluetooth radios.

The analysis comprises investigation of interference at both PHY and MAC layers of the 802.11b systems. At the PHY layer, the key calculation is the probability of the bit error for the various IEEE 802.11b data rates. At the MAC layer the calculation of the probability of Bluetooth transmitter overlapping in both time and frequency with 802.11b Direct Spread packet is most essential.

The system is modeled in an indoor environment. Two distinct system topologies are analyzed. One is a household and the other is an office environment. Signal propagation is characterized by a time and space-varying channel. Modeling of the wireless channel is done in a statistical fashion. The indoor wireless environment introduces a number of impairments into the channel; the most severe of them are path loss, shadowing, multipath fading and noise. The signal fading due to multipath propagation is modeled by the Rayleigh distribution, which is consistent with non-line of sight propagation. The shadowing is represented by a lognormal probability distribution.

Each of the four data rates provided by the IEEE 802.11b standard behaves differently in such environment, due to the fact that various coding and modulation techniques used at each data transmission rate have different responses to multipath fading. Consequently, in order to evaluate the total performance of the IEEE 802.11b system it will be necessary to examine each of the four data rates individually. Next, the effect of collocated Bluetooth piconets are introduced into the 802.11b system. The total probabilities of packet error of the IEEE 802.11b system are calculated taking in consideration wireless channel impairments and presence of Bluetooth radios.

Once the physical layer model has been determined and the packet error probabilities for the four data rates have been calculated, the interference at the MAC layer can be derived. This interference is characterized by the probability of collision of the IEEE 802.11b packet with Bluetooth packet. Two factors are in effect at this point: probability that packets will intersect in frequency and the probability of intersection in time. The intersection in frequency domain depends on the hopping pattern of the Bluetooth transmitter, while the collision in the time domain mainly depends on the utilization and the traffic patterns (voice, data) of Bluetooth piconets.

The results depict how changes in various parameters, such as the IEEE 802.11b packet size, piconet utilization and the number of piconets affect the IEEE 802.11b system performance. In particular, the performance of each of the four possible data rates of the IEEE 802.11b system in the presence of the Bluetooth are explained and compared.

1.4 Organization of The Thesis

The thesis is organized into 10 chapters including this chapter. In Chapter 2, the IEEE 802.11b standard is overviewed. The network topology and architecture are discussed in detail. The concepts of Spread Spectrum technology including DBPSK and DQPSK modulations are explained and corresponding bit error probability curves are plotted. The CCK modulation including Walsh Codes is reviewed and corresponding equations for the bit error probability are derived. In addition, the medium access for the IEEE 802.11b system is disclosed.

Chapter 3 gives a brief overview of the Bluetooth architecture including physical as well as medium access layers.

Chapter 4 proposes two distinctive network topologies for the analysis of interference. First one is in a household environment and second is in the office environment. Differences between them are explained.

Chapter 5 introduces details of the channel model characteristic to the indoor wireless environment. Channel model includes Large and Small Scale Fading. The effects of each of those phenomena on the signal strength are explained.

Chapter 6 analyses the performance of the IEEE 802.11b system in the multipath wireless channel. Specifically, it describes performance of each of the four data rates provided by the standard in the multipath channel. The probability of bit error and packet error are derived in this chapter as well.

In Chapter 7, the expression for the throughput of the system is derived and applied to every modulation scheme, proposed by the standard. In addition, the method

of throughput optimization by means of packet fragmentation is introduced and discussed.

Chapter 8 discusses the impact of the Bluetooth on the throughput of the 802.11b system, by analyzing performance of every modulation scheme in the multipath channel and additional interference due to presence of Bluetooth.

In Chapter 9, the performance of the 802.11b system in the office environment, with uniform Bluetooth piconet distribution is overviewed. Throughput optimization results are analyzed as well.

Chapter 10 discusses results, conclusions and future work.

Chapter 2

The IEEE 802.11b Standard Overview

2.1 Introduction

Final approval of the IEEE 802.11b standard for wireless local area networking (WLAN) two years ago has positioned this technology to fulfill the promise of truly mobile computing. The standard discloses WLAN network architecture, including physical and medium access specifications [3]. Following is an overview of the standard; this chapter presents aspects of the system architecture most essential to the work described in the thesis.

2.2 Network Topology

The basic topology of an 802.11b network is shown in Figure 2.1. A Basic Service Set (BSS) in its simplest form consists of two or more wireless nodes, or stations (STA), which have recognized each other and have established communication. This situation has a special designation, namely the Independent BSS (IBSS). Within an IBSS, STAs communicate directly with each other on a peer-to-peer level. This type of network is often formed on a temporary basis, and is commonly referred to as an ad hoc network.

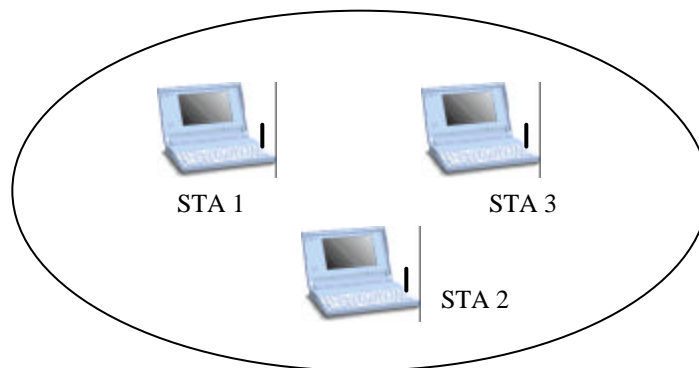


Figure 2.1. Peer-to-peer communication in ad hoc network

A more common and a far more flexible configuration is that of a BSS which contains an Access Point (AP). The main function of an AP is to form a bridge between wireless and wired LANs. When an AP is present within a BSS, STAs do not communicate on a peer-to-peer basis. Instead, all communications between STAs or between a STA and a wired network client go through the AP. APs are not mobile, and form part of a wired network infrastructure. A BSS in this configuration is said to be operating in the infrastructure mode.

The Extended Service Set (ESS) shown in Figure 2 consists of a series of BSSs (each containing an AP) connected together by means of a Distribution System (DS). Although the DS could be any type of network (including wireless network), it is almost invariably an Ethernet LAN. Within an ESS, STAs can roam from one BSS to another and communicate with any mobile or fixed client in a manner that is completely transparent in the protocol stack above MAC sublayer. The ESS enables coverage to extend well beyond the range of a WLAN radio.

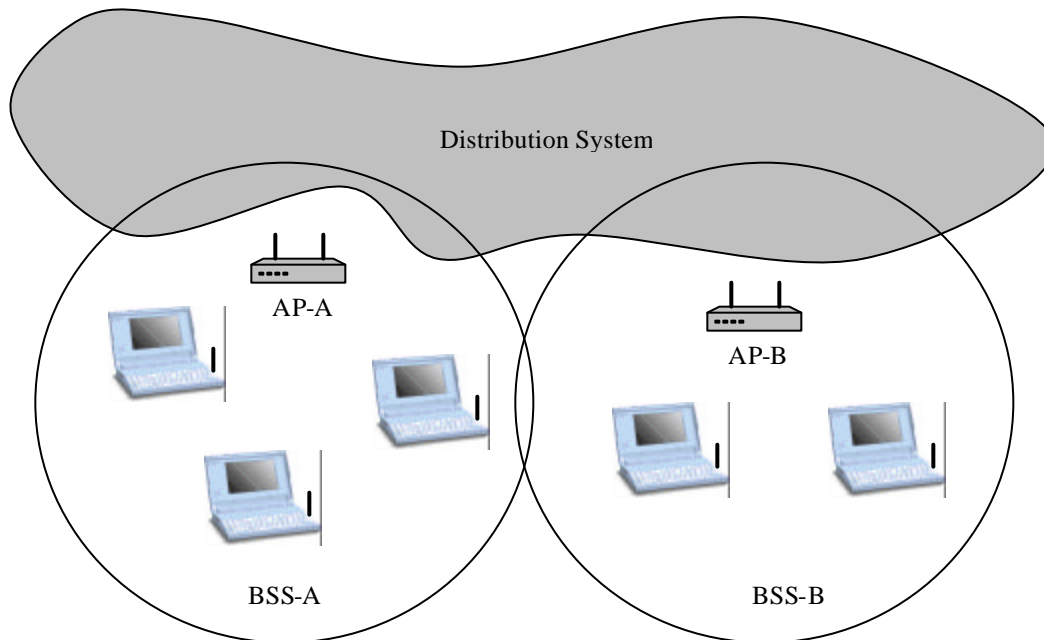


Figure 2.2. ESS provides extended coverage

2.3 Radio Technology

The IEEE 802.11b standard actually provides for three variations of the PHY. These include Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), and Infrared. In practice, only the first one, DSSS, has any significant presence in the market. The DSSS PHY option was designed specifically to conform to FCC regulations (FCC 15.247) for operation in the 2.4GHz ISM band. The 2.4GHz ISM band is practically attractive because it enjoys worldwide allocations for unlicensed operation, as summarized in Table 2.1.

Table 2.1. Global Spectrum Allocation at 2.4GHz

Region	Allocated Spectrum
US	2.4000 – 2.4835GHz
Europe	2.4000 – 2.4835GHz
Japan	2.4710 – 2.4970GHz
France	2.4465 – 2.4835GHz
Spain	2.4450 – 2.4750GHz

For the DSSS operation the available bandwidth is divided into channels, each occupying approximately 20MHz. Although there are 11 channels identified for DSSS system in the US and Europe, there is a lot of overlap. When multiple APs are located in close proximity, it is recommended to use frequency separation of at least 25MHz. Therefore, the ISM band will accommodate three non-overlapping channels in a total bandwidth of 83.5MHz.

In most of the WLAN products on the market based on the IEEE 802.11b technology the transmitter is designed as a Direct Sequence Spread Spectrum Phase Shift

Keying (DSSS PSK) modulator, which is capable of handling data rates of up to 11Mbps. The system implements various modulation modes for every transmission rate, which are Differential Binary Phase Shift Keying (DBPSK) for 1Mbps, Differential Quaternary Phase Shift Keying (DQPSK) for 2Mbps, and Complementary Code Keying (CCK) for 5.5Mbps and 11Mbps. The preamble and header of the frame, Figure 3, are always transmitted as the DBPSK waveform (1Mbps), while data packets can be configured for DBPSK, DQPSK or CCK. The duration of the preamble and the header is 192 μ s. The Signal Field in the header of the packet indicates what modulation is used in the rest of the packet. The preamble is used by the receiver to achieve initial synchronization while the header includes the necessary data fields of the communications protocol to establish the physical layer link. The preamble and header are added to every packet transmitted on the LAN at the PHY layer of the system.

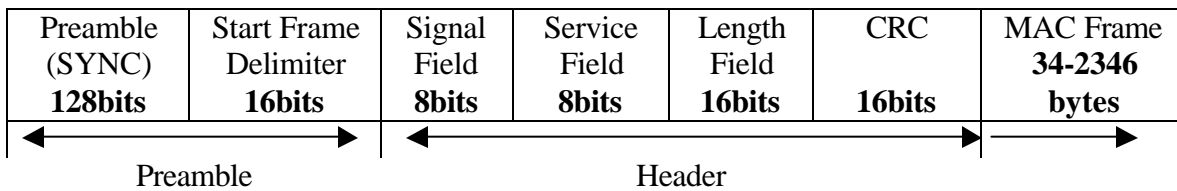


Figure 2.3. The IEEE 802.11b frame format

According to the FCC regulations (FCC 15.247) for operation in the 2.4GHz ISM band the nominal power of the transmitter is 100mWatt or 20dBm. This signal strength was chosen to accommodate coverage of the approximately 100-meter radius area and to limit the battery power consumption.

2.3.1 Spread Spectrum Modulator

The modulator is designed to generate DBPSK, DQPSK and CCK spread spectrum signals. The modulator changes its rate after the header, when data transmission uses DQPSK or CCK. The modulator can support data rates of 1, 2, 5.5, 11Mbps.

Differential Quadrature (*I/Q*) modulation is used at the baseband for all modulation modes DBPSK, DQPSK and CCK. In the 1Mbps DBPSK mode, *I* and *Q* channels of the modulator are connected together.

Spread spectrum is employed in IEEE 802.11b to decrease the problem of interference due to other systems operating in the ISM band. By means of spread spectrum the energy radiated by the transmitter is spread out over a wider amount of the RF spectrum than would otherwise be used and thus increase the processing gain at the receiver where the signal is going to be dispersed. The spreading is performed by multiplying (Exclusive Or) binary data by a pseudorandom (PN) binary waveform. In the case of DBPSK and DQPSK the PN code is an 11-chip long Barker sequence. Barker codes are short unique codes that exhibit very good correlation properties. For the CCK modulation 8-chip long Walsh codes are employed.

One of the essential reference points in the analysis is a Signal to Noise ratio (SNR). In this analysis the SNR is represented by energy per chip (E_c) to the power spectral density of noise (N_0) ratio

$$\frac{E_c}{N_0} = \frac{\text{Transmitter_Signal_Strength}}{N_0 \cdot \text{Chip_Rate}} \quad (2.1)$$

The SNR depends on the chip rate of the system; consequently, for every transmission rate this quantity is going to be the same. The difference is going to be in the number of bits represented by a chip (length of the pseudorandom sequence), which means that

energy per bit to noise ratio is going to differ from one data rate to another. The N_0 here is a power spectral density of the Additive White Gaussian Noise (AWGN) of the system and is going to be discussed further. The chip rate of the system is fixed at 11Mchips/s.

