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Voice Performance Evaluation of BLUETOOTH System in the Presence of IEEE802.11b WLAN System

By
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Abstract

This thesis uses the protocols of IEEE 802.15 (BLUETOOTH) and IEEE 802.11b (WLAN) to develop a BLUETOOTH radio system model on an OPNET platform. Typically, the wireless model is a simple model of BLUETOOTH technology implemented in C programming language, and assisted by the MATLAB programming language. In the environment, the WLAN, piconets, medical or microwave facilities may affect the performance of the BLUETOOTH system. In this thesis, IEEE 802.11b WLAN and piconets will be investigated and implemented as the interference sources in the simulation environment.

The goal of the radio simulation is to explore the voice performance, under the limitations and restrictions of the current BLUETOOTH technology specifications. The performance is evaluated in terms of packet throughput, which is the packet loss rate of BLUETOOTH, and the quality of voice in terms of the MOS rating. This simulation will hopefully help the BLUETOOTH system designers and decision-makers in gaining insight into the system performance analysis and enable them to get a better solution for some designing issue.

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I am deeply grateful to Dr. Oliver Yang, my supervisor, for his knowledgeable guidance, helpful comments and suggestions, as well as the scientific approach of research work and documentation. I would also like to express my appreciation to members of CCNR in the University of Ottawa from whom I can learn the advanced wireless technologies. I am thankful to my colleagues in our research lab for their fruitful discussions and always being available to the constant help.

I owe a great debt of thanks to my wife, Hong Yu, for her understanding, encouragement, and endless support without which this work may never have been undertaken.

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Table of Abbreviations and Acronyms

Term	*Definition*	*Section No. of 1st appearance*
ACL	Asynchronization Link	2.3
A/D	Analog to Digital conversion	1.4
ADPCM	Adaptive Differential Pulse Code Modulation	5.2
AWGN	Additive White Gaussian Noise	1.1.4
BER	Bit Error Rate	1.1.2
BPSK	Binary Phase Shift Keying	1.2
BSIG	The BLUETOOTH Special Interest Group	1.1.1
BTCP	BLUETOOTH Topology Construction Protocol	1.1.1
BT-rate	BLUETOOTH packet-lost-rate	4.2.3
CCK	Complementary Code Keying	1.1.2
CCNR	Computer Communication Network Research group	Title page
CRC	Cyclic Redundancy Check	2.6.2
CVSD	Continuous Variable Slope Delta Modulation	1.1.3
DCF	Distributed Coordination Function	2.2
DIFS	Distributed Inter-Frame Space	2.2
DSSS	Direct Sequence Spread Spectrum	2.2
FEC	Forward Error Correction	2.1
FHSS	Frequency Hopping Spread Spectrum	2.2
GFSK	Gaussian Frequency Shift Keying	1.1.4
GSM	Global System Mobile	1.1.3
HCI	Host Control Interface	2.3
L2CAP	The Logic Link Control and Adaptation Protocol	1.4
LC	Link Control	2.6.2
LOS	Length Of sight	3.1.3
LMP	Link Manager Protocol	2.3
MAC	Medium Access Control	1.4
MATLAB	A software that can help you to do analysis	1.4
MOS	Mean Opinion Score	1.4
MPDU	MAC sub-layer Protocol Data Units	Appendix c.1
NIST	National Institute of Standards and Technology	1.2
OPNET	A software that can help you to do analysis	1.2

PCM	Pulse Code Modulation	1.1.3
PDA	PERSONAL DIGITAL ASSISTANT	1.1.1
PHY	Physical	1.4
PL	Path Loss	3.1.3
PLCP	Physical Layer Convergence Procedure	2.6.1
PMD	Physical Medium Dependent	2.6.1
PPP	Point to Point Protocol	2.3
QOS	Quality of Service	1.2
QPSK	Quadrate Phase Shift Keying	1.1.4
RF	Radio Frequency	1.1.4
SIFS	Short Inter Frame Space (SIFS)	4.2.2
SNR	Signal to Noise Ratio	1.1.6
TDM	Time Division Multiplexed	Reference page
WLAN	Wireless Local Area Network	1.1.1
WM	Wireless MediumAppendix C.1	Appendix C.1

Table of Symbols and Notations

Symbol	Description	*Section No. of 1st appearance*
Dbb	Distance between the BLUETOOTH transmitter and receiver	4.1
Dbw	Distance between the BLUETOOTH receiver and WLAN	4.1
I_K	Bessel function with index (k)	3.1.2
P(3bits)	No error probability in three bits	3.2.3
$p(\gamma)$	The bit error probability	3.1.2
P_b	Bit error rate	3.2.3
Pe	The final BER going through small fading channel	3.1.4
P_HV2_Access	Probability of no error in HV2 Access part	3.2.3
P_HV2_Payload	Probability of no error in HV2 Payload part	3.2.3
P_HV2_Header	Probability of no error in HV2 Header part	3.2.3
P_HV2_lost	Probability of no error in a HV2 BLUETOOTH packet	3.2.3
PL(d)	Path loss (dB) over distance *d*	3.1.3
P_{pico}	Error probability when several piconets are at present	4.1
$P_{ra}(\Gamma)$	pdf of Rayleigh distribution	3.1.4
p_r	Power of receiver	3.1.3
P_t	Power of transmitter	3.1.3
X_σ	Zero-mean Gaussian distributed random variable (in dB)	3.1.3
a	Constant	3.1.2
b	Constant	3.1.2
d_0	Close-in reference distance	3.1.3
n	Path loss exponent	3.1.3
λ	Wavelength signal (cm)	3.1.3
γ	SNR	3.1.2
ρ	Constant	3.1.2

Ch1. Introduction

1.1 Literature Review

Since the appearance of BLUETOOTH [MiBi02] technology in 2000, BLUETOOTH and other wireless communication networks have been going on a great development. This progress has been driven by the invention and maturity of new technologies and techniques. Also it has enabled more complicated applications. Similarly, the increasing requirements of applications have accelerated the development of quality of service, capacity and flexibility of this kind of wireless communication system.

1.1.1 BLUETOOTH Architecture and History [BSIG99]

The BLUETOOTH wireless technology is the new hot connectivity standard for 2000, providing low cost wireless voice & data communications to link mobile phones, PCs, PDAs, digital cameras, and other portable information appliances.

The BLUETOOTH Special Interest Group (BSIG) has produced a specification [BSIG99] for the technology to enable short-range (area of 10 meters in diameters) wireless voice and data communications anywhere in the world. The BLUETOOTH wireless technology is created to solve a simple problem: to replace the cables used on mobile devices with radio frequency waves. The technology encompasses a simple low-cost, low-power, global radio system for integration into mobile devices. Such devices can form a quick "piconet" and several piconets can form an ad_hoc “SCATTERNET”. Paper [SaBh01] introduces the BLUETOOTH Topology Construction Protocol (BTCP) on piconets and SCATTERNET. This technology creates many useful mobile usage models because the connections can occur while mobile devices are being carried in pockets and briefcases (therefore, there are no line-of-sight restrictions). They have following characteristics:

1) Open specification: BSIG made the specifications for BLUETOOTH wireless communication publicly available and royalty free.

2) Short-range wireless: BLUETOOTH wireless technology is specifically designed for short-range (~10 meters) communication.

3) Voice and data: Traditional lines between computing and communications environment are continually becoming less distinct.

4) 2.4 GHz operation frequency: The spectrum is divided into 79 channels/1 MHz per channel. FHSS (Frequency Hopping Spread Spectrum) is used.

There have been hundreds of papers that address the issues on BLUETOOTH for this two to three years. Papers like [Zurb01] [Bian00] [ChRa01] [Fain00] [Haar00] discuss about radio network performance. Paper [Varo02] investigates the throughput of BLUETOOTH data transmission. Paper [Sabh01] describes BLUETOOTH network construction. It is a great help to understand the constitution and architecture issues of BLUETOOTH from them. Papers [ChRa01], [Fain00], [Golm01b], [Goch01] discuss the interference issues when Wireless Local Area Network (WLAN) IEEE 802.11b is available. Papers [Bamb98], [Deka01], [Fa00], [FoMi93], [Golm01c] are trying to find a solution to minimize that kind of interference. Paper [CoSa01] uses signal capture model to study the SCATTERNET performance, taking inter-piconet interference into consideration with different geographical distributions of units and traffic intensity. Other aspects, like fading investigations, can be found in paper [SoDy01b]. Paper [Haar00] discusses the quality of BLUETOOTH voice over a certain number of WLAN devices in a certain geographic distribution, but it has an unreasonable assumption of bit error rate equal to 0.5. In a matter of fact, it skips the analysis of bit error rate in physical channel model and uses a fixed BER instead.

BLUETOOTH standard was introduced in 2000, and its products began to appear in 2002. Even though there are some various applications available now, the cost of BLUETOOTH facility still seems too high to be accepted by public. As time passes and scalability of manufacturing improves, this should not be a problem.

Actually, relationship between BLUETOOTH and WLAN is co-existing. BLUETOOTH has some virtues when compared with WLAN, such as low power consumption, easy to use, and simple implementation. Since it works within a short range (~10 meters), it should be a useful compensation to WLAN (~100 meters) and cellular networks (~10 km). The interference between WLAN and BLUETOOTH can be solved through various solutions: setting up different hopping tables, adapting power control and using 802.11a standard.

In the next few years, there will be a lot of promising applications of BLUETOOTH to be showed up. For example, establishing BLUETOOTH SCATTERNET can be another way to a home wireless network solution. In a word, BLUETOOTH has and will have a correspondent position in wireless communication world.

1.1.2 Interference Modeling and Physical Layer Fading Issues

There are several situations can degrade the performance of a BLUETOOTH system. Multi-piconets, WLAN IEEE 802.11b, power of BLUETOOTH units, background noise, and distance between BLUETOOTH transmitter and receiver units are same important factors. Most of current papers have discussed some of above issues.

Paper [Golm01b] considers the WLAN interference and uses probability analysis approach to derive the packet error for BLUETOOTH. The analytical results are obtained using detailed simulation models for an interference scenario consisting of BLUETOOTH and WLAN devices. However, it did not consider the multi-piconet interference and the multi-path fading of BLUETOOTH signals.

Paper [Kame00] is based on the characteristics as described in the BLUETOOTH website, (https://www.BLUETOOTH.org/) and IEEE 802.11 specifications for CCK. (Complementary Code Keying) It has the same disadvantage as the one above.

Paper [Haar00] considers the geographic distribution of 802.11 units and the traffic intensity based on threshold of a specific BER (Bit Error Rate). It is another approach to investigate the interference of BLUETOOTH system.

Paper [CoDa03] is the newest paper that is working on BLUETOOTH interference. It declares that the bit error rate of the BLUETOOTH system is an exponential function of parameters SNR, A and B (A and B are constant based on the different modulations). The performance of its evaluation focuses on data communications.

Paper [SoDy01a] considers WLAN as the interference source and implements a simulation, which took the following considerations:

1) WLAN uses DSSS (Direct Sequence Spread Spectrum) 1MHz to 11 MHz spreading methods

2) Large scale fading

3) Ricean distribution is used as its channel model

4) LDI receiver (Limiter-discriminator and integrate and dump filter) is used

This paper explores the relationship between the bit error rate and the signal to noise ratio. Simulations are employed to evaluate the physical layer performance of BLUETOOTH and IEEE 802.11b receivers, mainly but not exclusively, in interference-limited environments. It is another approach to study the performance evaluation.