2.3.2 DBPSK and DQPSK Modulations

The operation of the differential phase shift keying (DPSK) modulation can be better explained after understanding the regular phase shift keying (PSK). In a PSK, the M signal waveforms are represented [5] as

$$s_m(t) = g(t) \cdot \cos \left[2\pi f_c t + \frac{2\pi}{M} (m-1) \right] \quad m=1,2,\dots,M$$

$$= g(t) \cdot \cos \left[\frac{2\pi}{M} (m-1) \right] \cdot \cos(2\pi f_c t) - g(t) \cdot \sin \left[\frac{2\pi}{M} (m-1) \right] \cdot \sin(2\pi f_c t), \quad (2.2)$$

where $g(t)$ is a signal pulse shape. The M represents possible phases of the carrier that conveys the transmitted information. The BPSK modulation is represented in the equation 2.2 by the $M = 2$, two phases, whereas the QPSK is represented by $M = 4$, four phases.

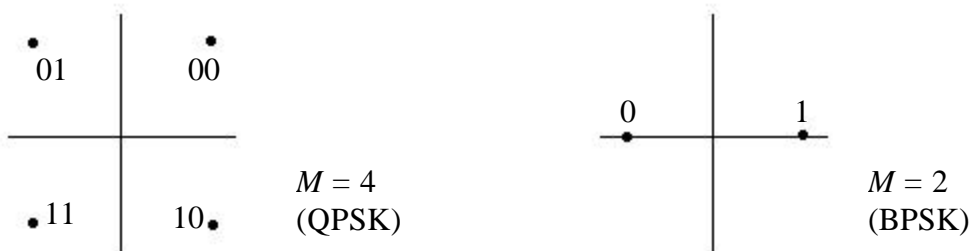


Figure 2.4. Signal Space Diagram for PSK signals

The DPSK modulation differs from the PSK in a way that there is no direct phase assignment to every symbol; instead, the difference between the current and previous phase is detected and that change in phase indicates the change in the symbol. For example, in the simplest form of DBPSK, 1 may cause a phase shift of π whereas 0 causes no phase change, or vice versa. At the receiver the phase of each symbol is compared with that of the previous symbol, which means that there is a need for delaying the received signal by one symbol length in time. A phase change indicates a 1 is received, no phase change 0. The differential phase shift keying is employed in the IEEE 802.11b standard because differential modulation overcomes the need for coherent detection necessary in PSK systems, in other words there is no need for estimation of the carrier phase, therefore the receiver design [4] is much simpler. Spectrally the DBPSK signal is similar to that of a BPSK signal, however there is 1dBm advantage in processing gain.

For DBPSK modulation the bit error probability in the AWGN channel is

$$P_e = \frac{1}{2} \exp\left(-\frac{E_b}{N_0}\right) \quad (2.4)$$

In the case of DQPSK, where $M = 4$, we have in effect two binary phase-modulation signals in phase quadrature, and the equation [5] is

$$P_e = Q_1(a, b) - \frac{1}{2} I_0(ab) \exp\left(-\frac{1}{2}(a^2 + b^2)\right) \quad (2.5)$$

where $Q_1(a, b)$ is the Marcum Q function, $I_0(ab)$ is the modified Bessel function of zero order and parameters a and b are defined as

$$a = \sqrt{\frac{2E_b}{N_0} \cdot \left(1 - \sqrt{\frac{1}{2}}\right)} \quad \text{and} \quad b = \sqrt{\frac{2E_b}{N_0} \cdot \left(1 + \sqrt{\frac{1}{2}}\right)}. \quad (2.6)$$

The 11-chip direct sequence spreading increases the processing gain at the receiver of the DBPSK system by $10\log\left(\frac{11\text{chips}}{1\text{bit}}\right)=10.4\text{dB}$. For DQPSK modulation the processing gain is $10\log\left(\frac{11\text{chips}}{2\text{bit}}\right)=7.4\text{dB}$, since 2 bits encoded into every chip. The practical data rate reached under the DBPSK modulation is 1Mbit/s or 1Msymbol/s, where each symbol is 11chips and represents one bit. For the DQPSK modulation the data rate reached is 2Mbit/s or 1Msymbol/s, where each symbol is 11chips and represents two bits.

From the Figure 2.5(a) we can observe the difference in bit error probability of DBPSK and DQPSK in the AWGN vs. $\frac{E_b}{N_0}$ measured in dB.

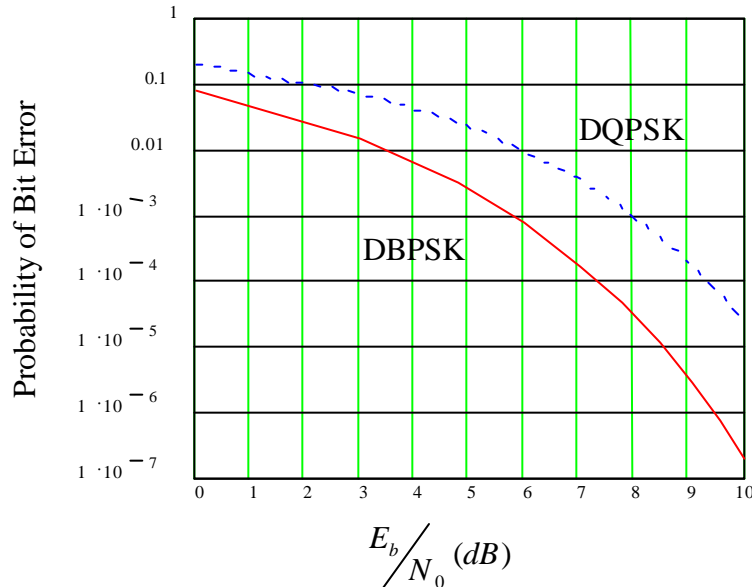


Figure 2.5. BER graphs for DBPSK and DQPSK in AWGN

2.3.3 CCK Modulation

For the CCK modes, the spreading code length is 8 chips and based on complementary codes. The transmitter inputs the data and portions it into 4-bits or 8-bits. At 5.5 Mbps, it uses 2 of those 4 bits to select one of 4 complex spread sequences from a table of CCK sequences and then DQPSK modulates that symbol with remaining 2 bits. At 11Mbps, 8 bits are used, where 6 bits are used to select one of 64 spread sequences for a symbol, and 2 remaining bits are used for modulation. Thus, the total possible number of combinations of sequences and carrier phases is 256.

CCK is a variation on M-ary BiOrthogonal Keying (MBOK) modulation where one of the M unique (nearly orthogonal) signal codewords is chosen for transmission. CCK uses the complex set of Walsh/Hadamard functions known as Complementary Codes. Walsh codes are formed by performing a simple operation [6] as illustrated in Figure 2.7. For the 2-ary case, the basic symbols are formed by taking a 2×2 matrix of 1s and inverting the lower right quadrant of the matrix. To form the 4-ary case, take 4 of the 2×2 matrices and make a 4×4 matrix with the lower right hand quadrant again inverted. The procedure is repeated for the 8-ary case and beyond.

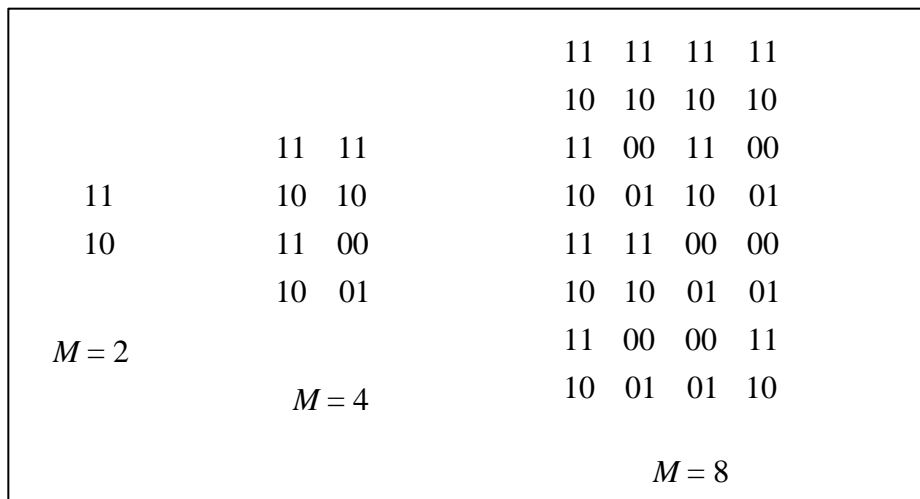


Figure 2.6. Forming Walsh Codes by successive folding

The bit error probability at the receiver in the AGWN [5] is

$$P_e = 1 - \int_{-X}^{\infty} \left(\frac{1}{\sqrt{2\mathbf{p}}} \cdot \int_{-(v+X)}^{v+X} \exp\left(-\frac{y^2}{2}\right) dy \right)^{\frac{M}{2}-1} \cdot \exp\left(-\frac{v^2}{2}\right) dv, \quad (2.7)$$

where $X = \sqrt{\frac{2E_b}{N_0}}$. This probability depends on the M . For the 5.5Mbps data rate $M =$

4, and for the 11Mbps $M = 8$. For the 5.5Mbps data rate 4 bits are encoded into the 8-chip long code word consequently the processing gain is only

$$PG = 10 \log\left(\frac{8\text{chips}}{4\text{bit}}\right) = 3\text{dB}, \quad (2.8)$$

for the 11Mbps data rate there is no spreading gain at all, since 8 bits are encoded in to the 8-chip sequence. We can see the graphical representation of the high data rate modulation schemes in Figure 2.8.

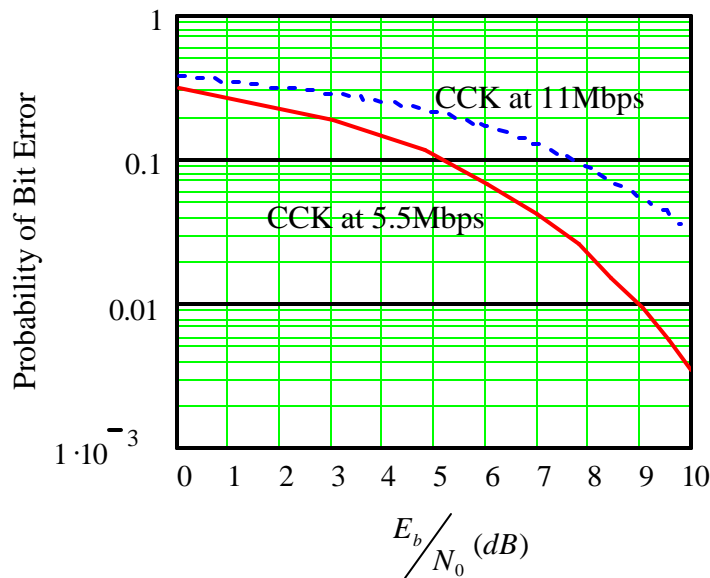


Figure 2.8. BER graphs for CCK modulation schemes

To insure that the modulation has the same bandwidth as the lower data rates modulations, the chipping rate is kept at 11Mchip/s while the symbol rate is increased to 1.375 MSymbol/s.

2.4 Medium Access

The basic medium access protocol of the 802.11b standard is a Distributed Coordination Function (DCF) that allows for automatic medium sharing through the use of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm and a random back-off time following a busy medium condition. In addition, all traffic uses immediate positive acknowledgement (ACK frame), where retransmission is scheduled by the sender if no ACK is received, which is Stop-and-Wait Automatic Repeat Request (ARQ) error control mechanism. Carrier sense is performed both through physical and virtual mechanisms. The virtual carrier sense mechanism is achieved by distributing reservation information announcing the impending use of the medium; it is accomplished by the exchange of Request To Send (RTS) and Clear To Send (CTS) frames. In addition the various inter frame spaces are used to differentiate between different types of transmissions. For example, before each transmission a station has to wait Distributed Inter Frame Space (DIFS) in order not to disturb other ongoing transmissions, which might be only separated by a Short Inter Frame Space (SIFS).

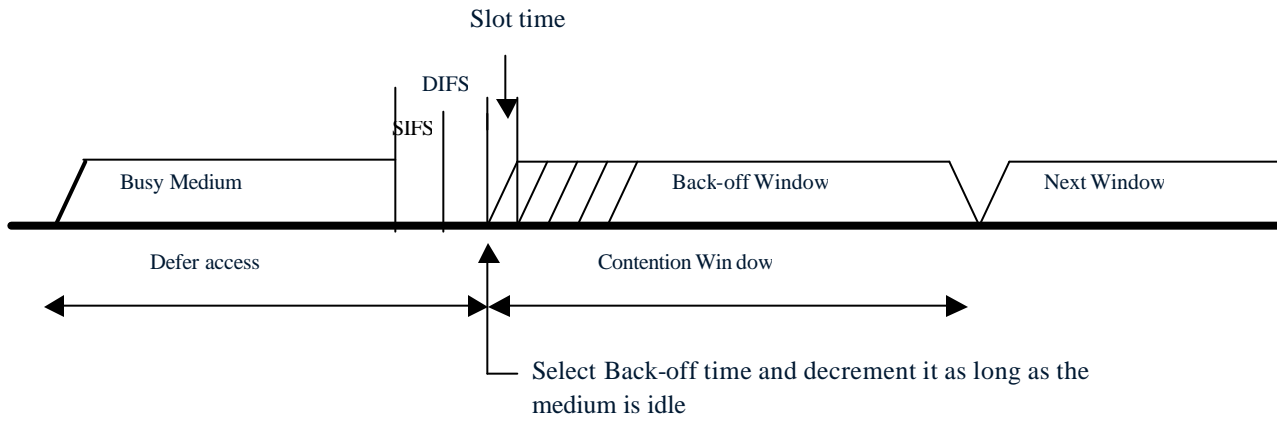


Figure 2.8. Basic CSMA/CA operation

There are many different types of frames provided by the standard but the most essential to this analysis are the data frames. The data frames can vary from 100 to 2350 bytes, where total overhead at both PHY and MAC layers is 80 bytes.

Chapter 3

Bluetooth Architecture Overview

3.1 Introduction

The Bluetooth wireless technology is an open specification for a small-form-factor, low-cost, personal area network connection among mobile computers, mobile phones and other devices. The Bluetooth wireless technology specification provides secure, radio-based transmission of data and voice. It delivers opportunities for rapid, ad hoc, automatic, wireless connections, even when devices are not within the line of sight. The Bluetooth wireless technology uses a globally available frequency range to ensure interoperability no matter where you travel.

The Bluetooth wireless technology was developed by the Bluetooth Special Interest Group, which was founded in 1998 to define an industry-wide specification for connecting personal and business mobile devices. More than 1,400 companies are now members of the Special Interest Group, signifying the industry's unprecedented acceptance of the Bluetooth wireless technology.

3.2 Radio Technology

Bluetooth is a single chip, low-power, wireless communication module. The radio operates in the globally available 2.4GHz ISM band. Bluetooth uses Frequency Hopping Spread Spectrum (FHSS) technology at a rate of 1600 hops/sec and Gaussian Frequency Shift Keying (GFSK) modulation. Since the radio link is based on the FHSS, multiple channels (frequency hopping sequences) can co-exist in the same wide band without

interfering with each other. Two or more units sharing the same channel form a piconet, where one unit acts as a master, controlling the communication in the piconet and the others act as slaves.

In the United States, a maximum of 79-1MHz wide channels are specified in the hopping set [7]. The first channel has a center frequency of 2.402GHz, and all subsequent channels are spaced 1MHz apart. FCC mandates the 1MHz separation for the 2.4GHz ISM band. The channel separation corresponds to 1Mbps of instantaneous bandwidth.

Bluetooth channels use a frequency-hop/time-division-duplex (FH/TDD) scheme. The channel is divided into 625millisecond (ms) intervals, called slots, where a different hop frequency is used for each slot. The master transmission starts in even-numbered slots, while the slave transmission starts in odd-numbered slots. Packets can be 1,3 and 5 slots long and are transmitted in consecutive slots; 1 slot packet is 625 bit long. In the Bluetooth architecture, multiple piconets with overlapping area of coverage can co-exist since their frequency hopping patterns are mutually orthogonal.

The operating range of the Bluetooth radio should be within 10-meter radius; consequently the nominal power at the transmitter is 1mWatt or 0dBm.

Chapter 4

Network Topology

4.1 Introduction

It is very likely that WLAN and WPAN system will operate in the close proximity in the household or office environment. The network infrastructure, number of radio devices, as well as utilization of the networks both WLAN and WPAN will differ in each of these locations. Consequently, in order to provide objective performance analysis of the IEEE 802.11b system it is necessary to define and analyze each of these locations individually.

4.2 Household Environment

The first scenario involves a household or small office environment: single infrastructure BSS including, an access point (AP), one or two stations (STA) and the same number of Bluetooth piconets. In this scenario, there are two possible situations for which the Bluetooth piconet is going to have greatest interference with the 802.11b transmission.

First one, Figure 4.1, occurs when there is a transmission from AP to STA and interfering BT piconets are in the vicinity of the STA.

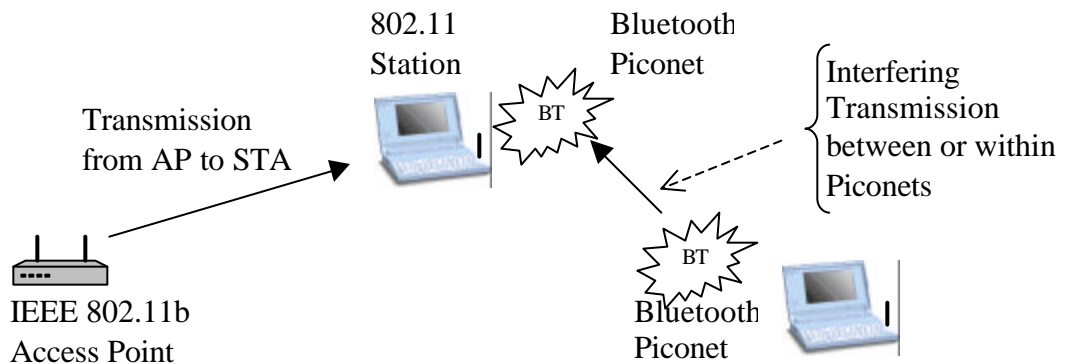


Figure 4.1. Household network topology

The second situation is when a STA transmits data to AP and BT piconets are near the AP. Both of the situations produce the same interference and therefore results of this analysis can be applied to either of them. This scenario is going to be discussed first.

4.3 Office Environment

In an office environment there could be up to three infrastructure BSS positioned in the same geographical area, to extend the coverage. Every BSS controls large number of STAs positioned in every cubicle of the office and there is a Bluetooth piconet associated with every station as well.

Following rules are applied:

- a. We have rectangular office of 1600 m² in area.
- b. The average density is one STA every 36m².
- c. There are $\frac{1600}{36} = 45$ STA in the office and 45 BT.

In this environment the number of Bluetooth piconets interfering with the IEEE 802.11b transmission depends upon range from AP.

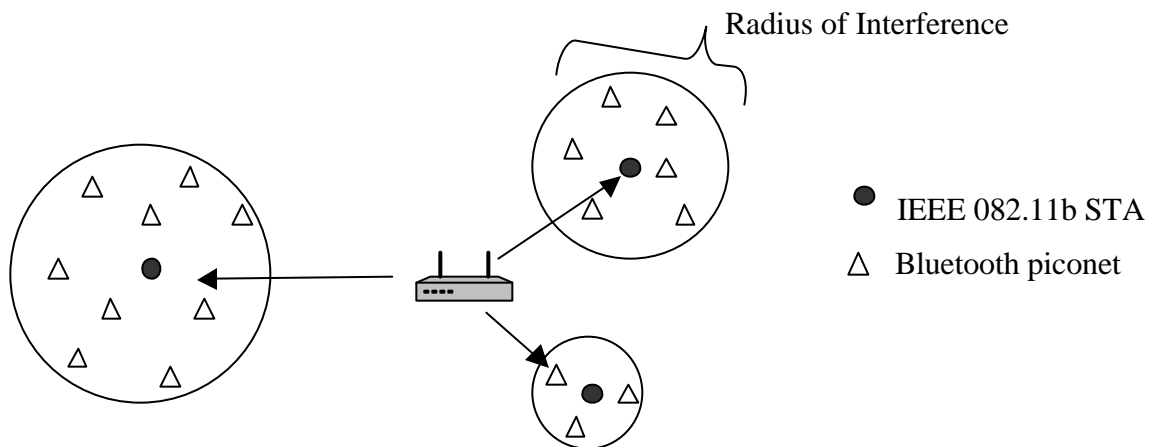


Figure 4.2. Office network topology

Therefore, as we go further from AP the signal strength at the STA becomes weaker and because of the uniform distribution of the Bluetooth devices in the office the combined interference impact from those devices becomes greater.

Chapter 5

Channel Model

5.1 Introduction

In a wireless communication system, the transmitted signal is affected by a time and space varying channel, which introduces a plurality of channel impairments such as attenuation, multipath, linear distortion and noise in the desired signal. Hence accurate knowledge of the propagation characteristics associated with the mobile radio channel is required in performance evaluation of the wireless system. Modeling radio channel is typically done in a statistical fashion. Three different and mutually independent propagation phenomena influence the power of the received signal: path loss, shadowing and multipath fading. A practical example of wireless channel impulse response [8] is,

$$\text{Channel}(dB) = PL(d) + X_s + Y \quad (5.1)$$

The first two terms represent the large scale fading. The third term represents the equivalent complex low pass impulse response due to small-scale fading.

5.2 Large Scale Fading

Large scale fading represents average power or path loss over a large area as a function of distance. This phenomenon is affected by prominent environment features such as office walls, floors, ceilings and fixtures. The receiver is often hidden or shadowed by these features and the statistics of large scale fading provides a way of computing estimated signal power or path loss as a function of distance.

5.2.1 Path Loss

The path loss can be written in the logarithmic scale as

$$L(d) = PL(d_0) + 10 \cdot n \cdot \log_{10} \left(\frac{d}{d_0} \right) + X_s \quad (5.2)$$

The constant $PL(d_0)$ is the median path loss at a distance of one meter from the transmitter and this is a function of the transmitter receiver heights, the carrier frequency, and the type of environment. It is given by

$$PL(d_0) = 20 \log \left(\frac{4\pi d_0}{\lambda} \right) = 40dB \quad (5.3)$$

where λ is a wavelength of 2.4GHz wave and is equivalent to 12.5cm, d_0 is 1 meter.

From one meter and on the path loss is described by

$$PL(d) = 10 \cdot 3.5 \cdot \log \left(\frac{d}{d_0} \right) \quad (5.4)$$

where $n = 3.5$ is the path loss coefficient characteristic to the indoor environment. In general n can vary from 1.5 to 5. The factor X_s accounts for shadow fading due to obstructions.

Since the maximum operating range of the IEEE 802.11b radio is 100 meters, we are going to analyze the interference within that range, $1 < d < 100m$. Taking in consideration the signal strength of the transmitter is 100mW or 20dBm, the following (Figure 5.2) representation of the path loss for the indoor environment can be derived.

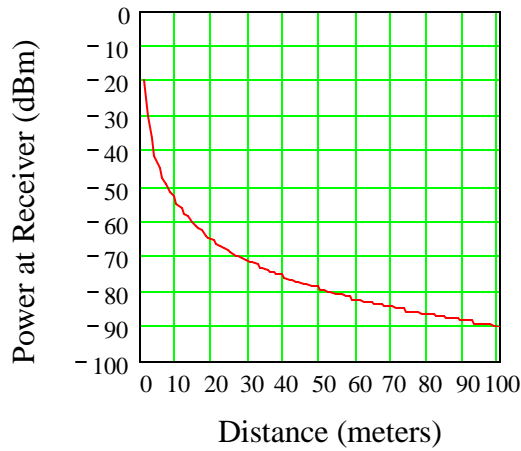


Figure 5.1. Path Loss in the Wireless Indoor Channel

We observe that the graph in figure 5.2 starts from -20dBm and not from 20dBm , which is not an error; 40dB is lost in the first meter.

5.2.2 Shadowing

The statistical component of long term fading is called shadow fading, which is modeled by a lognormal random variable [9]. $X_s = 10 \cdot \log_{10}(x_s)$ is a Gaussian with a mean (μ) of zero and variance (σ) that ranges from 6 to 12dB depending on the environment.

The Probability Density Function (PDF) of the lognormal distribution is

$$g(x) = \frac{1}{\sqrt{2\pi s x}} \cdot \exp\left(\frac{-\ln^2 x}{2s^2}\right) \quad (5.5)$$

and the Cumulative Distribution Function (CDF) is

$$G(r) = \int_{-\infty}^r \frac{1}{\sqrt{2\pi s x}} \cdot \exp\left(\frac{-\ln^2 x}{2s^2}\right) dx. \quad (5.6)$$

The corresponding graphical representation of the PDF and CDF presented in figure 5.1.

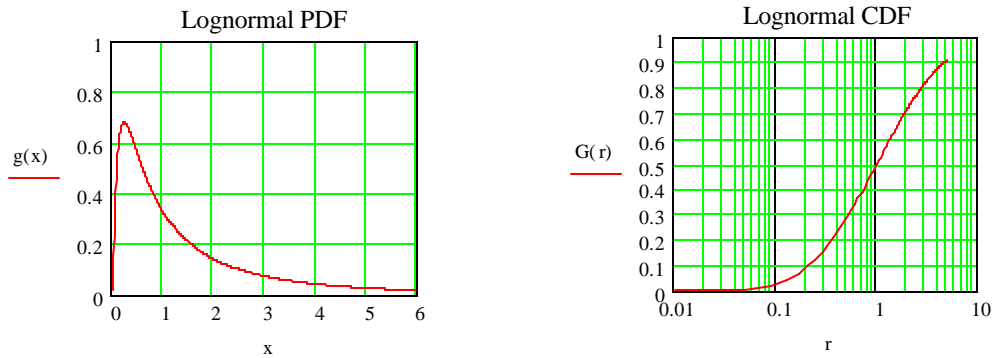


Figure 5.2. Lognormal Random Variable

In this analysis the variance of 8dB is chosen.

5.3 Small Scale Fading

Small scale fading deals with large dynamic variations in the received signal amplitude and phase as a result of small changes in the spatial separation between the transmitter and receiver. In radio channel, small scale fading will appear superimposed on a large scale fading. Small scale fading changes rapidly and the dynamic behavior of receiver subsystems such as tracking loops, equalizers as well as the bit error rate (*BER*) of the system will be affected significantly by the behavior of small scale fading. Hence, much effort in modeling and simulating of wireless channel is focused on this type of fading.