Paper [ErHa01] describes a set of channel models that is suitable for fixed wireless applications. In this paper, COST 231 WALFISCH-IKEGAMI MODEL is introduced. This model can be used for both urban and suburban environments. There are three factors that make up the model: free space loss, rooftop to street diffraction, multi-screen loss. Rapport [Rapp96] shows that the average large-scale-path loss for an arbitrary T-R separation is expressed as a function of distance by using a path loss exponent n. It shows that free space loss and rooftop reflection can be factors to affect the signal transmission. Rayleigh distribution is usually used to describe the envelop of an individual multi-path component. Therefore, it can describe multi-screen loss. The probability of error in a slow and flat fading channels can be obtained in the equation of [Rapp96]. Papers [PuNi00] [Nata60] describe that Rayleigh; Ricean and Nakagami distribution can be followed by small scale fading. But paper [Skla97] says that the Rayleigh pdf results from having no non-faded component of the signal; thus, for a single link it represents the pdf associated with the worst case of fading per mean received signal power. Therefore, Rayleigh distribution is chosen to model small scale fading in this thesis.

1.1.3 Speech Coding

Speech coding is a technique that converts human speech from its analog signal to digital form in order for us to store and transmit in a more efficient way. The four most important attributes of speech coding are bit rate, delay, complexity, and quality. For improving them and satisfying our needs, many coding techniques are developed. This is witnessed clearly by the developing history of G.711 (PCM), G.726 (ADPCM), G.728 (CELP), RPE-LTP (GSM), G.729 (CS-ACELP) and CVSD (Continuous Variable Slope Delta Modulation) [pg.161,BSIG99]. The paper [Schr97] gives us a brief review how those of coding techniques are developed and how the comparisons are made. Those speech-coding methods are applied in different areas of the industry. Specification [BSIG99] explains that CVSD is kind of cost saving and reliable technique comparing to PCM and ADPCM in short-range application of voice. Thus, it is chosen to be the speech coding method of the BLUETOOTH system.

1.1.4 Gaussian Frequency Shift Keying Modulation (GFSK)

Modulation is the process of encoding information from a message source to a manner suitable for transmission. It generally involves translating a base-band message signal to a band-pass signal at a very high frequency. Probability of error for different modulations in AWGN (Additive White Gaussian Noise) channel is not the same. The BLUETOOTH system use GFSK (Gaussian Frequency Shift Keying) modulation.

Paper [Fain00] discusses that WLAN uses DPSK (Differential Phase Shift Keying) or QPSK (Quadrature Phase Shift Keying), and its probability of error can be expressed as a function of signal to noise ratio. Papers [VaRo02] and [Proa01] discusses the GFSK modulation and its probability of error. Based on this, probability of fading error can be obtained from equations of [Rapp96].

1.2 Motivation of Research

The situations and issues of the wireless communication system described in the previous section, along with the applicable schemes and the existing problems, have attracted much research interests. In a meeting with industry two years ago, it was felt that BLUETOOTH was a promising technology for wireless-voice in short distance such as office environment. Therefore, one would like to understand the voice performance of the BLUETOOTH system, especially in the presence of IEEE 802.11 interference (to the BLUETOOTH transmission).

After reviewing the papers in Section1.1.2, it is found that although they offer many different approaches to the interference of IEEE 802.11b, they have various shortcomings such as those mentioned for the physical channel modeling. Therefore, we would like to thoroughly study and analyze the physical channel, and to find out the exact quality of voice when the WLAN and piconets are in the vicinity of BLUETOOTH devices.

In year 2000, two undergraduate students began their research on BLUETOOTH, and obtained same initial quality comparison of BLUETOOTH voice based on BPSK (Binary phase-shift keying) modulation over different bit error rate. During this period, some knowledge to establish the BLUETOOTH system on OPNET was also obtained from NIST (National Institute of Standards and Technology), a main organization that did some research works in wireless networking. Therefore, I would like to re-evaluate the BLUETOOTH OPNET system, and to complete and extend their work by providing more mathematical models and implementing more MAC and physical-layer protocols. Even though there was limited information at that time, I started to investigate building mathematical models and mathematical analysis.

Finally, our experience on the analysis and performance of the BLUETOOTH system and its variants has motivated us to find a solution to minimize influence of interference.

1.3 Objectives

The objective of the research written in this thesis is to develop a model for voice performance analysis of the BLUETOOTH/IEEE 802.15 system in the presence of the interfering WLAN/IEEE 802.11b. Therefore, we would like to determine the quality of BLUETOOTH voice in terms of various interferences, complexity and implementation. Their results can be made available for reference and their solutions may be imbedded into real radio networks. All of them are important to construct a network module for the wireless network and to implement related physical channel models into simulation test bed. Specifically our research in this thesis focuses on the following objectives

1. To study and analyze BLUETOOTH and wireless LAN communication protocols and their architectures.
2. To determine voice quality of BLUETOOTH voice in terms of various interferences, complexity and implementation.
3. To investigate the performance of BLUETOOTH voice in the presence of WLAN interference source, or when both WLAN devices and piconets interference devices are present.
4. To find out a way to build a physical channel model to understand the relationship between packet lost rate and those of multi-parameters.

5. To propose improvement of the quality of voice.

1.4 Methodology and Approaches

For our analysis, we shall use wireless theory to establish the propagation model in the physical channel, which can in turn help us evaluate performance of proposed system. We shall use different models for indoor radio channels: lognormal model for LOS large fading and Raleigh model for small-scale fading. Modeling of the wireless radio channel is done in a statistical fashion. The most important components of the wireless channel including path loss, shadowing, multi-path fading and background noise are described and their impact analyzed. The model comprises analysis of both PHY (Physical) and MAC (Medium Access Control) layers of the BLUETOOTH systems. At the PHY layer the probability of the bit error is derived based on different interference sources. At the MAC layer the probability of IEEE 802.11b FHSS and DSSS transmitter overlapping in both time and frequency with BLUETOOTH packet is calculated. Various types of environments are considered and system performance is evaluated for each of them. The optimization of power technique for the performance optimization is introduced and its effect of the system is also decided.

Throughout this thesis an OPNET model that captures the performance impact of IEEE802.11 interference, parameterized by the IEEE 802.11 data rate, frequency hopping pattern, packet size and the number of BLUETOOTH piconets, as well as the distance between the collocating IEEE 802.11b signal transmitter and the BLUETOOTH radio receiver has been developed. In establishing our model, we shall use OPNET to build our network configuration model and use MATLAB as assistance. Considerations for using OPNET are:

1) Mathematical analysis cannot solve all problems in the real world due to its limit. Simulations offer an alternative approach to the solution.
2) A simulation tool, OPNET, can be used to simulate the complexity and uncertainty desired in this research. It can provide similar wireless module in its library.
3) Performance evaluation can be easily done via analysis of simulation data.

The reasons that MATLAB has been used are as follows:

1) MATLAB, as another tool, can also offer A/D (Analog to Digital conversion) and D/A conversion solution through MATLAB coding.

2) MATLAB, an easy tool, can be used to display some results in a graphical interface that are hard to be display in other platforms.

3) CVSD speech coding can be realized in MATLAB.

Based on the network model, we shall create process models of master, slave and WLAN node. BASEBAND protocols and L2CAP protocols in the BLUETOOTH specification shall be implemented in these process models. Access mechanism of WLAN shall be written in the WLAN process model. For displaying analysis results in Chapter 3 and 4, we shall use C codes or MATLAB codes to implement empirical formulas.

CVSD (Continuous Variable Slope Delta modulation), the speech coding technique of BLUETOOTH system, uses 64 kbits/s (generally at least 32k) log PCM format as its input to create a relatively more robust binary output format. When we are investigating CVSD, we should be converting voice signals into binary information through the help of MATLAB. All actions can be done through writing MATLAB coding. This kind of A/D, D/A conversion should be used to create inputs and outputs of our system on OPNET.

Finally, MOS (mean opinion scores) rating shall be obtained through converting packet loss rate to mean opinion scores. Audio files can be evaluated through comparison of MOS rating.

1.5 Contributions

The contributions of this thesis are:

1) Implementing the physical channel model in OPNET.

2) Evaluating the performance when both piconet interference and WLAN interference sources are present together.

3) Creating a propagation model of BLUETOOTH in OPNET, which captures factors like large fading, small-scale fading, background noise and interference from WLAN and SCATTERNET into a propagation channel.

4) Creating an end-to-end simulation set on OPNET platform to evaluate voice performance of BLUETOOTH system

5) Using MATLAB to integrate CVSD, in which A/D, D/A conversion between voice and binary information can be made.

6) Analyzing the BLUETOOTH voice quality under interference from IEEE802.11b, which is specified as several interference situations: FHSS 1MHz, FHSS 2MHz, DSSS 1MHz, DSSS 2MHz, DSSS5MHz and DSSS 11Mhz. This kind of analysis probably is the first kind in current papers.

1.6 Thesis Organization

The reminder of the thesis is organized as follows:

Chapter 2 introduces the basic modeling system. Chapter 3 describes some factors that can affect the performance evaluation of the BLUETOOTH system, and the role those factors play in our network system. Chapter 4 discusses the resulting packet-loss-rate over different interference environments. Result of QOS of voice will be discussed in Chapter 5. Chapter 6 gives conclusion summary and discusses the future work.

Part of this thesis has been published in the following conference.

[JiangYa02a] Bo Jiang and Oliver Yang, " Performance evaluation of BLUETOOTH system in the presence of WLAN IEEE 802.11 system", CCECE2003, Montreal, May5-7, 2003.

Ch2. System Modeling and Operation

This chapter describes the physical environment and operation of the BLUETOOTH system under study. It will explain how system and interface of the network architecture are captured in the network model, node model, process model and packet model of our OPNET simulations. Also assumptions are provided at the end of this chapter.

2.1 The Wireless Network Environment

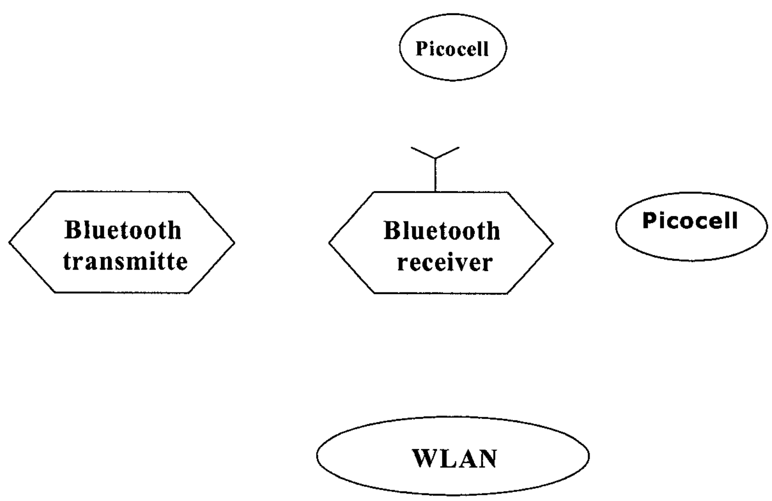


Figure 2.1 BLUETOOTH in a room environment with interference

Figure 2.1 depicts a typical wireless network environment, the gradual separation among entities in the 10 meters range. In this environment, the BLUETOOTH transmitter sends voice packets to the BLUETOOTH receiver through air at the FHSS 2.4 GHz frequency band. A WLAN transmitter is 1 meter to 30 meters away from the BLUETOOTH transmitter. It is also continually sending its packets to its destination at the FHSS/DSSS 2.4 GHz frequency band. Several picocells in other piconets are working on the same band to affect the transmission of BLUETOOTH. This is the network model of the BLUETOOTH system. The BLUETOOTH communication topology is that one master can communicate at most 7 slaves in active status and up to 255-parked slaves. All slaves communicating with a single master create, what the specification calls, a picoent.