In a multipath channel a received signal is superposition of a large number of reflected waves. All reflected waves are assumed to add coherently. The received signal is in the simplified form of equation 2.2,

$$s(t) = I \cos(w_c t) + Q \sin(w_c t) \quad (5.7)$$

where I and Q are the in-phase and quadrature components of the signal $s(t)$, respectively. They consist of many reflections and are independent Gaussian distributed random variables with identical probability density functions, with zero mean and variance equal to the local-mean reflected power \bar{p} . Due to the large number of obstacles to the propagations in the indoor environment the line-of-sight components are negligible, so the instantaneous power of the interfering signal

$$p = \frac{1}{2} \mathbf{r}^2 = \frac{1}{2} I^2 + \frac{1}{2} Q^2 \quad (5.8)$$

is exponentially distributed, equation 5.9a, about the local-mean power \bar{p} , and the envelope amplitude \mathbf{r} has Rayleigh Probability Density Function (PDF), equation 5.9b.

$$(a) \quad f_p(p/\bar{p}) = \frac{1}{\bar{p}} \exp\left(-\frac{p}{\bar{p}}\right)$$

$$(b) \quad f_r(\mathbf{r}/\bar{p}) = \frac{1}{\bar{p}^2} \exp\left(-\frac{\mathbf{r}^2}{2\bar{p}^2}\right) \quad (c) \quad F(r) = 1 - \exp\left(-\frac{r^2}{\bar{p}^2}\right) \quad (5.9)$$

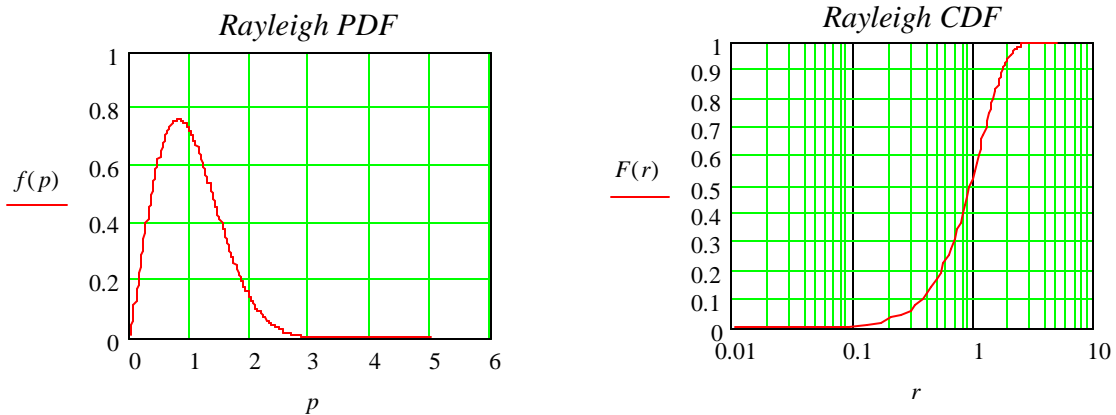


Figure 5.3. Rayleigh Random Variable

5.4 Channel Noise

The noise at the receiver's antenna can be divided into two categories: in-band and out-of-band noise. Both in-band and out-of-band noise can degrade the performance of a wireless communication system. Out-of-band noise can usually be filtered out because the energy in the system's frequency band does not carry any useful information. In band noise is much more problematic.

Noise can be categorized as either "white" or "colored." White noise generally describes "wideband" interference from multiple sources without any coordination between them. It can be modeled as Gaussian random process where successive samples of the process are statistically uncorrelated. Typically, the energy associated with white noise is distributed evenly across the frequency band and does not have any deterministic behavior over time or frequency. It is called the Additive White Gaussian noise (AWGN) and is determined by the product of Boltzman constant (k), the environmental temperature ($T= 293K$) given in Kelvin Degrees and bandwidth of the system. The noise power spectral density is

$$N_0(dB) = 10\log\left(\frac{k \cdot T \cdot BandWidth(1Hz)}{1Watt}\right) = -174dB \quad (5.10)$$

Colored noise is usually "narrow band" interference transmitted by intentional radiators and has a specific behavior in time and frequency; Bluetooth radios create exactly that kind of noise. The total noise in the IEEE 802.11b system is

$$N_{total}(dB) = N_0(dB) + N_{bluetooth}(dB) \quad (5.11)$$

Chapter 6

The IEEE 802.11b Performance in Multipath Wireless Channel

6.1 Introduction

Before introducing Bluetooth into the system we analyze the performance of the IEEE 802.11b system in the indoor environment, regardless of location (household or office).

802.11b modem can operate at four different data rates 1, 2, 5.5 and 11Mbps.

Varying the modulation and the channel coding techniques produces these data rates.

Performance of the modulations associated with these data rates in the AWGN has been discussed in chapter 2, and were described by its corresponding Probability of Bit Error (P_e or BER) curves. However, in order to evaluate performance of particular modulation in the presence of fading channel, it is necessary to average the $P_e(x)$ of the modulation in AWGN channels over the possible ranges of signal strengths due to fading. Hence, the P_e in multipath Rayleigh channel can be obtained by averaging the $P_e(x)$ in AWGN channels over the fading probability density function of Rayleigh channel given in equation 5.9a. The total probability of bit error formula is

$$P_e = \int_0^{\infty} P_e(x) \cdot f(x) dx , \quad (6.1)$$

where $P_e(x)$ is the probability of error for an arbitrary modulation at a specific value of signal to noise ratio x in AWGN and $f(x)$ is the probability density function of x due to the fading channel. For this analysis the signal to noise ratio is represented in the equation 2.1, where the energy per chip depends on the distance between the transmitter and receiver, which in turn varies from 1 to 100 meters.

Also, equation 2.1 depends on the chip rate of the system; consequently, for every transmission rate that quantity is going to be the same. The difference is going to be in the number of chips used to represent one bit, which means that energy per bit to noise ratio is going to differ from one data rate to another.

6.2 DBPSK Performance

The data rate of 1Mbps is reached under the differential binary phase shift keying modulation. Every transmitted bit is encoded (spread) into 11-chip Barker symbol. Chips are transmitted at 11Mchips/s for consequent data rate of 1Mbps. Bit error probability for DBPSK modulation in AWGN is represented by the equation 2.4 and the multipath fading wireless channel is modeled by the Rayleigh distribution, equation 5.9a. Consequently, the total P_e of the DBPSK system in the Rayleigh multipath channel is

$$\begin{aligned}
 P_e &= \int_0^{\infty} \frac{1}{2} \cdot \exp(-x) \cdot \frac{1}{E_b/N_0} \cdot \exp\left(-\frac{x}{E_b/N_0}\right) dx = \\
 &= \frac{1}{2} \cdot \frac{1}{E_b/N_0} \cdot \int_0^{\infty} \exp\left(-x \cdot \left(\frac{1 + E_b/N_0}{E_b/N_0}\right)\right) dx = \\
 &= \frac{1}{2 \cdot \left(1 + E_b/N_0\right)}
 \end{aligned} \tag{6.2}$$

where E_b is the energy per bit, E_c is the energy per chip, and $E_b = 11 \cdot E_c$ for the DBPSK modulation.

6.3 DQPSK Performance

The data rate of 2Mbps is reached with differential quadrature phase shift keying modulation. Every 2 transmitted bits are encoded (spread) into 11-chip symbol. Each symbol is generated by Barker code. Chips are transmitted at 11Mcps for consequent data rate of 2Mbps. Probability of chip error for DQPSK modulation is represented by the equation 2.5. The probability of bit error, $P_e(x)$, in AWGN is represented by the equation 5.9b and the multipath fading wireless channel is modeled by the Rayleigh distribution, equation 5.9a. .

Consequently, the total P_e of the DQPSK system in the Rayleigh multipath channel is

$$P_e = \int_0^{\infty} \left(Q_1(a, b) - \frac{1}{2} I_0(ab) \exp\left(-\frac{1}{2}(a^2 + b^2)\right) \right) \cdot \frac{1}{E_b/N_0} \cdot \exp\left(-\frac{x}{E_b/N_0}\right) dx \quad (6.4)$$

where $Q_1(a, b)$ is the Marcum Q function, $I_0(ab)$ is the modified Bessel function of zero order and parameters a and b are defined as

$$a = \sqrt{\frac{2E_b}{N_0} \cdot \left(1 - \sqrt{\frac{1}{2}}\right)} \quad \text{and} \quad b = \sqrt{\frac{2E_b}{N_0} \cdot \left(1 + \sqrt{\frac{1}{2}}\right)}$$

where E_b is the energy per bit, E_c is the energy per chip, and $E_b = 5.5 \cdot E_c$ for the DQPSK modulation.

6.4 CCK Performance

For the CCK modulation the P_e formula for M-ary Bi-Orthogonal Keying is used. To reach the data rate of 5.5Mbps every 4 transmitted bits are encoded (spread) into 8-chip symbol. Each symbol is generated by a Walsh code. Chips are transmitted at 11Mcps for consequent data rate of 5.5Mbps. To reach the data rate of 11Mbps every 8 transmitted bits are encoded into the 8-chip symbol. Probability of error for the CCK modulation in AWGN is described by the equation 2.6. Consequently, the total P_e of the system in the multipath channel is

$$P_e = \int_0^{\infty} \left[1 - \int_{-x}^{\infty} \left(\frac{1}{\sqrt{2p}} \cdot \int_{-(v+x)}^{v+x} \exp\left(-\frac{y^2}{2}\right) dy \right)^{\frac{M}{2}-1} \cdot \exp\left(-\frac{v^2}{2}\right) dv \right] \cdot \frac{1}{2 \cdot \bar{p}} \exp\left(-\frac{x}{2 \cdot \bar{p}}\right) dx \quad (6.5)$$

Since calculation of P_e is performed for more then a hundred values of distance, the use of the above formula is time consuming and inefficient. For my calculations I have replaced it by its approximation [5],

$$P_e = \frac{2^{k-1}}{2^k - 1} \left(\sum_{m=1}^{M-1} \frac{(-1)^{m+1} \binom{M-1}{m}}{1 + m + m8\Gamma} \right), \quad (6.6)$$

where $M = \frac{1}{2} \cdot 2^k$, k is a number of bits in the symbol and $\mathbf{G} = \sqrt{\frac{2E_b}{N_0}}$. For the 5.5Mbps

data rate $E_b = 2E_c$. For the 11Mbps data rate $E_b = E_c$, which means that there is no gain from spreading.

6.5 Total Performance

Using the equations for probability of bit error (P_e) in the Rayleigh multipath-fading channel for the four modulation schemes derived in sections 6.2, 6.3 and 6.4, the graphical representation of the P_e can be obtained. The figure 6.1 shows P_e curves in the Rayleigh Multipath Fading channel versus the for the four modulation schemes versus signal power at the receiver.

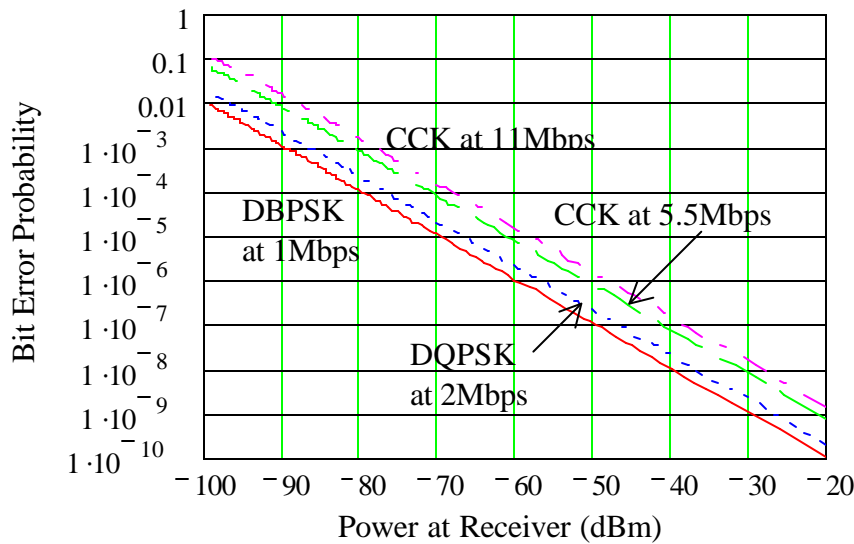


Figure 6.1. Probability of Bit Error

From the figure 6.1 we observe that the DBPSK modulation with data rate of 1Mbps has the best performance, this is due to its great resistance to the multipath fading due to spreading. CCK at 11Mbps has the worst performance, since there is no spreading.

From the figure 6.1, it can be concluded that in order to obtain great throughput provided by the 11Mbps data rate the distance of the operation of the system has to be sacrificed.

If the great distance of operation is essential, than the throughput has to be sacrificed.

Once the P_e of the system is determined it is possible to calculate the packet error rate (PER) formula for the system. In this derivation we will assume that P_e is independent from bit to bit. This is a valid assumption for the indoor office environment, where a multiple reflections, from the walls and furniture of the room, of the original signal are added at the receiver for every bit. The PER is derived in following fashion:

$1 - P_e$, probability of correct reception of one bit,

$\prod_{i=0}^n (1 - P_{e,i})$, probability of correct reception of n bits, where ever bit is received

correctly,

$P^n = (1 - P_e)^n$, probability of correct reception of n bits, where P_e 's are independent,

$1 - P^n$, probability of incorrect reception of n bits,

$$PER = 1 - (1 - P_e)^{\text{number of bits in the packet}} \quad (6.7)$$

By substituting the P_e of every data rate into the equation 6.7 the Figure 6.2 is generated.

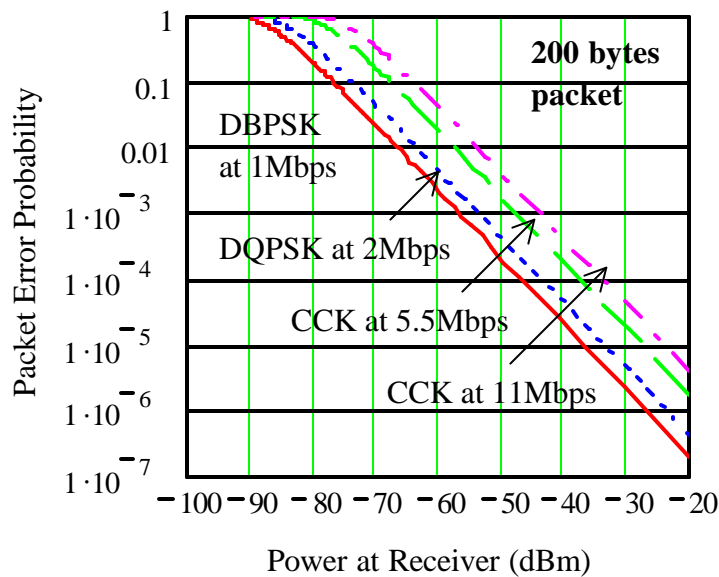


Figure 6.2. Probability of Packet Error

Figures 6.1 and 6.2 are very similar, in 6.2 DBPSK modulation at 1Mbps has the lowest probability of packet error and 11Mbps has the highest *PER*. However, we observe that graphs are shifted, for example, figure 6.1, at -70dBm , 1Mbps data rate had $P_e = 10^{-5}$, at the same signal power at the receiver, figure 6.2, $PER \sim 10^{-2}$, which is 3 orders of magnitude higher. The *PER* of the system is closely related to the number of bits in the packet, which is clearly visible from the equation 6.7; the greater is a packet size the greater is the *PER* of the system.

Chapter 7

Throughput Calculation

7.1 Introduction

In order to determine the throughput of the system it is necessary to analyze the MAC layer of the IEEE 802.11b system; specifically the fact that a Stop-And-Wait is protocol implemented. A data packet consists of overhead (preamble and header) and the data portion. The time to transmit this packet is shown below

$$t_T = DIFS + Overhead + \frac{Data(bits)}{Rate(bits/sec)} + SIFS + ACK \quad (7.1)$$

DIFS, *SIFS* as well as *ACK* frame are considered here because they are necessary to ensure a correct reception of packet. In the Stop-And-Wait protocol [10] if a packet is received in error the receiver does not send an *ACK* back to the sender and waits until the packet is retransmitted. Following is a list of parameters defined by the protocol:

$$SIFS = 10\text{msec}, DIFS = 50\text{msec}, ACK = 112\text{msec}$$

$$Overhead = Preamble + Header = 144\text{msec} + 48\text{msec} = 192\text{msec}$$

$$Rate = 1\text{Mbps or } 2\text{Mbps or } 5.5\text{Mbps or } 11\text{Mbps}$$

$$Data = 1000\text{bytes}$$

<i>Rate</i>	<i>1Mbps</i>	<i>2Mbps</i>	<i>5.5Mbps</i>	<i>11Mbps</i>
<i>t_T</i>	<i>8.4msec</i>	<i>4.2msec</i>	<i>1.6msec</i>	<i>0.9msec</i>

The probability of a packet being received in error is *PER*, derived in the previous chapter, and is replaced by *p* in the following calculation for simplicity. Then, the average time for a correct transmission to be received is given by

$$T_w = t_T + (1-p) \cdot \sum_{i=1}^{\infty} i \cdot p^i \cdot t_T \quad (7.2)$$

This expression indicates that to get to the i th retry the packet must have been delivered in error i times. The probability of receiving it correctly on the i th retry is just $(1-p)$.

Following analysis can be used to simplify equation 7.2.

$$\begin{aligned} (1-p) \cdot \sum_{i=1}^{\infty} i \cdot p^i \cdot t_T &= t_T \cdot p \cdot (1-p) \cdot \sum_{i=1}^{\infty} i \cdot p^{i-1} = t_T \cdot p \cdot (1-p) \cdot \frac{d}{dp} \left[\sum_{i=1}^{\infty} p^i \right] = \\ &= t_T \cdot p \cdot (1-p) \cdot \frac{d}{dp} \left[\frac{p}{1-p} \right] = t_T \cdot p \cdot (1-p) \cdot \frac{1}{(1-p)^2} = \frac{t_T \cdot p}{(1-p)} \\ T_w &= t_T + (1-p) \cdot \sum_{i=1}^{\infty} i \cdot p^i \cdot t_T = t_T + \frac{t_T \cdot p}{1-p} \end{aligned} \quad (7.3)$$

Once formula for the average time for the correct transmission is derived the formula for the throughput can be derived.

$$\text{Throughput (bits/sec)} = \frac{\text{Data}}{T_w} = \frac{\text{Data}}{t_T} \cdot (1 - \text{PER}) \quad (7.4)$$

Once the general formula for the throughput is determined we can apply appropriate *Data* (bits/packet) and *PER* to it and generate graphs for the throughput for four different modulations schemes, Figure 7.1.

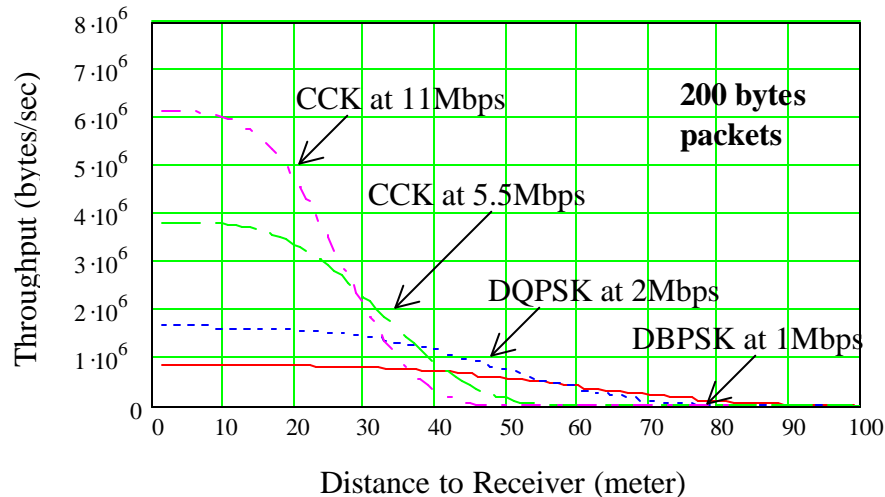


Figure 7.1 Throughput of the IEEE 802.11b system (No Bluetooth)

From the figure 7.1 we can observe the efficiency of each data rate versus distance.

11Mbps gives best throughput for the first 28 meters, then 5.5Mbps performs the best for the next 10 meters, then 2Mbps becomes more efficient for 20 meters and finally at 60 meters 1Mbps gives best throughput.

7.2 Throughput Optimization

One way to optimize the total throughput of the system is to optimize the throughput of each of the data rates. In the previous chapter we concluded that the *PER* of the system depends on the packet size, and the greater the packet size, the greater is *PER*; consequently, controlling the packet size at each of the data rates can accomplish throughput optimization. Fragmentation is allowed in the IEEE 802.11b standard at the MAC layer; so that the fragment size could vary from 100 to 2350 bytes.

Figures 7.2 through 7.5 represent throughputs for the 11, 5.5, 2 and 1Mbps data rates, respectively versus various fragment sizes. Each of the data rates plotted at three distances between transmitter and the receiver. Distances are chosen in consideration with the best operating range of the given data rate. For example, from figure 7.1, 11Mbps data rate is most efficient within the first 30 meters therefore curves of the throughput at 10, 20 and 30 meters are plotted. We observe that for the stations in the area of radius 10 meters from the AP the maximum throughput of 8.5Mbps is reached at maximum possible fragment size of 2350 bytes. For the station located 10 meters further (20m) there is a distinct peak in throughput, 4.8Mbps, at 600 bytes long fragments. Finally, for the stations 30 meters away from AP, 250 bytes fragments are required to reach maximum throughput of 2Mbps.

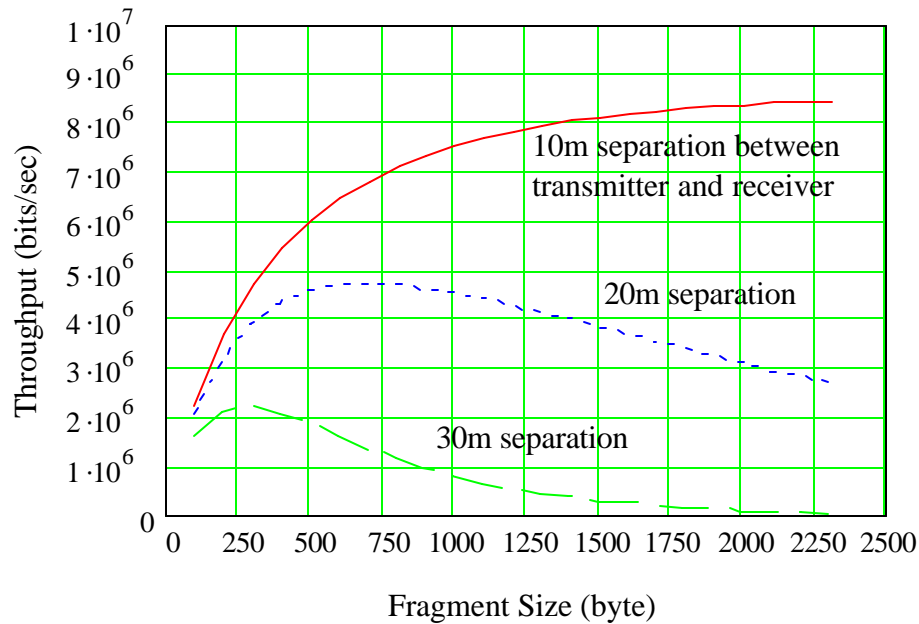


Figure 7.2. Packet optimization for 11Mbps data rate

However, it is not feasible from, the point of few of system design, to accommodate all of the possible fragment sizes. Therefore, I propose to use two different fragment sizes for the transmission at 11Mbps data rate; first is 1250 bytes and another 500 bytes long fragment size. These fragment sizes are chosen as an average fragment size in the area with radius of 1-15 meters and 15-30 meters respectively. Consequently, every packet passed to the MAC layer of the system from the higher layer will be fragmented to either 1250 bytes or 500 bytes depending on which fragment sizes produces better *PER*.

From the figure 7.3, we can conclude that for the 5.5Mbps data rate, an average fragment size would be 250 bytes, to optimize the throughput in the operating range of 30 to 50 meters between the transmitter and receiver.

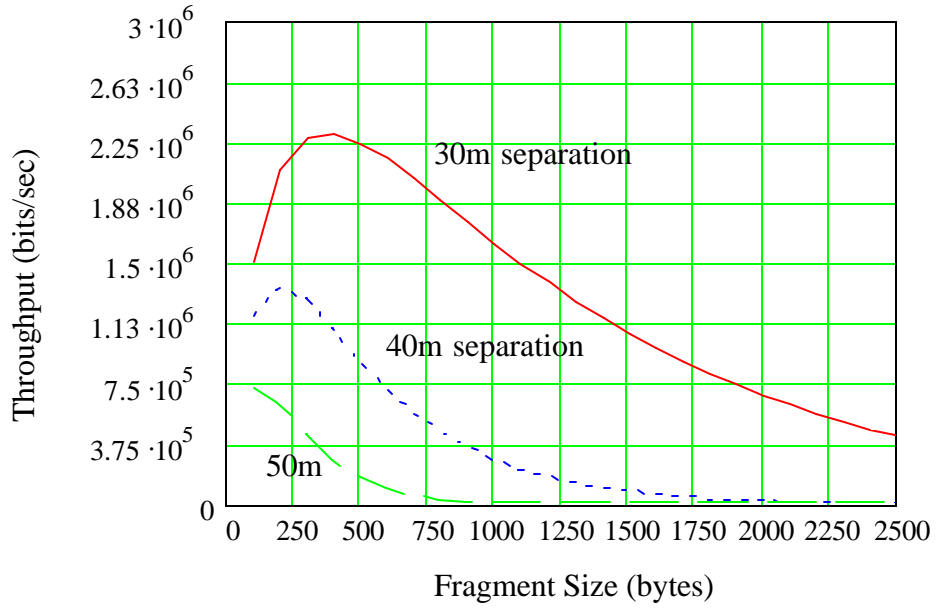


Figure 7.3. Packet optimization for 5.5Mbps data rate

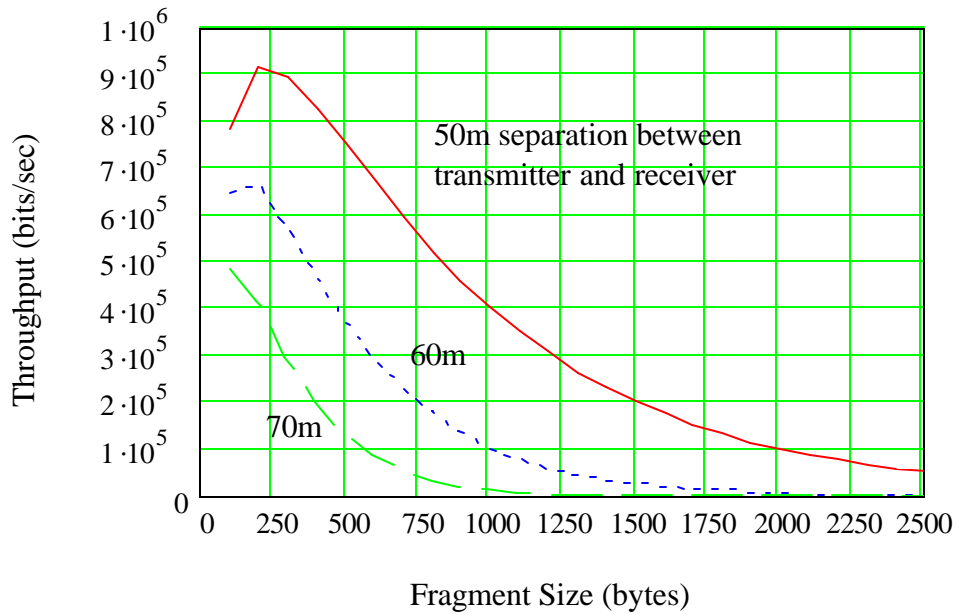


Figure 7.4. Packet optimization for 2Mbps data rate

For the 2Mbps data rate, figure 7.4, the 200 bytes fragments are the most appropriate to reach the optimum throughput requirement on the 50 to 70 meters range of operation.

For the 1Mbps data rate, figure 7.5, the minimum allowed fragment size of 100 bytes will be appropriate to optimize the throughput for the stations located beyond 80 meters from the AP.