When two or more piconets at least partially overlap in time and space, a SCATTERNET is formed as Figure 2.2 shows.

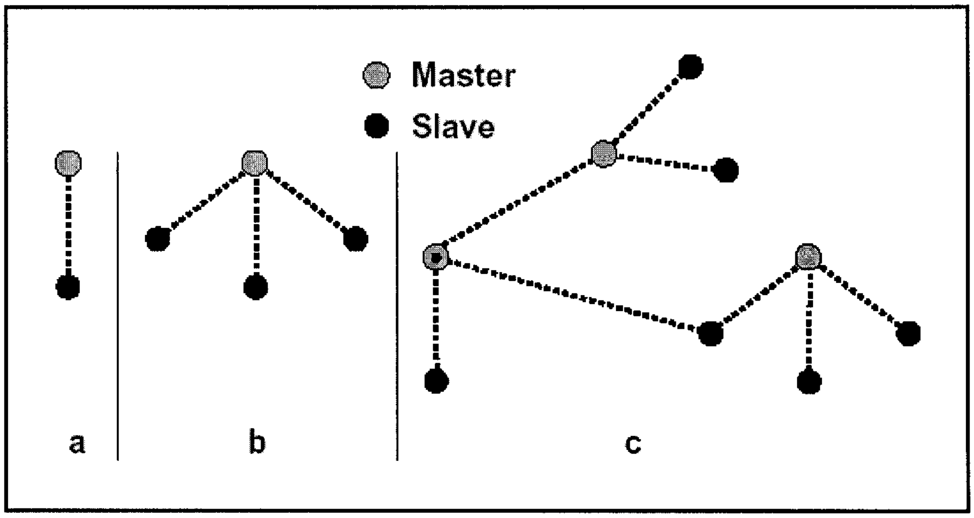


Figure 2.2 Piconets with a single slave operation. (a)a multi-slave operation (b) and a SCATTERNET operation (c).

In the physical air-channel, BLUETOOTH packets encounter background noise, large scale fading, small scale fading (multi-path), the piconet interference and WLAN interference. Some of those factors would change the bit error rate of the BLUETOOTH packets before they finally arrive at a BLUETOOTH receiver. Due to the FEC (Forward Error Correction) used in the packets, some packets can correct thesis error bits by themselves. Otherwise they are lost.

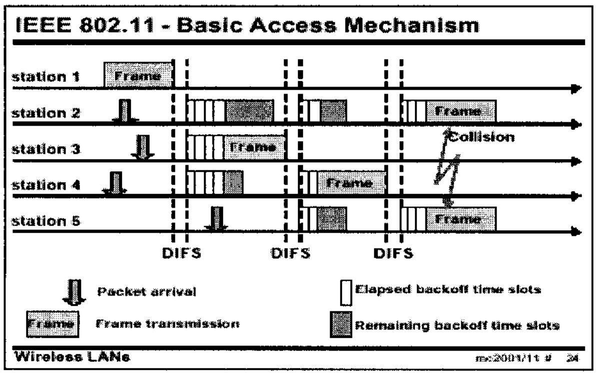
2.2 Network Operation

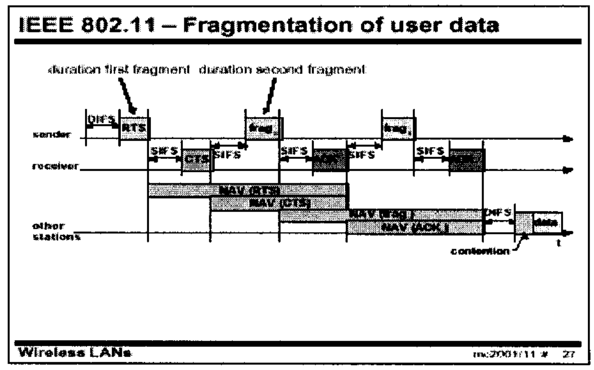
In this section, network operation of piconets and IEEE802.11b are introduced. Before the piconet connections are created, all BLUETOOTH devices are in "stand by" mode. Once one of devices initiates the connection it becomes the master of the piconet. All other BLUETOOTH devices become slaves in the piconet. The devices synchronize and then connect with each other. When establishing the connection, each device gets a MAC address. There can be seven active slaves at most in a piconet. Each of the active slaves has an assigned 3-bit Active Member Address. (AM_ADDR). Only the slave that is addressed by its AM_ADDR can return a packet in the next slave-to-master slot. If

AM_ADDR is not valid, the slave may only respond if it concerns its reserved SCO slave-to-master slot. Therefore, the master controls all transmission in order that no two devices can occupy the same channel in the same time. From Figure 2.8, the radio interfaces of the BLUETOOTH system are RX and TX nodes. The system clock of the master synchronizes the piconet 's clock. The master never modifies its system clock during the existence of the piconet; it keeps an exact interval of 625 microseconds between consecutive transmissions. The slaves adjust their native clocks with a timing offset in order to match the master clock. This offset is updated every time a packet is received from the master by comparing the exact RX timing of the received packet with the estimated RX timing; the slaves correct this offset for any timing misalignments. Note that the slave RX timing can be corrected with any packets sent in the master to slave slot, since only the channel Access Code is required to synchronize the slave. Doing so, a SCATTERNET is formed as piconets connect with each other and synchronize their clock.

BTCP is an asynchronous distributed protocol for building SCATTERNET on BLUETOOTH 1.0 specification. It cans starts with nodes that have no knowledge of their surroundings and units with the formation of a connected network satisfying all connectivity constraints posed by the BLUETOOTH technology. Due to the existence of multi piconets, interference appears when two units in difference piconets share the same channel and are transmitting signals at the same time.

The BLUETOOTH performance is affected by the presence of IEEE 802.11b. The primary medium access control (MAC) technique of IEEE 802.11b is called Distributed Coordination Function (DCF). There is two access scenarios: The BASIC access and RTS/CTS access. Even though RTS/CTS method is clearly superior to the BASIC access in transmission performance, the BASIC access method is used due to its importance in the WLAN industry. Figure 2.3a shows an example of the BASIC access mode. In the example, five Stations 1st to 5th share the same wireless channel. The first packet of Station1 arrives at first as shown. At the end of packet transmission, Station 3 waits for a DIFS (Distributed inter-frame space) and then chooses a back off time equal to Station 5 before transmitting the next packet. Note that the transmission of the packet occurs in the middle of the slot time (corresponding to a back off value). For Station 2, as a consequence of the channel being sensed busy, the back off time is frozen to its value 5, and the back off counter decrements again only when the channel is sensed idle for a DIFS. The stations 2 and 5 transmit their packets after the same number of backoff time slots, and therefore a collision happens.





(a) BASIC access (b) RTS/CTS access

Figure 2.3 IEEE 802.11b access scenario

Besides access mechanisms, WLAN 802.11 uses two frequency spread spectrum methods to delivery its messages:

1) FHSS (Frequency Hopping Spread Spectrum): In FHSS, the spread code is used to control a frequency agile local oscillator, the output of which is used to up convert the modulated RF carrier to the 2.4GHz band. The resulting RF output is referred as a hopping sequence. A replica of spreading code is applied at the receiver to recover the wanted information signal. The narrow band RF filter, along with any wide band signal or noise content, rejects other FHSS transmissions with different hopping sequences.

2) DSSS (Direct Sequence Spread Spectrum): IEEE 802.11b standard allows for 1,2,5.5 and 11Mbps operation using different modulation schemes. The 1 and 2M rates use the familiar BPSK and QPSK. For 5.5 and 11MHz operation, Complementary Code Keying is used. The process involves multiplying the base-band data signal by a wider bandwidth signal, which takes the forms of binary code.

2.3 The BLUETOOTH Protocol Stack

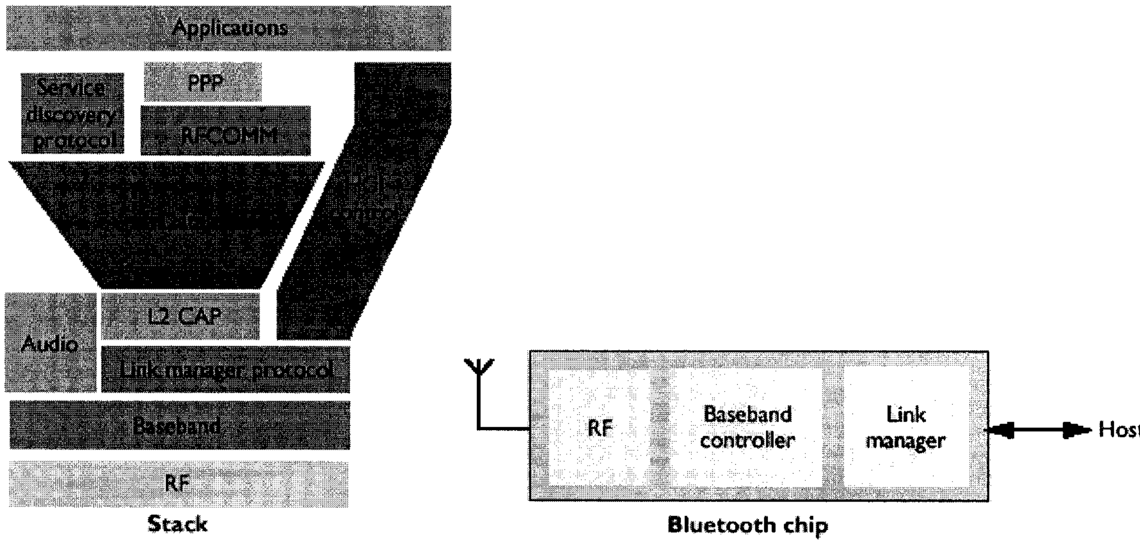


Figure 2.4 BLUETOOTH protocol stack

Figure 2.4 is the core of Specification V1.0 that defines all layers of the BLUETOOTH protocol stack [BSIG99]. These layers are different from the traditional seven OSI layers. That is mainly to support ad_hoc that can create a SCATTERNET, while saving power and accommodating more devices that lack resources to support classical network of all 7 layers. In our BLUETOOTH investigation, we only investigate the data-link layer and the physical layer of OSI model as described below.

The LMP (Link Management Protocol) defines connection methods between a master and slaves, the power control of devices, clock setup for all devices and roles of the BLUETOOTH nodes. These protocols are written in MAC (Median Access Control) layer.

The RF is the lowest layer. It specifies the power level of the transmitter and the receiver and their radio characteristics. Above the RF, the BASEBAND protocol defines the BLUETOOTH physical (PHY) and Media Access Control (MAC) processing. Devices discovery, voice (synchronous transmission), data (asynchronous transmission), packets types, error correction, hopping pattern, channel match, and control messages are defined in this protocol stack. This protocol is implemented as C code in our node modules.

The physical channel is put in the TX and the RX nodes of Figure 2.8. Some parameters, such as power, distance, bandwidth, temperature, frequency hopping, interference sources and FEC, are all required to form this channel. Starting from background noise, large-scale fading, and small fading to interference, these factors degrade the signal of packets, and the extent of degradation would decide if packets should be trashed or not.

The HCI (host control interface) gives an independent way for BLUETOOTH chips to communicate with their host processor through USB or PC-card. L2CAP (the Logic Link Control and Adaptation Protocol) shields all kinds of packet format from above layers, such as PPP (Point to Point) from Internet, and encapsulates them into BLUETOOTH packets format. RFCOMM specification defines a method to emulate RS232 cable connection into air link of BLUETOOTH. L2CAP protocols are implemented in Asynchronization Link (ACL) and MAC modules of Figure 2.8 after data packets are generated. All data packets are encapsulated as format of L2CAP.