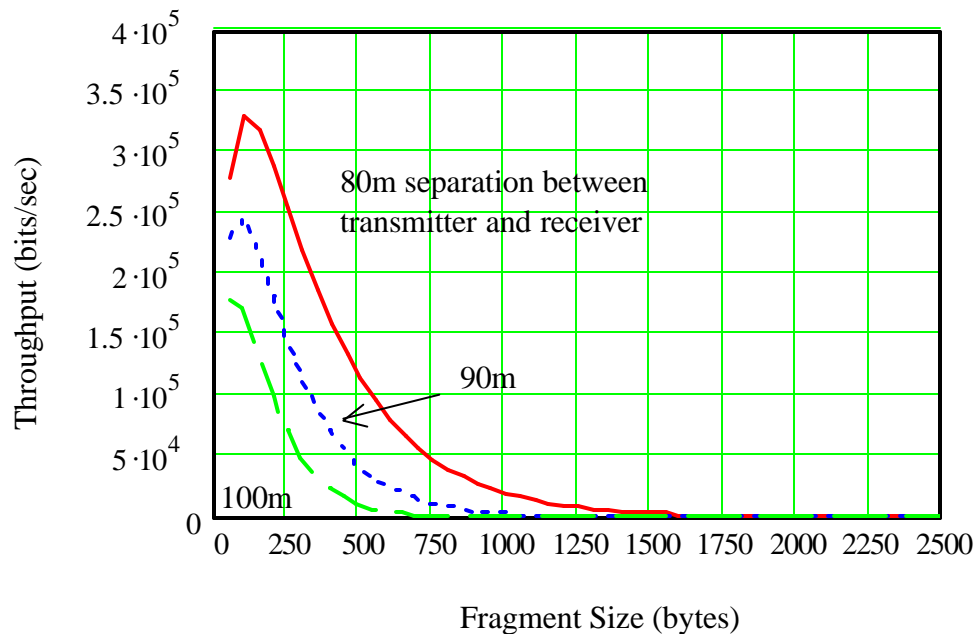


Figure 7.5. Packet optimization for 1Mbps data rate

Figure 7.6 presents an optimized throughput based on the fragment size specific to every data rate. By comparing figures 7.1, where a fixed packet size was used, and 7.6, where fragmentation is employed, we can see that the operating range of the system substantially increased and individually every data rate performs much better.

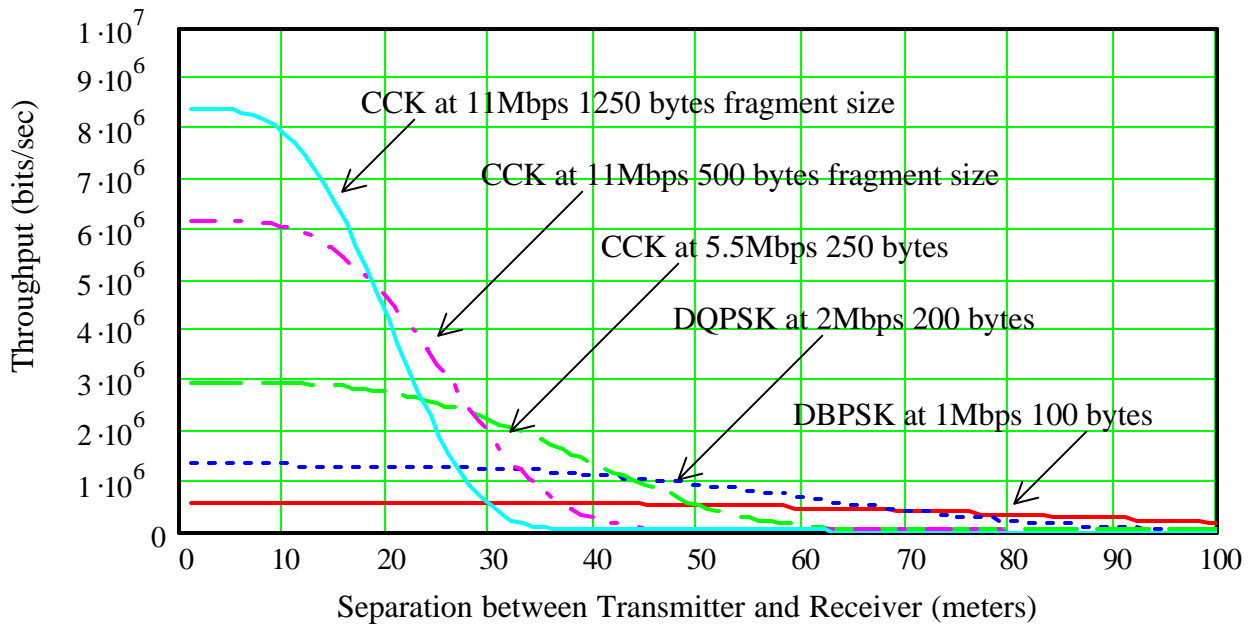


Figure 7.6. Throughput with Optimized Fragment Sizes

For example, for the first 10 meters of operation the throughput of the 11Mbps data rate, figure 7.1, hardly exceed 6Mbps, while optimized system (figure 7.6) have reached a throughput of 8.5Mbps. In addition, 1Mbps data rate could hardly reach 80 meters of operation (figure 7.1), while at the packet fragmented into 100 bytes, could extend system's coverage beyond 100 meters with throughput above 50Kbps. Consequently, the data rate switching with appropriate fragment size for each data rate has to be done.

Table below summarizes results of the analysis.

Best range of operation	1-20 meters	20-30 meters	30-45 meters	45-65 meters	65 -∞ meters
Data Rate/ Fragment Size	11Mbps 1250bytes	11Mbps 500bytes	5.5Mbps 250bytes	2Mbps 100bytes	1Mbps 100bytes
Throughput max/min	8.5Mbps/ 5Mbps	5Mbps/ 2.5Mbps	2.5Mbps/ 1Mbps	1Mbps/ 500Kbps	500Kbps/ 50Kbps

Table 7.1. Throughput Optimization Results

Chapter 8

Impact of Bluetooth on the IEEE 802.11b

8.1 Introduction

The IEEE 802.11b transmissions are affected much more from Bluetooth, then Bluetooth suffers from the 802.11b for number of reasons. Bluetooth is a fast frequency hopping system, 1600hops/sec; it combats the interference by simply avoiding it, jumping to another frequency. The area of operation of the IEEE 802.11b is much larger then the area of operation of Bluetooth, consequently signal strength of the 802.11b transmission attenuates below the power of the Bluetooth transmitter and becomes very susceptible to the interference. An overhead and a packet size are much smaller for Bluetooth as well, which means that very little data will be lost in the case of collision and the retransmission of the Bluetooth packet on a different frequency will occur very rapidly, while it will take longer time for 802.11 packets to be retransmitted.

8.2 Analysis of Interference

For the sake of simplicity I'll assume that there is one Bluetooth piconet is in the vicinity (1-5 meter) of WLAN station. The path loss for the Bluetooth radio signal is the same as for the 802.11b system since they both operate in the same frequency band; the only difference is that Bluetooth transmitter power is 1mW, in contrast to 100mW of 802.11, which is a 20dB difference.

We can define signal to noise ratio at the 802.11b receiver as following,

$$\frac{E_c}{I_{BT}} = \frac{\text{Signal power from AP}}{(\text{Noise Power} + \text{Signal power from BT interferer}) \cdot \text{Chip Rate}} \quad (8.1)$$

Now we can evaluate Signal to Noise ratios for various distances and derive bit error probability (P_e) of the 802.11b system in case of collision with Bluetooth. It makes no sense to display these curves because all values for all data rates are in the range of 0.495--0.5. The main interest is the probability of packet error. In order to determine PER we must integrate MAC and PHY layers of the systems. The probability of collision between the 802.11b packet and a packet from a Bluetooth piconet represented at the MAC layer is P_c and at the PHY layer is P_e , which we have found in chapter 5. Figure 8.1, below, depicts all of the parameters involved in the calculation of the PER .

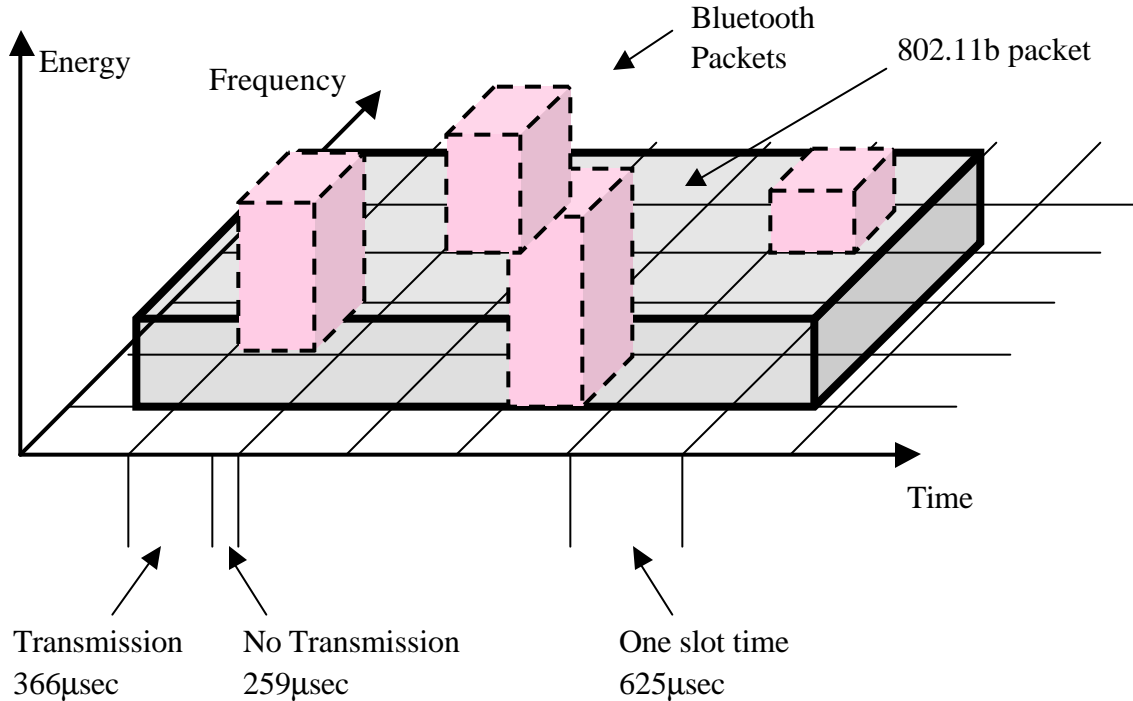


Figure 8.1. Components of Collision

From figure 8.1 we observe 802.11b packet affected by the interference from four Bluetooth packets. In order for the 802.11b and Bluetooth transmissions to collide, there have to be overlap in frequency and time. In order to have a bit error the signal to noise ratio $\left(\frac{E_c}{I_{BT}} \right)$ have to be sufficiently low. Combining probabilities all of these factors we are generating a total packet collision probability, PER .

Using simplified diagram below we can analyze the collision and to derive a formula for the PER of the IEEE 802.11b system in the Bluetooth environment.

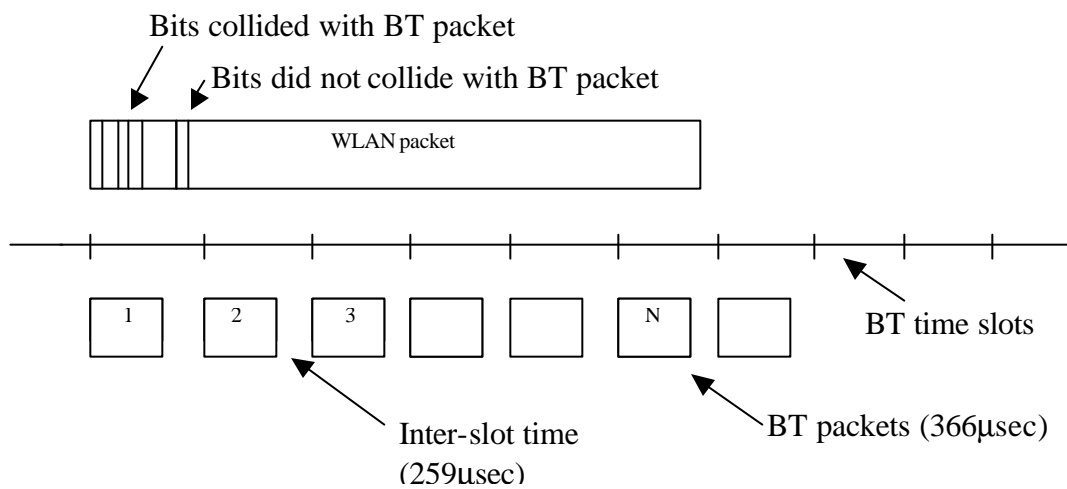


Figure 8.2. Collision in Time

The Bluetooth transmission is divided into the slot times, 625µsec long. However, the transmission is only 366µsec of the total slot time, and the remaining 259µsec of inter-slot time are silence. Taking this aspect of Bluetooth MAC layer architecture into the consideration we first find the slot error rate (SER) for the 802.11b system and then convert it into the PER .

$$SER = P\{Bad_Slot\} = 1 - P\{Good_Slot\}$$

$$P\{Good_Slot\} = P\{Good / Collision\} \cdot P_c + P\{Good / NoCollision\} \cdot (1 - P_c)$$

$$P\{Good / NoCollision\} = (1 - P_e\{No BT interference\})^{\text{bits in } 625\mu\text{s}}$$

$$P\{Good / Collision\} = \underbrace{(1 - P_e\{BT interference\})^{\text{bits in } 366\mu\text{s}}}_{\text{first term}} \cdot \underbrace{(1 - P_e\{No BT interference\})^{\text{bits in } 259\mu\text{s}}}_{\text{second term}}$$

The first term of the equation above describes probability of WLAN packet to be good for the first 366μsec (Bluetooth packet and AWGN) of Bluetooth time slot. The second term is the probability of WLAN packet to be good for the remaining 259μsec (only AWGN). The probability of collision at MAC layer, $P_c = m \cdot \frac{1}{3}$, where m is utilization of the Bluetooth system or probability that there is Bluetooth packet in the given time slot, and $\frac{1}{3}$ is a probability that the IEEE 802.11b packet and Bluetooth packet are going to interfere in frequency domain, since there are three non-overlapping collocated channels that 802.11b system can operate in.