2.4 The Simulation System

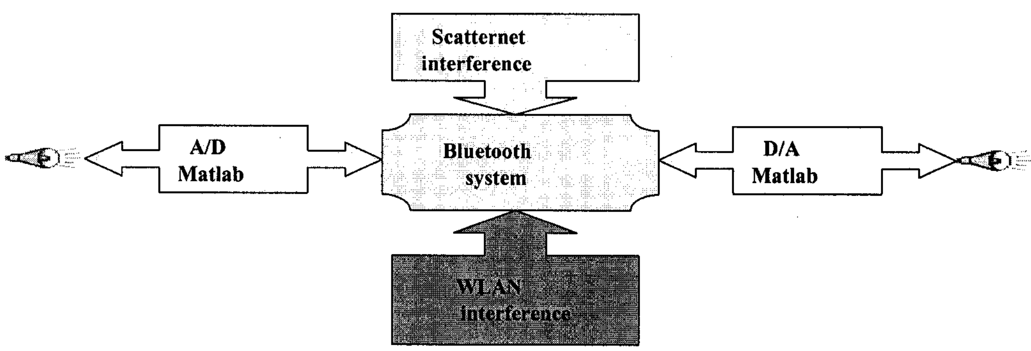


Figure 2.5 The Proposed Simulator

The architecture of the proposed simulator can be seen in Figure 2.5. The SCATTERNET, BLUETOOTH system and WLAN system are built on OPNET platform. C codes are written to implement the protocols and create the propagation model and interference models.

The initial input is the voice signal, which is recorded by "sound recorder", one of the PC's applications. MATLAB language is used in A/D and D/A conversion to apply the CVSD speech-coding algorithm and to prepare the binary input and output. Voice, the analog signal, is converted into digital format, a binary text file, as the input to the BLUETOOTH system. In the BLUETOOTH system, a master and a slave communicate with each other using the BLUETOOTH protocols. But the interference signals from different piconets and WLAN 802.11 can affect the voice transmission in the BLUETOOTH system to lead the voice packets drop. Due to the fact that voice packets carry the binary information of voice, some of digital information will be lost and are transferred into analog signal by D/A converter.

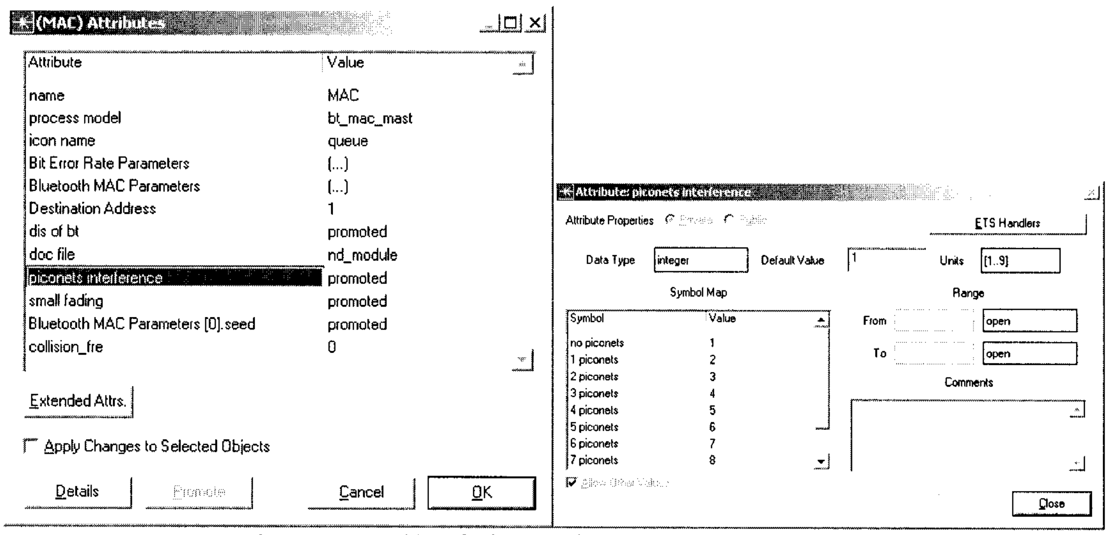


Figure 2.6 I/O of piconet interference on BLUETOOTH

As discussed in Section 3.2 later, the piconet interference is modeled by one parameter shown in Figure 2.6. Therefore, no module of the piconet interference is implemented in the physical channel.

2.5 OPNET Simulation Model

For evaluating the voice performance of the BLUETOOTH system, OPNET is chosen as the simulation tool. The reason is that OPNET can offer similar network architecture, WLAN module in OPNET library and part of BLUETOOTH C code.

The overall network architecture of the proposed BLUETOOTH system is simple. A master, a slave, a WLAN interference transmitter node and a WLAN packet receiver are put together. Three layers simulation in my OPNET platform is made. In Figure2.8, packets generator, MAC packets processing and TX/RX represent these three layers of

OSI model. Protocols like LMP, BASEBAND and L2CAP are implemented in these modules. They are provided in the network and interference models below.

2.5.1 BLUETOOTH Network Model

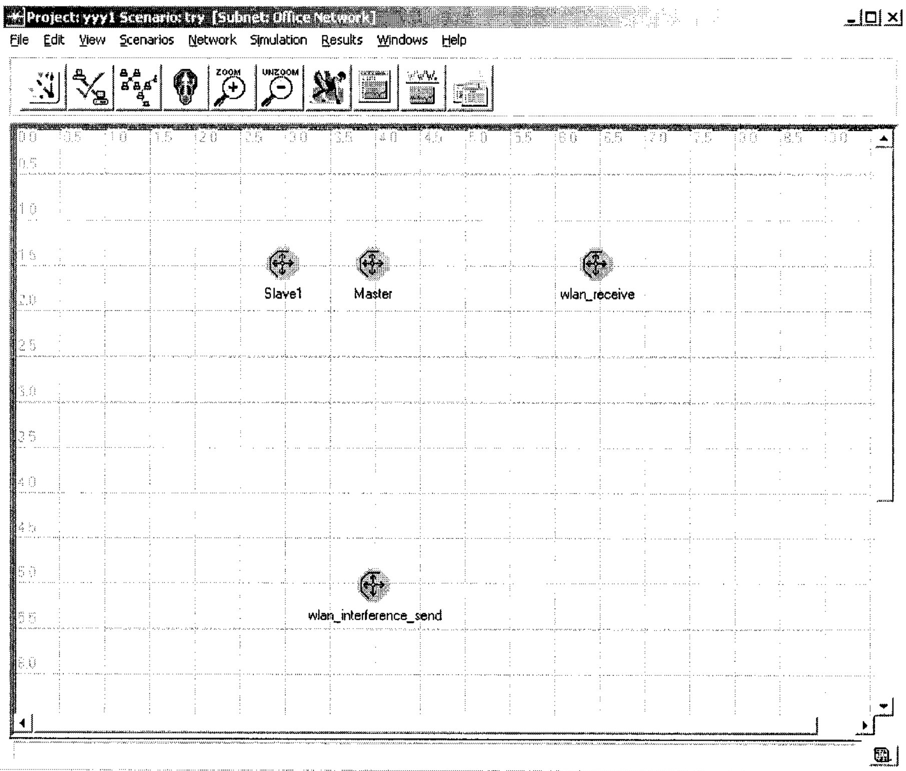


Figure 2.7 BLUETOOTH network module on OPNET

Figure 2.7 depicts the network model of the BLUETOOTH system under study. Because BLUETOOTH devices operate within a short range (~10metrs), the default distance between the master and the slave is set to 1 meter and the default distance between the Master and the WLAN interference is 4 meters as shown. (Reasons are explained in Ch4.2) But these distances can be changed early because they are promoted parameters in our simulation. Once a parameter is promoted, its value can be modified in different simulation sets without re-compilation. Also a WLAN receiver is responsible to collect interference packets from a WLAN transmitter (WLAN-interference-transmitter). Slave1 is designed as the BLUETOOTH transmitter to send voice packets to the master, which is designed as the BLUETOOTH receiver to receive packets from its slave. Slave will read bits input from the MATLAB digitalized voice.

2.5.2 OPNET Node Model

The node module captures the MAC layer and physical layers as shown in Fig 2.8. We use C codes to implement BLUETOOTH protocols (Figure 2.4) in the process model. The ACL module realizes L2CAP protocol to do asynchronies transmission for data packets. The SCO module realizes voice real-time synchronized transmission. In the MAC module, all packets will be processed according to BASEBAND protocol. The voice packets have the highest priority to be transmitted.

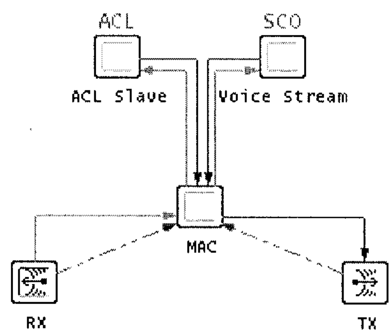


Figure 2.8 Node in OPNET

All physical channel characteristics of air will be written in the RX and the TX interface according to the RF specifications of BLUETOOTH. The piconet interference is actually being written here in C code as one parameter. All node modules of WLAN and BLUETOOTH have the same format as shown in the Figure 2.8 but have different process models inside.

2.5.3 OPNET Process Model

Process models are used to specify the behavior of processor and queue in the node domain. The SCO process model is used to create BLUETOOTH voice packets, which encapsulate upper layers packets. The ACL process model is used to create data packets and send them to a MAC node for processing. In the MAC process model, the BASEBAND and LMP protocols are implemented for communication among BLUETOOTH devices. Interference detection and how it works are also made here.

In the process model, scalar files are created from the source codes. After each end of the simulation, several data files, such as packet loss rate, distance between

BLUETOOTH and WLAN transmitter, MOS (Mean Opinion Score) rating levels and hopping pattern of WLAN will be recorded from the OPNET system kernel.

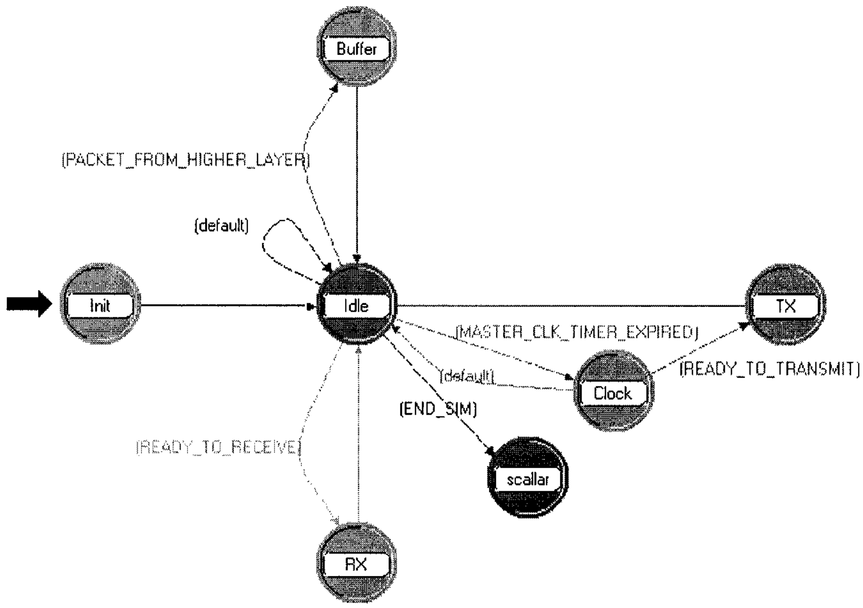


Figure 2.9 Process module of BLUETOOTH MAC module

2.5.3.1 BLUETOOTH Process Model

Figure 2.9 shown above is the MAC process module of the BLUETOOTH master. The state transition diagram depicts how a BLUETOOTH packet is processed or lost. This is the most important part of protocol implementation. If packets are from the SCO and ACL nodes (BLUETOOTH device itself), functions will be called to process them here and they will be in the RX or the TX radio interface waiting for transmission. If packets are coming from other BLUETOOTH devices or interference sources, they will be received on the RX state, in which functions will be called for processing. Statistic data are collected in the scalar state upon the termination of the simulation. The Clock state controls the creation of event at an interval of 625 microseconds per packet.

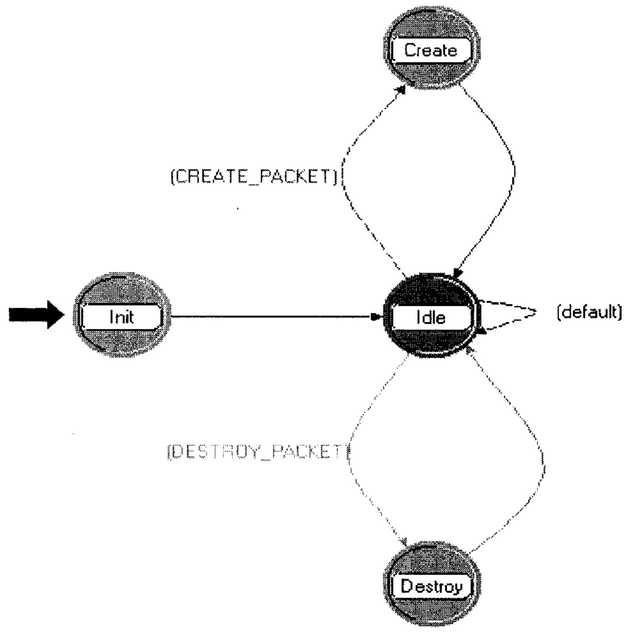


Figure 2.10 Process module of BLUETOOTH packet creator module

Figure 2.10 above is the process model in the SCO node. Voice packets are created here and transmitted to the MAC layer for processing. Upon receiving each qualified packet from other BLUETOOTH devices, statistics will be compiled and the packet will be destroyed.

2.5.3.2 WLAN Process Model

Wireless LAN process model is similar to the BLUETOOTH process model, but it does not have a packet-process function in coding. It can only create and transmit WLAN packets according to the WLAN packet format. We use a default traffic load of 100% so that packets are transmitted one by one all the time.

Packets are transmitted from the creator into the MAC node. In the buffer state, WLAN packet payload, head information and transmission rate are defined according to interface from outside. The frequency-hopping rate and access mechanism are also specified in order to let BLUETOOTH devices detect them.

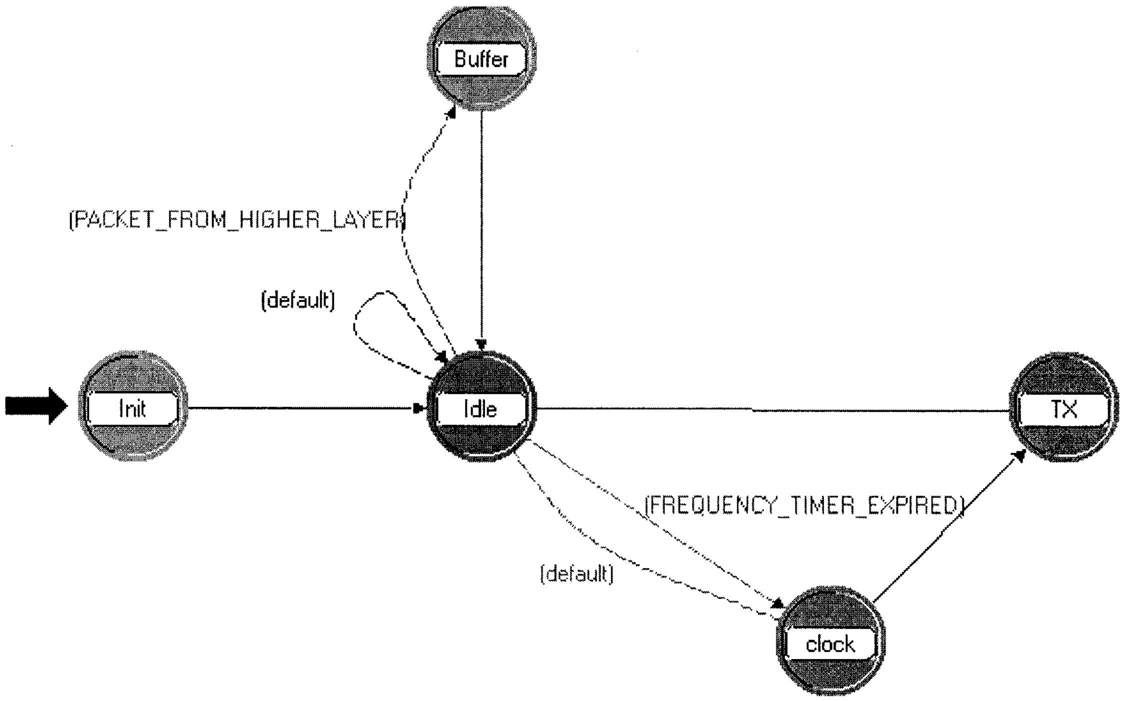


Figure 2.11 Process module of WLAN MAC node

2.6 OPNET Packets Formats

OPNET is an event driven simulator. In order to realize the BLUETOOTH protocols, the process models have to identify the types of packet format and collect information on them. Therefore, packets format of WLAN and BLUETOOTH in OPNET are introduced in this section.

2.6.1 WLAN Packets

The PHY services being provided to the IEEE 802.11b wireless LAN MAC by the 2.4 GHz DSSS system decides the packet format of the wireless LAN. The DSSS PHY layer consists of two protocol functions: the PLCP (Physical layer convergence procedure) and the PMD (Physical medium dependent) protocols. Details of these two protocols can be found in Appendix C.1.

The head of the PLCP shall consist of 128 bits of scrambled ones as Figure2.12. This field shall be provided so that the receiver can perform the necessary operations for synchronization. The PLCP packets are encapsulated into MAC layer packets and the length of MAC head is 240 bits as shown in Figure 2.12.

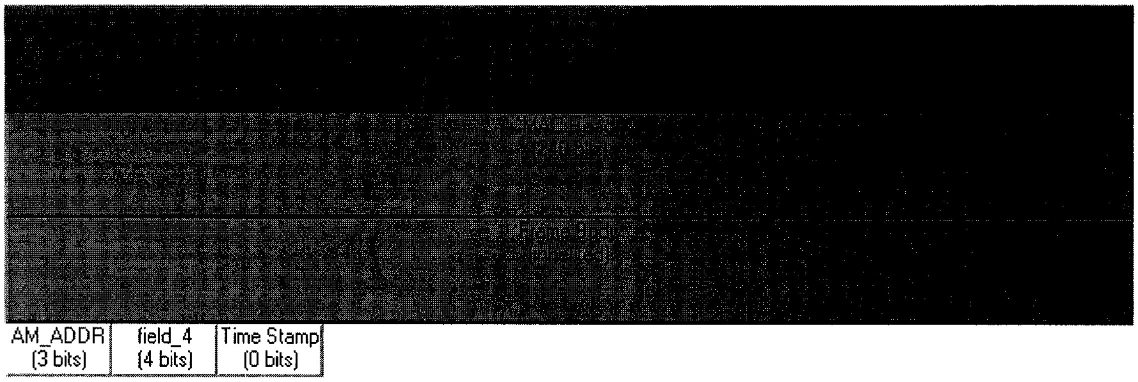


Figure 2.12 WLAN packet format

There are 240 MAC bits in a WLAN packet that can perform data link protocol in the MAC layer. In our simulation, packet length is set to 8000bits (refer to assumption).

2.6.2 BLUETOOTH Packet

There are three kinds of voice packet formats available, HV1, HV2 and HV3. They differ in the payload.

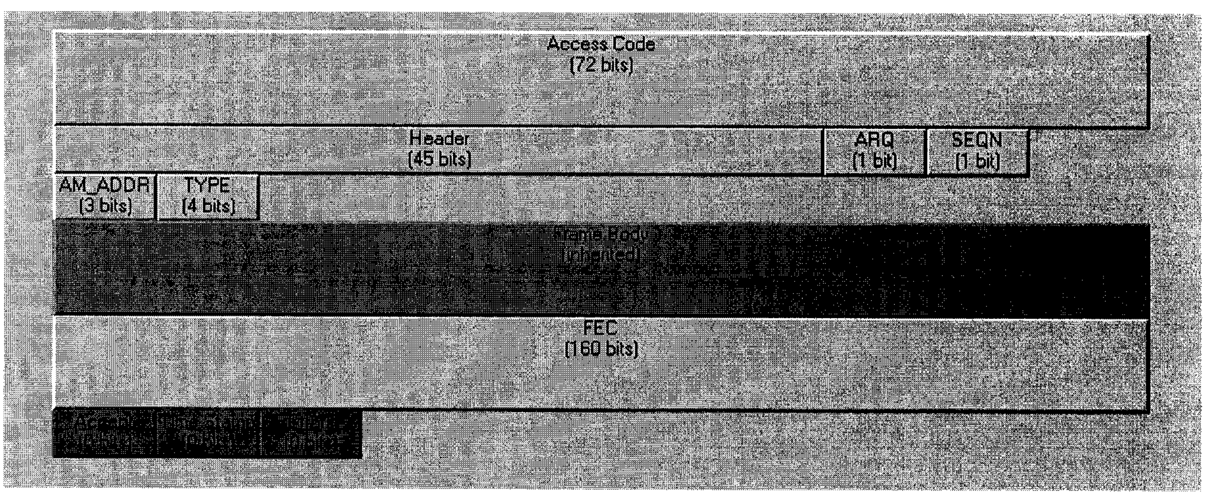


Figure 2.13 BLUETOOTH HV1 packet format

Figure 2.13 shows the three parts in the HV1 packet: the access part (72 bits), the header part (45bits), and the payload part (240bits) containing 160 bits FEC and 80 information bits (Frame Body).

Each HV voice packet starts with an Access Code. If a packet header follows, the Access Code is 72 bits long; otherwise the Access Code is 68 bits long. This Access Code is used in synchronization, DC offset compensation and identification. The Access Code identifies all packets exchanged on the channel of the piconet: the same channel Access Code precedes all packets sent in the same piconet. In the receiver of the BLUETOOTH unit, a sliding co-relater correlates the Access Code and triggers when a control threshold is exceeded. This trigging signal is used to determine the receiver timing. The Access Code is also used in paging and inquiry procedures. In this case, the Access Code itself is used as a signaling message and neither a header nor a payload is present. The Access Code consists of a preamble, a sync word, and possibly a trailer; the preamble is a fixed zero-one pattern of 4 symbols used to facilitate DC compensation. [BSIG99] In addition, the good auto correlation properties of the sync word improve on the timing synchronization process. In Figure 2.13, there are 72 bits of Access Code in total, including 8 bits of head-tailor and 64 bits of sync word. The sync word consists of 8 bits HEC and 54 information bits, which use 1/3 FEC protection.