Now we are ready to determine the packet error probability, PER .

$$P\{Good\ 802.11b\ Packet\} = P\{Good\ Slot\}^N$$

$$PER = 1 - P\{Good\ 802.11b\ Packet\} \quad (8.1)$$

N is the number of consecutive Bluetooth time slots that have data to transmit that 802.11b packet is going to overlap. N is calculated by dividing transmission time of 802.11b packet (t_T) by the Bluetooth time slot (625μsec). The longer is the transmission time, the greater is probability of overlap in time. We can deduce from this that

transmission of lower data rates, 1 and 2Mbps, which require longer time to transmit a packet will suffer much more from the Bluetooth, then the higher data rates, 5.5 and 11Mbps.

The equation 8.1 can be extended further to accommodate multiple Bluetooth piconets in the vicinity (1-5 meters) of the 802.11b station, which is characteristic to the office environment,

$$PER_{multiple\ piconets} = 1 - (1 - PER)^n,$$

where n is the number of interfering BT piconets,

Finally, if we set the packet size of 802.11b system to 500 bytes, the number of Bluetooth piconets to 1 (simple household environment), the utilization (μ) of the Bluetooth piconet to 0.3 (phone conversation), we obtain PER data in Figure 8.3.

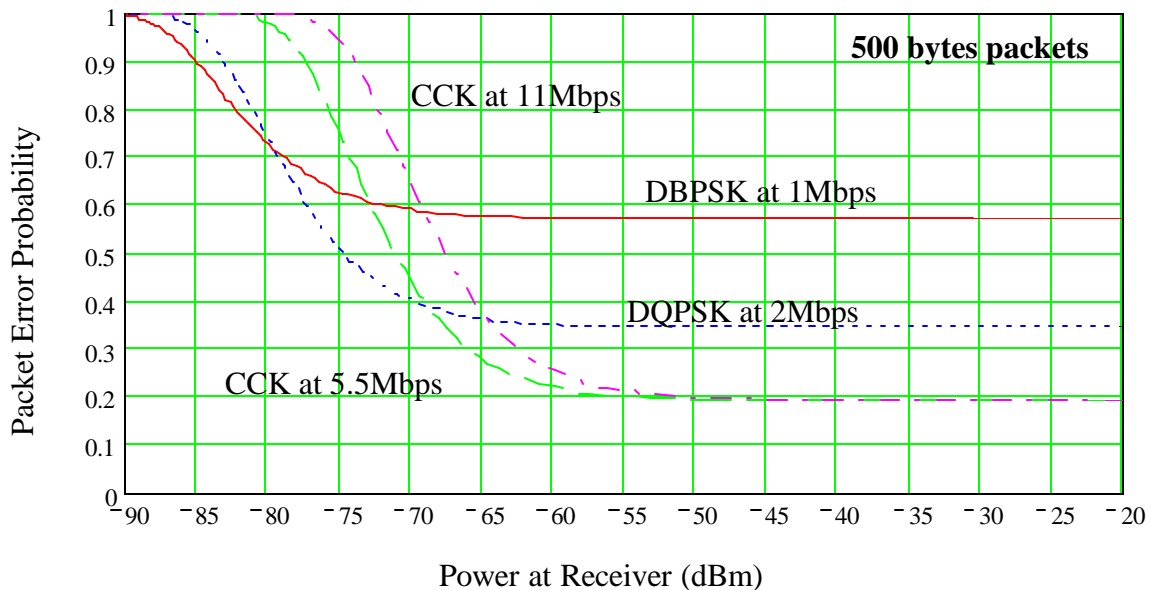


Figure 8.3. PER of 802.11b in Bluetooth environment

From the figure 8.3 we observe that the *PER* does not go below 0.1, which is very high *PER*. By comparing figures 6.2 and 8.3 we observe that at the higher signal strengths *PER* for 5.5 and 11Mbps data rates are much lower than 1 and 2Mbps, which confirms our previous observation, that Bluetooth has greater impact on the lower data rates. A surprising result in figure 8.3 is that 5.5 and 11Mbps have the same performance at higher energies. Another surprising result is that 1 and 2Mbps systems still have slightly better performance than 5.5 and 11Mbps at lower signal strengths, but for *PER* > 0.5 this improvement is of no practical value.

By observing the throughput curve of the IEEE 802.11b system in the presence of one Bluetooth piconet, Figure 8.4, we conclude that even though the packet error rates for 5.5 and 11Mbps are the same for higher energies, the throughput of 11Mbps is much greater than that of 5.5Mbps, due to the greater data transmission rate.

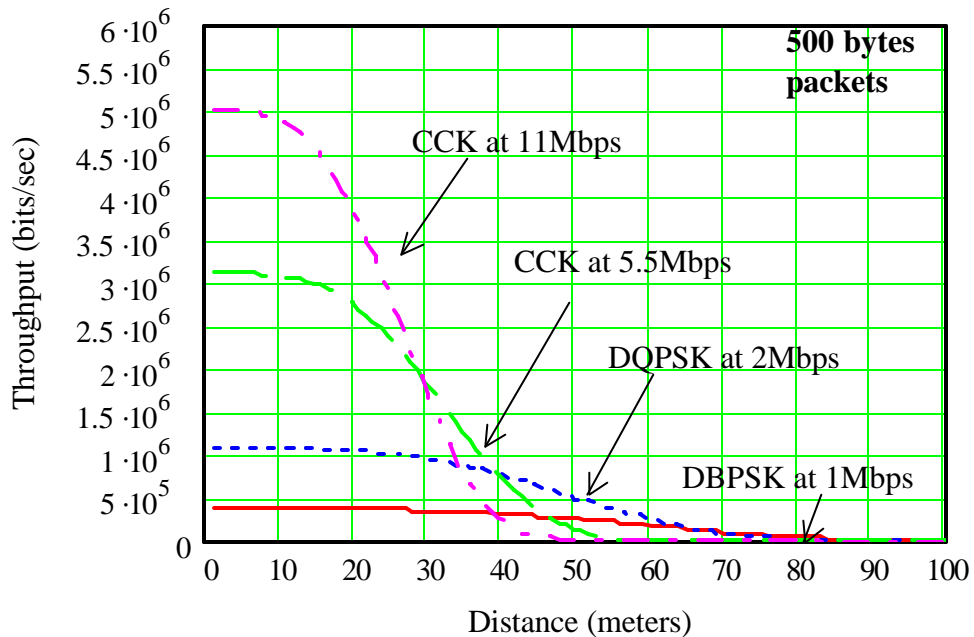


Figure 8.4. Throughput of the 802.11b system in a presence of one interfering piconet

The cases above involves a single Bluetooth piconet at 1-5meter distance from the 802.11b station, where Bluetooth radios have transmissions one third of time ($m = 1/3$).

Next we observe the effects of three interfering piconets in the vicinity (1-5 meters) of the WLAN station.

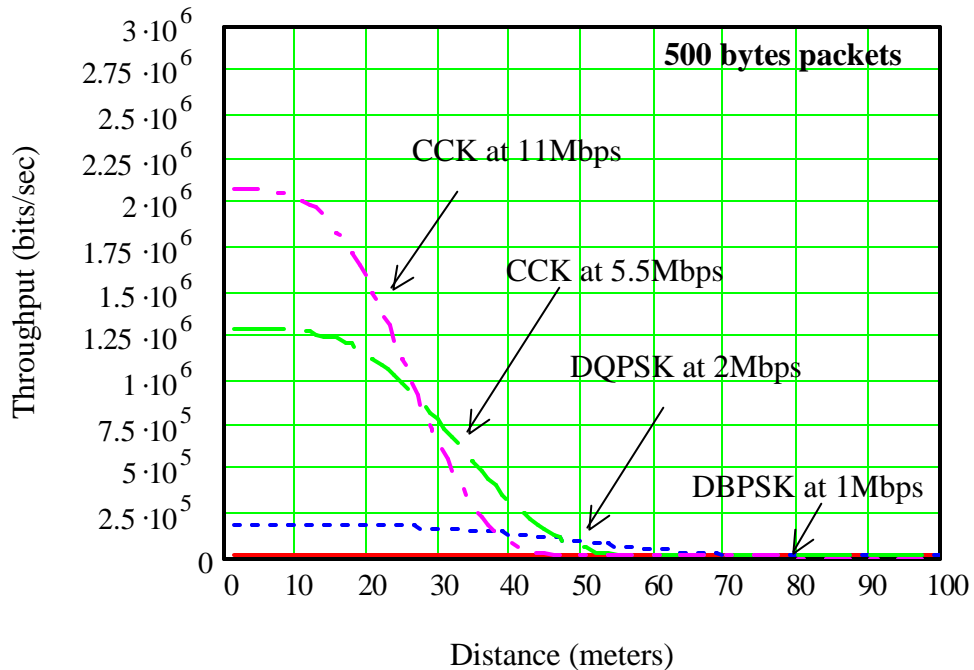


Figure 8.5. Throughput of the 802.11b system in a presence of three interfering piconet

The increase in the number of piconets, Figure 8.5, leads to complete annihilation of 1Mbps, drastic reduction in the throughput of 2Mbps data rates, and decrease by 5Mbps in the throughputs of 11 and 5.5Mbps systems. However we can still observe the graceful degradation in the throughput of the network with respect to distance. In addition, distinct divisions between higher data rates are present.

8.3 Throughput Optimization

Considering the analysis of the previous chapter, the optimization by packet fragmentation produced a considerable improvement in the system's throughput. Let's employ the same technique that was used in section 7.2 to optimize the throughput of the IEEE 802.11b system in the presence of a single Bluetooth interferer. This scenario is analogous to the household or a small office environment. Let's consider one Bluetooth piconet present in the vicinity, 1-5 meters, from the 802.11b station.

Figure 8.6 the represents throughput for the 11Mbps data rate for three distances (10, 20, 30 meters) between the 802.11b transmitter and receiver.

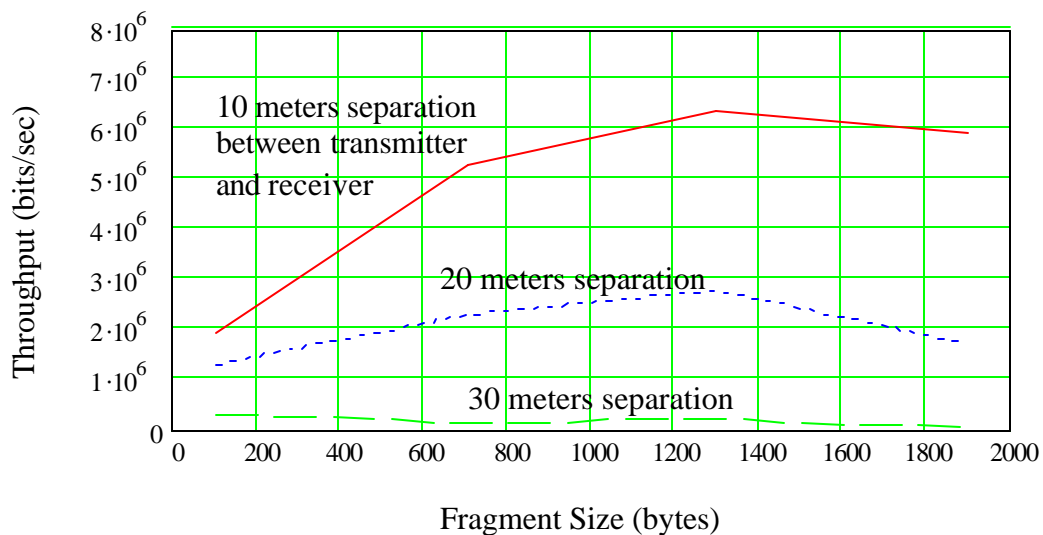


Figure 8.6. Optimization of the 11Mbps in presence of Bluetooth

Applying analysis introduced in section 7.2 an average packet size that will optimize the throughput at this data rate is 1300 bytes for all distances.

In figure 8.7 we observe the throughput for 5.5Mbps data rate at 30, 40 and 50 meters separation between the transmitter and receiver. An average fragment size that produces a good throughput for all three distances would be 200 bytes.