The 54 bits header in Figure 2.13 contains Link Control (LC) information and consists of 6 fields of 18 bits. They use 36 bits error correction code. Therefore, 36 bits of error correction plus 18 control bits become 54 bits of sync word. The 18 bits field is:

1) AM_ADDR: 3- bit active member address
2) TYPE: 4-bit type code
3) ARQ: 1-bit acknowledge indication
4) SEQN: 1-bit sequence number
5) HEC: 8-bit header error check
6) FLOW: 1-bit flow control

In Figure 2.13, FEC (160bits) is the payload part of packets that can carry information bits. The HV1 packet carries 10 information bytes, which is 80 information bits. The 80 bits are protected with a 1/3-repetition code FEC. No CRC (Cyclic Redundancy Check) is needed. The payload length is fixed at 240 bits. Since a HV1 packet can carry 1.25ms of speech at a 64 kb/s rate, such packet has to be sent every two-time slots.

The only difference among HV1, HV2 and HV3 is in the payload part of a packet. HV2 uses (15,10) hamming code, thus requiring 160 information bits and 80 correction bits. HV3 does not have error correction capability and therefore its payload of 240 bits is entirely information.

2.7 Assumptions

The following assumptions are used throughout the thesis

1. WLAN traffic load is one hundred percent in order for us to measure the worst interference level.
2. Bit error rate of the piconets packets is 0.5 to simulate the worst piconet interference level.
3. All BLUETOOTH devices within a SCATTERNET can transmit their packets synchronously. This is because every BLUETOOTH device has an internal system clock for synchronization. The BLUETOOTH clock of the master determines the timing and the frequency hopping on the channel of a piconet. When a piconet is established, the master clock is communicated to the slaves. Each slave synchronizes its native clock to the master clock, and any offsets have to be updated regularly even when the clocks are free running. Likewise, when piconets are trying to form a SCATTERNET, a bridge (master/slave) node will synchronize different clocks.
4. No propagation delay is considered in a short-range area.
5. Background temperature is set at 290k, the normal room temperature of 17°C. Experiments at different room temperatures and noise figures show that temperature does not have much impact on fading performances.
6. Noise figure is set as 10dB (audio noise in background)
7. The power of transmitter is 25mw, a typical power class for WLAN according to 802.11b standard.
8. The exponent of Lognormal Shadowing is 3.5 for indoor environment, a typical fading index.
9. Close-in reference distance (d_0) of Lognormal Shadowing is set at 1 meter in order to calculate large scale fading. This is because BLUETOOTH is in 10

meters short range. Therefore, 1 meter is the minimum distance for reference. This value is used to calculate the large scale fading of signal.

10. We consider small scale fading in a slow and flat fading channel because only slow movement is expected.

11. BLUETOOTH power of transmitter is 1mw and it uses omni antenna, a typical 802.15 power class.

12. Because more piconets interference leads to the worst quality of voice that cannot be heard, we shall state with two interference piconets.

13 Bits in BLUETOOTH packets are independent from each other.

Ch3. Performance Analysis under Fading Environments

This chapter will discuss how channel-fading factors can affect the transmission of the BLUETOOTH packets. The factors are background noise, large scale fading, and multi-path fading. Performance evaluation will first be done without any interference sources. piconets interference and IEEE802.11b interference will be discussed in Chapter 4 later.

3.1 Physical Channel Access

Under normal situation without interferences, a BLUETOOTH packet in air medium will undergo large-scale fading, multi-path (small scale) fading and background noise. Packets loss rate is a function of BER that can be obtained through measuring SNR, which in turn can be obtained through calculating background noise and fading figures. Speech in the presence of background noise or even over a distance is therefore challenging for everyone.

3.1.1 Background Noise

Background noise is an important factor that affects the transmission bit error rate. It is the function of the temperature of the environment and signal bandwidth. The normal thermal noise power at normal temperature (290k) can be easily calculated as $KTBF = 4 * 10^{-14}$ watts = -134 dBw = -104dbm where K is the Bolzmann constant 1.38×10^{-23}. T is the room temperature, and B is the noise power density (See assumption 2.6). Parameter F is the bandwidth of the BLUETOOTH system. Because BLUETOOTH uses FHSS 1MHz system, the bandwidth is 1 MHz. This parameter, *KTBF*, will be inserted into the proposed project as a constant of noise.

3.1.2 GFSK Modulation

The BLUETOOTH system uses GFSK (Gaussian Frequency Shift Keying) modulation with a BT=0.5. The modulation index must be between 0.28 and 0.35. We choose 0.35 in the proposed simulation sets. A binary one is represented by a positive frequency deviation, and a binary zero is represented by a negative frequency deviation (pp.23 of [BSIG99]). Since we use GFSK modulation in BLUETOOTH, we shall summarize a few characteristic equations [VaRo02] [Proa01] for GFSK that will be used later. For example, eqn (3.4) will be used to calculate the probability of error in small scale fading channel.

When the modulation index (h) of GFSK is from 0.28 to 0.35, let ρ be a constant as shown in eqn (3.1)

$$\rho = \frac{\sin(2\pi h)}{2\pi h} \quad . \tag{3.1}$$

Then two other constants a and b can be defined as:

$$a = \sqrt{\frac{\gamma}{2}\left(1 - \sqrt{1-\rho^2}\right)} \quad , \tag{3.2}$$

$$b = \sqrt{\frac{\gamma}{2}\left(1 + \sqrt{1+\rho^2}\right)} \quad . \tag{3.3}$$

The bit error probability can be expressed as [Proa01] or [VaRo02]

$$p(\gamma) = e^{-\frac{\gamma}{2}} \times \left(0.5 I_0(ab) + \sum_{k=1}^{\infty}\left(\frac{a}{b}\right)^k I_K(ab)\right) \quad . \tag{3.4}$$

Where I_K is Bessel function with index (k) and γ is the SNR

3.1.3 Large Scale Path Loss for The BLUETOOTH System

Large-scale Path Loss represents the average path loss of power over a large area as a function of distance (Refer to Section 3.9 of [Rapp96]). Prominent environment features such as the distance between a transmitter and a receiver, floors, ceilings and fixtures all affect this phenomenon. The signal arriving the receiver is often distorted or shadowed by these features. Statistical model of the large-scale path loss provides a way of computing estimated signal power on path loss as a function of distance. Of the several path loss models, we adopt the Lognormal Shadowing as follows:

Let *PL(d)* be the path loss (dB) over the distance *d* of receiver away from transmitter, X_σ be a zero-mean Gaussian distributed random variable (in dB) with standard deviation σ, [Rapp96] d_0 be close-in reference distance, *n* be path loss exponent, then we have:

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \quad . \qquad (3.5)$$

X_σ could be ignored from the average aspect. With assumptions in Section 2.7, d_0 is set as 1 meter and λ as 12.5cm. Therefore they have:

$$PL(d_0) = 20\log\left(\frac{4\pi d_0}{\lambda}\right) = 40dB \quad . \qquad (3.6)$$

With the assumption in Section2.7, we set the exponent n as 3.5 for indoor environment. Therefore, power of receiver (watt) P_r can be written as a function of power of transmitter P_t and distance *d*.

$$PL(d) = 40dB + 10 * 3.5 * \log(d) \quad , \qquad (3.7)$$

$$p_r = \frac{P_t}{10^4 * d^{3.5}} \cdot (3.8)$$

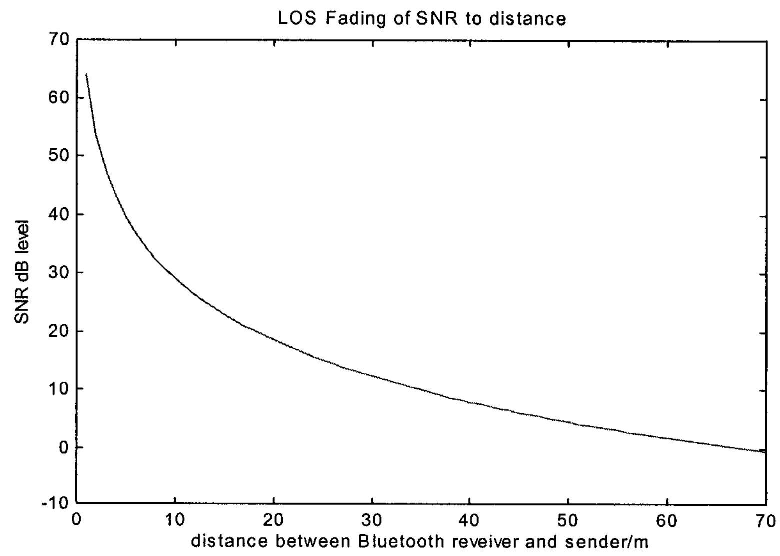
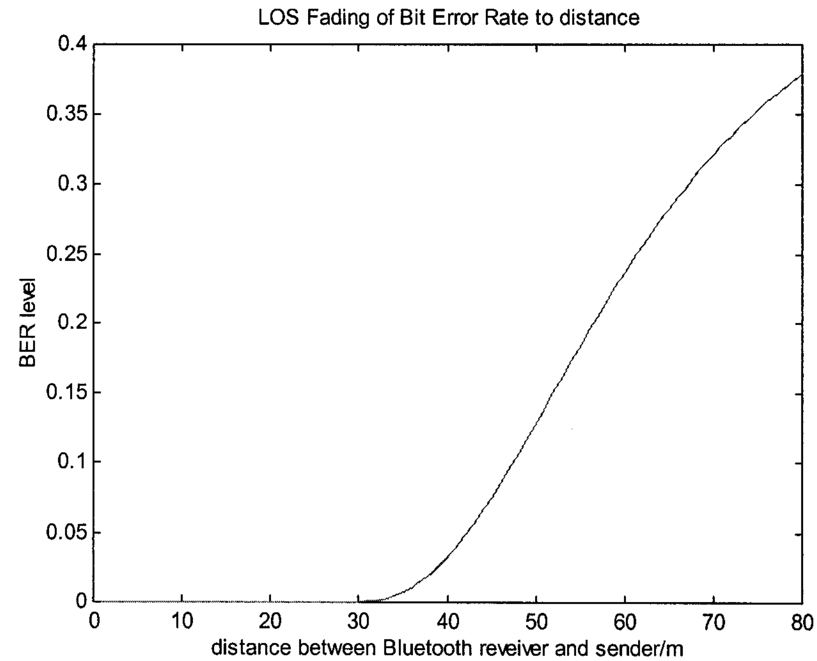
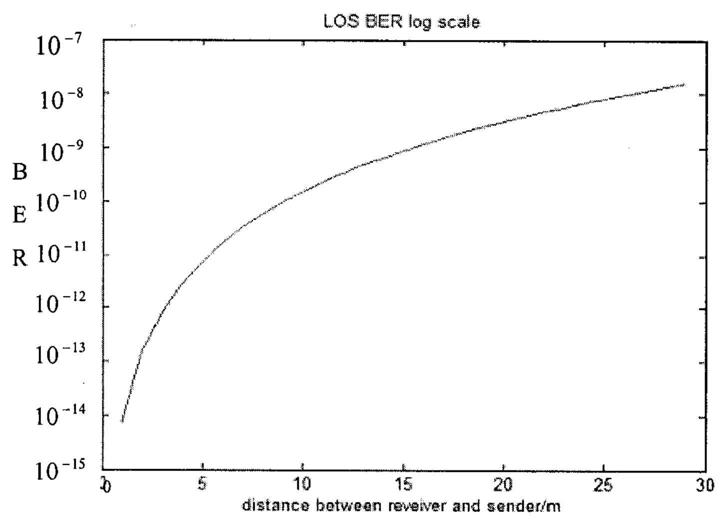


Figure 3.1 SNR to the distance between BT receiver and BT transmitter (large scale path loss only)

SNR can be obtained from receiver power (eqn (3.8)) over background noise (Refer to Section 3.1.1). When only large-scale path loss is present, SNR decreases with increase of the distance between the BLUETOOTH transmitter and receiver.



(a) Dbt via BER when only path fading is available



(b) Log-scale curve of (a) when BER scale is set at log scale

Figure 3.2 BER via distance between BT transmitter and BT receiver

Figure 3.2 (a) shows that if distance between the BLUETOOTH transmitter and the receiver is increasing from 1m to 70m, SNR will dramatically decrease to below 30dB.

Since the BLUETOOTH system uses GFSK, we may find its bit error rate early from (eqn(3.4)). Observe that Bit Error Rate will stay very low when *Dbb* is less than 20 meters (Figure 3.2(b)) since the amount of background noise is very small (Section 3.1.1). From the Figure 3.2, we can see BER will increase to more than 30% if *Dbb* is more than 70 meters. Figure 3.2 (b) displays that BER of the Bluetooth is not zero when *Dbb* is from 0 to 30 meters.

3.1.4 Small Scale Fading (Raleigh Fading distribution)

Small scale fading is used to describe the rapid fluctuation of the amplitude of a radio signal over a short period of time. Usually multi-path reflection in a small area, and slow movement can cause attenuation or distortion of signal. Some papers suggest using Nakagami [Nata60], Ricean or Rayleigh distributions to describe envelop of small scale fading. The Nakagami fading represents a wide range of multi-path channels via the m fading parameter. For instance, Natagami-m distribution includes the one-sided Gaussian distribution (m=1/2) and Rayleigh distribution (m=1) as special cases. If using Ricean distribution to describe envelop of small scale fading, this distribution is often described in terms of a parameter K that is defined as Ricean factor. When K is minus infinite, Ricean distribution degrades to a Rayleigh distribution. It represents the Rayleigh pdf associated with the worst case of fading per mean received signal power, e.q.,[Skla97] Therefore, we use Raleigh Fading Distribution to simulate small fading.

Usually, the type of fading experienced by a signal propagating through a radio channel depends on the nature of the transmitted signal with respect to the characteristics of the channel. In room condition, BLUETOOTH and WLAN devices cannot move fast. Therefore, we only consider flat and slow fading caused by multi-path variation of signal and low Doppler spread. The probability of error in AWGN channels can be viewed as a conditional error probability. That is to say, bit error probability in slow, flat fading can be obtained by averaging the error in AWGN channels over the fading probability density function.

Let *Pe* is the final BER going through small fading channel.

$$Pe = \int_0^\infty P_{ra}(\gamma)p(\gamma)d\gamma \quad . \qquad (3.9)$$

The $p(\gamma)$ is the probability of error for GFSK modulation at a signal to noise ratio γ. $P_{ra}(\gamma)$ is the probability density function of γ due to the fading channel. Now we assume that the fading channel is Rayleigh (Rayleigh fading is commonly used to describe the envelop of an individual multi-path component, [Section 4.6, Rapp96] and pdf of Rayleigh is:

$$P_{ra}(\gamma) = \frac{1}{\Gamma}\exp\left(-\frac{\gamma}{\Gamma}\right) \quad . \tag{3.10}$$

where Γ is the average signal to noise ratio in GFSK modulation measured from Section 3.1.3. Therefore, the probability of bit error rate of signal in GFSK passing through small scale fading channel – Rayleigh fading channel is:

$$Pe = \int_0^\infty e^{-\frac{\gamma}{2}}\left(0.5I_0(ab) + \sum_{k=1}^{\infty}\left(\frac{a}{b}\right)^k I_K(ab)\right) * \frac{1}{\Gamma} * \exp\left(-\frac{\gamma}{\Gamma}\right) d\gamma \quad . \tag{3.11}$$

Programs have been written in C language to calculate the differentiated area to obtain the value of error probability of bits using equation (3.11). In order to obtain an accurate *Pe* shown in eqn (3.11), proper values of sampling frequency for γ and number of the samples ($0 \sim \infty$) have to be determined for different Γ values.

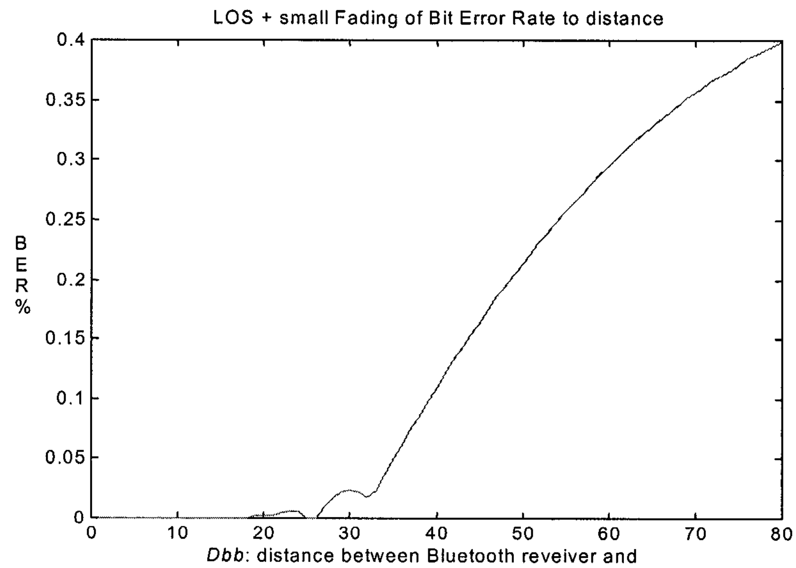


Figure 3.3 Bit error rate via distance between BT transmitter and BT receiver

Given the values of parameters like room temperature, signal bandwidth (See Section 2.7), the probability of error over the distance of path fading can be shown as Figure 3.3.

Changing parameters, like the power of transmitter, *KTBF* in Section 3.1.1, and the path distance can lead to a different value of SNR over the distance and also lead to a different threshold of BER over distance of path fading.

Figure 3.3 shows the performance of BLUETOOTH signal as it goes through both large-scale path loss and small-scale fading. Mathematically, error probability (Eqn3.11) is the function of signal to noise ratio Γ, and by incorporating Γ as a function of *Dbb*, we show in Figure 3.3 the BER as a function of *Dbb*. Since the performance is affected by multi-path component of signals, the BER does not appear to be stable when the distance between BT transmitter and receiver is about 20 to 30 meters. The reason is that the Signal to Noise Ratio (SNR) of the signal is not big enough in that area and the power of the signal can be strengthened or weakened when signal goes into small-scale environment due to multi-path reflection. Also in this area, the multi-reflection attenuation is heavier and presents some unstable status. This value leads to different values of packet loss rate performance to different packet types.

3.2 Hamming Code and Repetition code

After bit error rate going through fading in Section 3.1 is investigated, the packet loss rate performance needs to be evaluated. Since every voice packet has its own error correction part (FEC), the packets loss rate is different due to different types of FEC payload scheme. In this section, Hamming code and repetition code [Lin83] are the main components of voice packet's FEC. The Mathematical solution will be discussed for each voice packet format.

3.2.1 Packet Component

This packet format is the BLUETOOTH voice packet format – HV. If transmitting data, BLUETOOTH will use DM format that will not be introduced here because it is not used in my simulation for this thesis. BLUETOOTH has three kinds of voice packets type, HV1, HV2 and HV3. They have the same format as shown in Figure 3.4, but different FEC payload. HV1 is the basic packet format in the BLUETOOTH voice transmission. For the HV1 packet, it carries 10 information bytes. The bytes are protected with a rate of 1/3 FEC. The payload length is fixed at 240 bits.

Access code 72 bits	Header 54 bits	Payload 240 bits

Figure 3.4 BLUETOOTH packet format

3.2.2 Hamming Code in Access Code

LSB 4	64	4 MSB
PREAMBLE	SYNC WORD	TRAILER

Figure 3.5 Access Code in BLUETOOTH packet

Three kinds of voice packets use the same Access Code part as shown in Figure 3.5. The first part of Packet, 72 Access Code bits, uses hamming code (64, 30). The sync words are based on a (64,30) expurgated block code [BSIG99] with an overlay (bit-wise XOR) of a 64 bit full length PN-sequence such that hamming distance is *d min* =14. Since (64,30) Hamming code can guarantee the correction of all error patterns of $t=\lfloor(\text{dmin}-1)/2\rfloor$ or fewer errors, where $\lfloor\ \rfloor$ is the floor operator, we can correct all errors less than 6 in this case. Let *Pb* be the average bit error rate and assume those bits to be independent of each other (refer to assumption 2.7-13). Then the probability of no error of HV in Access part is therefore:

$$Pr\_Ac\_ok = \sum_{i=0}^{6} C_{64}^{i} P_b^{\,i} (1-P_b)^{64-i} \quad . \tag{3.12}$$

3.2.3 HV1 packet's Header and Payload Parts

HV1 packet type uses repetition code in Header and Payload part. The (3,1) repetition code can correct any single error bit out of three bits, but it cannot correct two or three error bits out of three. If some error bits cannot be corrected, the whole packet will be lost. Therefore, the performance is measured by probability of no error. Let P_b be bit error rate and *P(3bits)* be no error probability.

$$P(3bits) = 3P_b(1-P_b)^2 + (1-P_b)^3 \quad . \tag{3.13}$$

For the Header (54 bits) and Payload (240 bits) parts, let *Pr_H_Payload* be the no error probability.

$$Pr\_HV1\_Payload = P(3bits)^{\frac{54}{3}+\frac{240}{3}} \quad . \qquad (3.14)$$

From eqn (3.12) and (3.14), total packet loss rate is then

$$P\_HV1\_lost = 1 - Pr\_Ac\_ok * Pr\_HV1\_Payload \quad . \qquad (3.15)$$

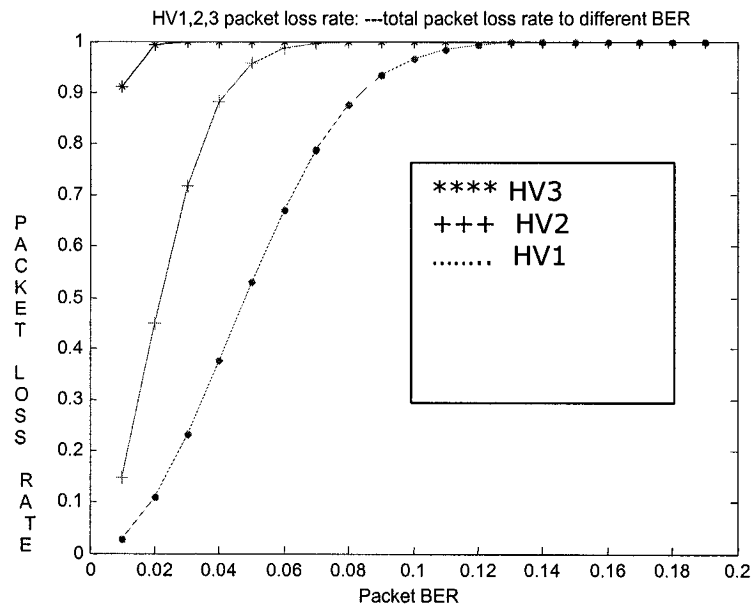


Figure 3.6 Packet-loss-rate via BER for three HV packets

Figure 3.6 shows the tendency of packet loss rate via different BER. The curve displays the situation when considering the all three parts of the packet. We can see that if BER is above 5 percent, the total packet loss rate will be higher than 50%.