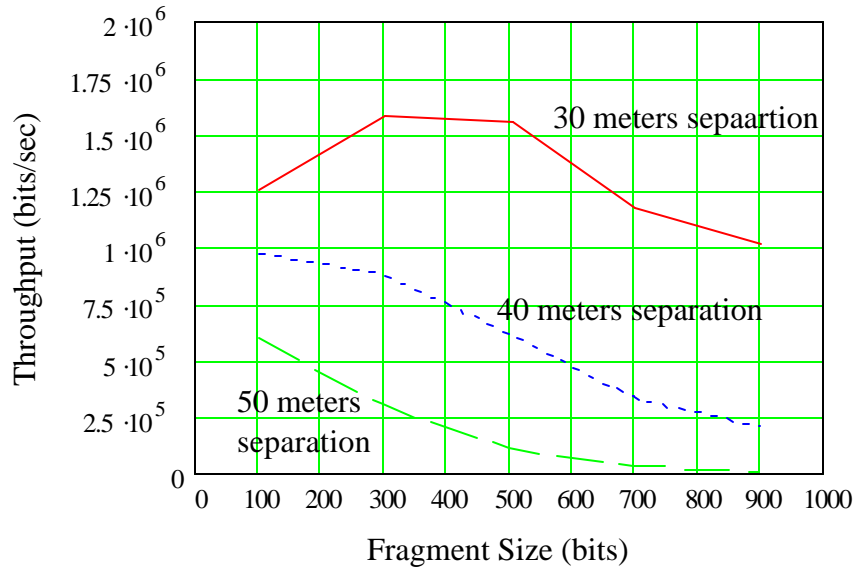


Figure 8.7. Optimization of the 5.5Mbps in presence of Bluetooth

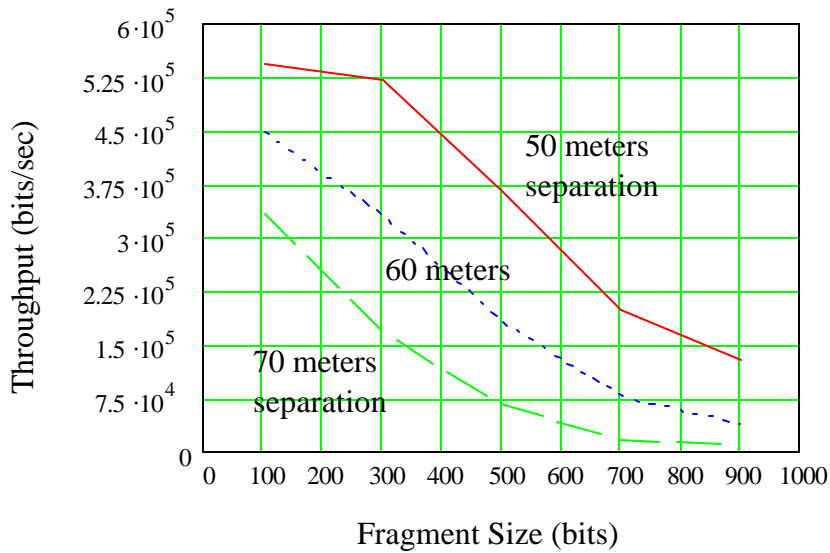


Figure 8.8. Optimization of the 2Mbps in presence of Bluetooth

In figure 8.8 we observe the throughput for 2Mbps data rate at 50, 60 and 70 meters separation between the transmitter and receiver. An average fragment size for all three distances would be 100 bytes.

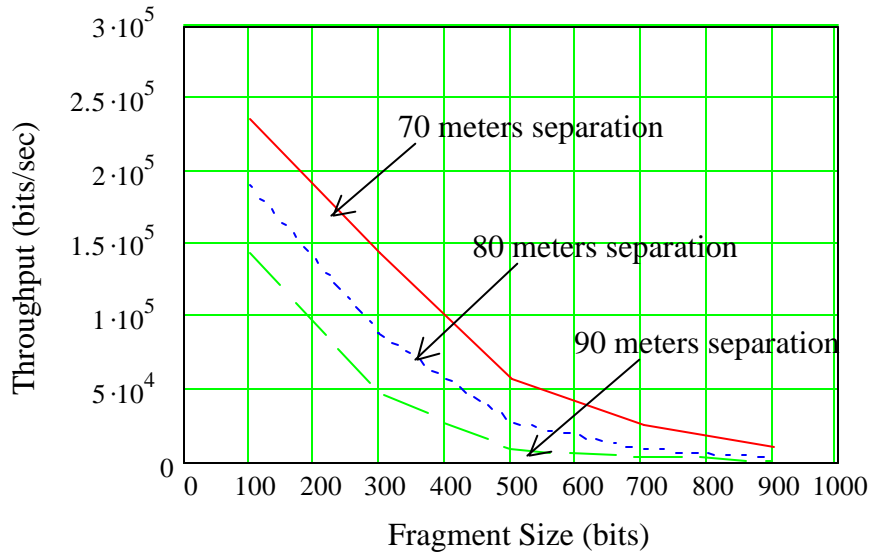


Figure 8.9. Optimization of the 1Mbps in presence of Bluetooth

In figure 8.9 we observe the throughput for 1Mbps data rate at 70, 80 and 90 meters separation between the transmitter and receiver. An average fragment size for all three distances would be 100 bytes, which is the smallest possible fragment size allowed by the standard.

Now lets combine the results of the previous calculation and derive final optimized throughput curve for all distances.

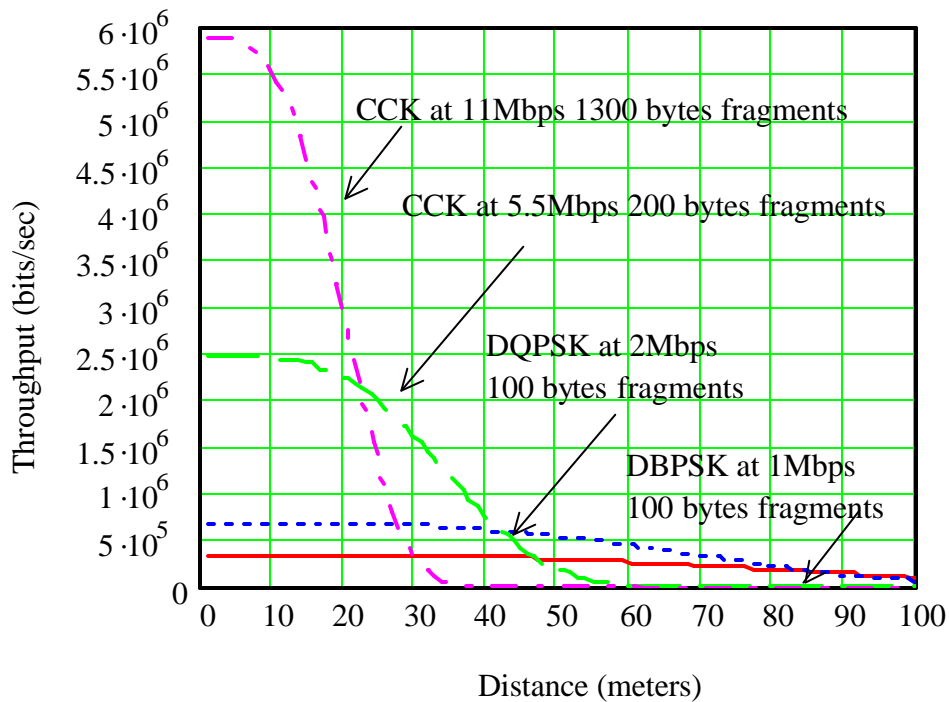


Figure 8.10. Optimized throughput of the 802.11b system in a presence of single Bluetooth

By comparing figures 8.4 and 8.10, we observe that the operating range of the system substantially increased, as well as individual throughputs. For example, for the first 10 meters of operation the throughput of the 11Mbps data rate, figure 8.4, does not exceed 5Mbps, while optimized system (figure 8.10) have reached a throughput of 6Mbps. In addition, 1Mbps data rate could hardly reach 80 meters of operation (figure 8.4) with 500 bytes packets, while at the packet fragmented into 100 bytes, could extend system's coverage beyond 100 meters with throughput above 50Kbps even in the presence of interfering Bluetooth. One more important factor has to be noted; fragmentation plays especially important role in this scenario, where we have interference from Bluetooth. The shorter is 802.11b packet, the faster it is going to be transmitted, consequently there is a lesser chance that it is going to collide with Bluetooth packet.

Consequently, the data rate switching with appropriate fragment size for each data rate has to be done. Table below summarizes results of the analysis.

Best range of operation	1-25 meters	25-45 meters	45-80 meters	80 - ∞ meters
Data Rate/ Fragment Size	11Mbps 1300bytes	5.5Mbps 200bytes	2Mbps 100bytes	1Mbps 100bytes
Throughput max/min	6Mbps/ 2.5Mbps	2.5Mbps/ 750kbps	750kbps/ 250kbps	250Kbps/ 50Kbps

Table 8.1. Throughput Optimization Results

Chapter 9

Performance in the Office Environment

9.1 Introduction

The analysis performed in the previous chapters was oriented toward a household or a small office environment; it involved a single BSS including one AP, one STA and few Bluetooth piconets. However, as it was already proposed in the chapter 4 there is a need for a complete analysis of all plausible network implementations and a large office environment provides a unique atmosphere for such analysis.

9.2 Performance Analysis

As proposed in section 4.3, as the distance between AP and STA increases, the signal strength at the STA becomes weaker and consequently, the number of interfering BT piconets becomes greater. Since we introduced an office topology in chapter 4, we can estimate the number of interfering Bluetooth piconets for any distance between the transmitter and receiver. Once we know the number of interfering piconets we can plot the throughput graphs for different data rates in the office environment. In figure 9.1 we present the throughput for four data rates in the large office environment. The results from chapter 8 are used here as well, so that optimized fragment sizes are used for every data rate.

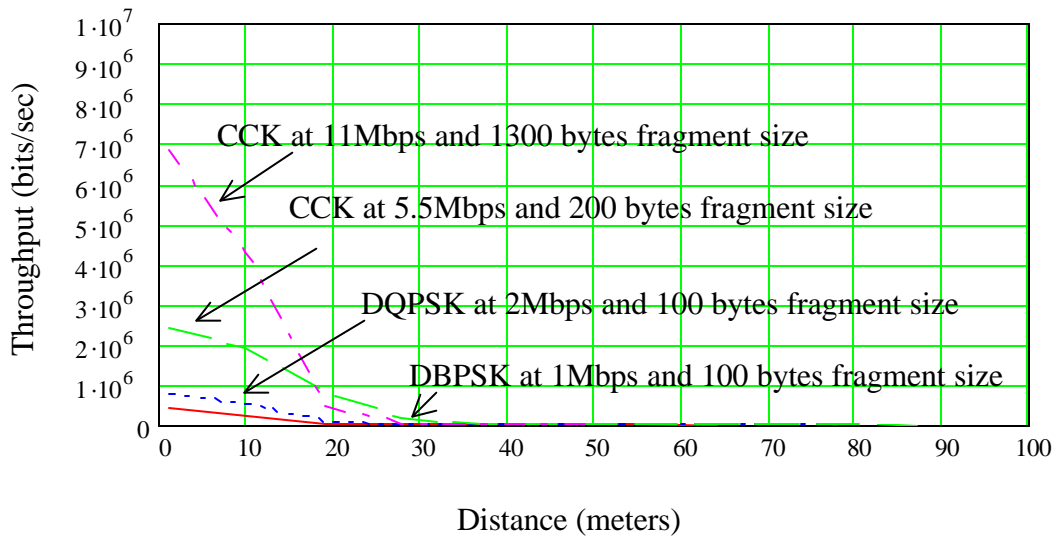


Figure 9.1. Throughput of the 802.11b in Office Environment

From the graph 9.1 we can see that large office environment is an extreme case where drastic throughput degradation is present for all data rates, as well as range of operation is reduced dramatically. The 11Mbps data rate is the most effective of all data rates in the present conditions, because of the shortest transmission time. CCK at 11Mbps provides the highest throughput for the 25-30 meters area.

Consequently, for the office environment with uniform Bluetooth piconet distribution it is efficient to divide all of the office area into the cells, 25-30 meter in radius, with AP in the center and operating at a fixed 11Mbps data rate with 1300 bytes fragment size.

Chapter 10

Summary, Conclusions and Future Work

The objective of the research disclosed in this thesis was to develop a model for performance analysis of the IEEE 802.11b system in the presence of the interfering Bluetooth radio transmissions. Throughout this thesis a model that captures the performance impact of Bluetooth interference on the IEEE 802.11b packet reception, parameterized by the IEEE 802.11b data rate, packet size, the number of Bluetooth piconets and the piconet utilization, as well as distance between the collocating IEEE 802.11b and Bluetooth radios has been developed.

The indoor radio channel was defined and its impact of the IEEE 802.11b system was analyzed. Modeling of the wireless channel is done in a statistical fashion. The most essential components of the wireless channel such as path loss, shadowing, multipath fading and noise were described and their impact was analyzed.

The model comprised analysis of both PHY and MAC layers of the 802.11b systems. At the PHY layer the probability of the bit error for the various IEEE 802.11b data rates was derived. At the MAC layer the probability of Bluetooth transmitter overlapping in both time and frequency with 802.11b Direct Spread packet was calculated.

Various types of environments were reviewed and system performance was analyzed for each of them. The optimization technique for the performance optimization was introduced and its effect of the system was determined.

The effect that collocated Bluetooth radios have on the IEEE 802.11b system is quite impressive, especially in the large office environments. In this environment the operation of the 1Mbps and 2Mbps data rates is completely suppressed by the heavy interference, and only 11Mbps data rate with short packet transmission time provides reasonable throughput for a 30-meter radius area. In the household environment, where Bluetooth distribution is very scarce the IEEE 802.11b system can operate at all for data rates, thus providing long operating range.

The analysis developed in this thesis is quite generic and can be used to analyze interference issues between other kinds of wireless systems, in the indoor as well as outdoor environments. By varying modulation techniques, channel coding schemes as well as shadow and multipath fading distributions the analysis can be applied to other wireless systems.

In regard to interference analysis between the IEEE 802.11b system and Bluetooth, a study of the reverse effect, namely impact of the IEEE 802.11b transmission on the Bluetooth system, can extend this work.

The results of this research suggest a need for a rate switching algorithm, where switching is going to be based on the probability of packet error. Also, packet fragmentation for every data rate must be used to achieve throughput optimization.

In addition, the results of this research suggest a need for some sort of algorithm for controlling the interference between the systems. For example a medium sensing and channel access scheme added to the IEEE 802.11b standard for detecting Bluetooth presence and regulating channel access for both systems, thus preventing interference.

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