3.2.4 Packet HV2

The **HV2** packets, which are protected by a rate 2/3 FEC, have 20 information bytes. Since the payload length is fixed at 240 bits and the FEC scheme is a (15,10) shortened Hamming code, each block of 10 information bits is encoded into a 15 bits codeword and total number of block is 240/15=16. This code can correct all single errors (max 16) and detect all double errors in each codeword.

If bit error rate is P_b, from equations in previous sections, the no error probability of access part of HV2 is

$$P\_HV2\_Access = \sum_{i=0}^{6} C_{64}^{i} P_b^{\,i} (1-P_b)^{64-i} \quad . \tag{3.16}$$

Since the Header part of HV2 uses (3,1) repetition code and the number of code words is 54/3=18, the no error probability of header part of HV2 is given by

$$P\_HV2\_Header = \left(3P_b(1-P_b)^2 + (1-P_b)^3\right)^{18} \quad . \tag{3.17}$$

The no error probability of Payload part of HV2 can be obtained as

$$P\_HV2\_Payload = \left((1-P_b)^{15} + 15P_b * (1-P_b)^{14}\right)^{16} \quad . \tag{3.18}$$

Therefore, the total packet loss rate of HV2 is

$$P\_HV2\_lost = 1 - P\_HV2\_Header * P\_HV2\_Payload * P\_HV2\_Access \quad . \tag{3.19}$$

3.2.5 Packet HV3

The **HV3** packets, which are not protected by any FEC, have 240 information bits. Since the payload length is fixed at 240 bits and the FEC scheme is a (15,10) shortened Hamming code, each block of 10 information bits is encoded into a 15 bits codeword and total number of block is 240/15=16. This code can correct all single errors (max 16) and detect all double errors in each codeword.

If bit error rate is P_b, from equations in previous sections, the no error probability of access part of HV3 is

$$P\_HV3\_Access = \sum_{i=0}^{6} C_{64}^{i} P_b^{\,i} (1-P_b)^{64-i} \quad . \tag{3.20}$$

Since the Header parts of HV3 packet uses (3,1) repetition code and the number of code words is 54/3=18, the no error probability of header part of HV3 is given by

$$P\_HV3\_Header = \left(3P_b(1-P_b)^2 + (1-P_b)^3\right)^{18} \quad . \tag{3.21}$$

The no error probability of Payload part of HV3 can be obtained as

$$P\_HV3\_Payload = (1-P_b)^{240} \quad . \tag{3.22}$$

Therefore, the total packet loss rate of HV3 is

$$P\_HV3\_lost = 1 - P\_HV3\_Header * P\_HV3\_Payload * P\_H32\_Access \quad . \tag{3.23}$$

From Figure 3.6, we can see FEC of HV1 packets can have the strongest error correction ability among several different FECs. Normally if BER reaches over 5%, packet loss rate will be greater than 40%. If we choose HV3 – the top curve, packet loss rate will remain at very high level since it has the least ability of error correction.

3.3 Performance Evaluation

There are many parameters one can consider in our simulation. Some important parameters are listed in Appendix A.1. In order to reduce some unnecessary simulation sets, some parameters have to be fixed. The large fading index is set to 3.5 for normal room situation, and the power of the BLUETOOTH transmitter is set to 1 mw and other power classes of BLUETOOTH will be discussed at Section 4.5. Since the effect of temperature to BLUETOOTH is limited (from Figure 3.8), we fix the room temperature at 290k ($17^{o}c$). WLAN packets-length is set to 8000 bits; power class of WLAN is typically set to 25 mw. Performance evaluation should focus on the following parameters:

1) BLUETOOTH packet types
2) Distance between BLUETOOTH transmitter and receiver
3) WLAN spreading methods
4) WLAN transmission rates

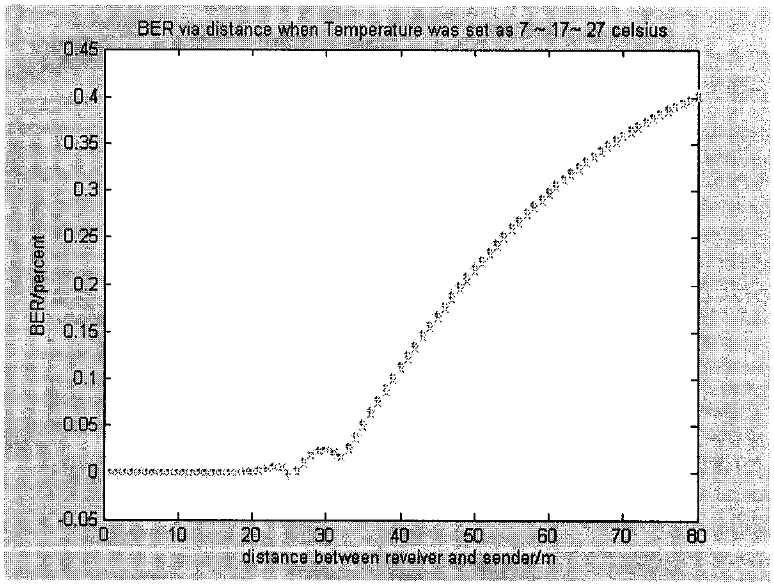


Figure 3.7 BER when temperature is set as 7~17~27 Celsius

5) Distance between BLUETOOTH receiver and WLAN transmitter
6) Number of piconets

Figure 3.7 shows that changing tendency of BER is nearly the same when room temperature is at the 7-27 Celsius range. One can see that temperature parameter has little effect on BLUETOOTH transmission BER.

This section only investigates the packet loss rate in a BLUETOOTH system without interference from 802.11b and piconet. From Section 3.2, we have the relationship of BER and packet loss rate due to different packet formats. The Figure 3.8 and 3.9 show that the packet loss rate is different from various situations, such as LOS fading, small fading. All Figures in this section are drawn by equations (in this chapter) implemented on MATLAB; they are not the simulation results.

Figure 3.8 show that when only considering large-scale fading, HV1, HV2 and HV3 do not have big difference. Only when the distance of the BLUETOOTH devices reaches 30 meters, can we see their differences. From Figure 3.8, the packet loss rate will keep at a low level if the distance between the BLUETOOTH transmitter and BLUETOOTH receiver is less tan 30 meters away. But the condition is that there is no small scale fading considered.

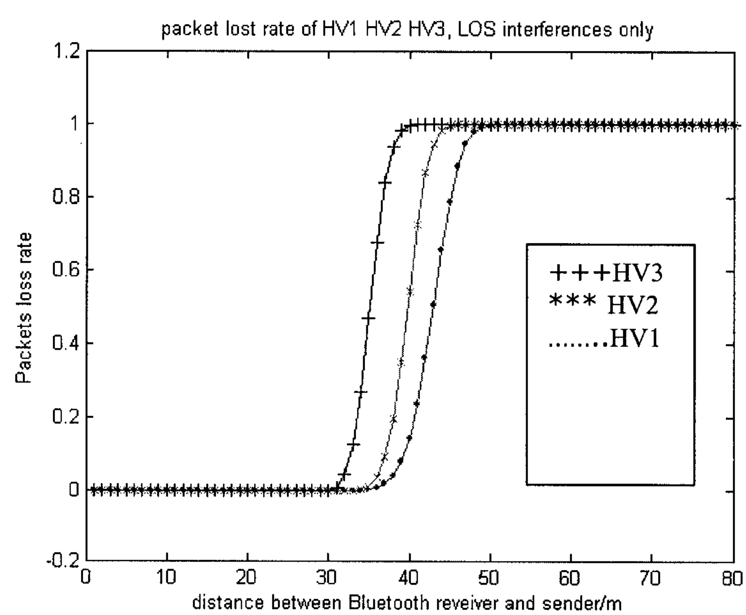


Figure 3.8 Packet-loss-rate with only large scale fading

The strong correction ability of HV1 FEC leads to its better performance comparing to other packet types. (Refer to Figure 3.8) When the path loss distance is longer than 40 meters, HV1 begins to drop its packets.

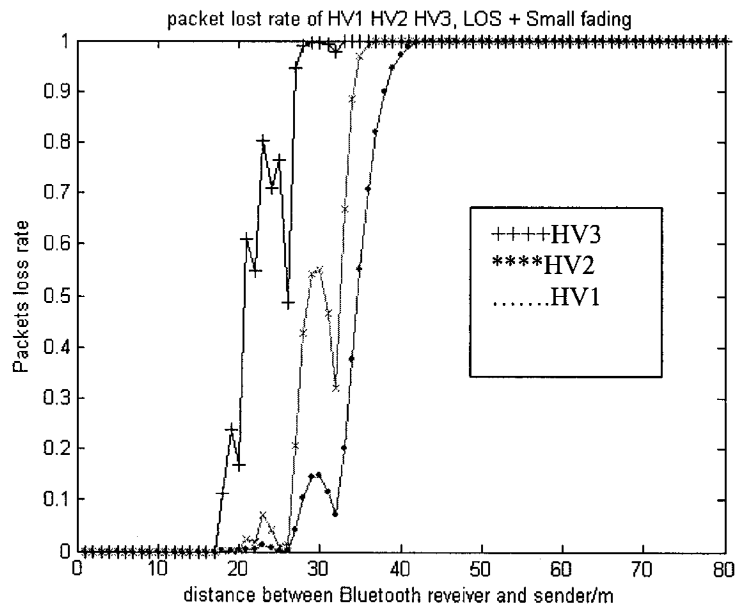


Figure 3.9 Packet-loss-rate in fading channel

In Figure 3.9, if we consider the factor of small scale fading, the packet loss rate shows some kind of unstable status when the distance is between 20-40 meters due to the characteristic of multi-path reflection. (Figure 3.3 shows an unstable BER and this BER leads to unstable packet loss rate here). Of course, HV1 has the best performance among three voice packet types.

3.4 Concluding Remarks

The accuracy, realistic, reliability and throughput are the major aspects in the physical channel modeling. In order to meet these requirements, the following designed issues have been implemented in the simulation.

1) Large fading: Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance, whether in outdoor or indoor radio channels. Therefore, lognormal path fading model is chosen.

2) Small scale fading: In room environment, WLAN facilities and BLUETOOTH facilities cannot move very fast (walking speed), then we don't need to consider Doppler frequency shift. The Rayleigh pdf represents the pdf associates with the worst case of fading per mean received signal power. Therefore, it is chosen in our simulation.

3) Power GFSK modulation: BLUETOOTH devices use GFSK modulation (in Section 3.1.2) and it is important to investigate physical channel modeling.

4) Background noise: A normal room environment is considered to calculate background noise, such as temperature and noise Figure (10 dB).

5) The parameter K (the Kth order of Bessel function) is used to calculate Bit Error Rate. By experience from simulation using C++ code, K can be set as 200 that we can obtain relatively accuracy.

6) In order to calculate bit error rate of signal passing through large and small scale fading, sampling frequency has to be decided to calculate eqn (3.11).

The result of the above implementation of physical fading channel shows that fading can be one factor to lead to a certain packet loss rate to the transmission of the BLUETOOTH system. But this effectiveness is not serious if the BLUETOOTH transmitter is within 15 meters away from the BLUETOOTH receiver and no other interference sources are available.

Ch4. Performance Evaluation in Different Interference Environments

While Ch3 evaluates the performance under a fading environment, this chapter shall focus on the IEEE 802.11b WLAN interference and piconet interference. The OPNET simulator will evaluate the BLUETOOTH performance.

The resulting Figures of simulation will be shown as a BLUETOOTH packet loss rate against the distance between the BLUETOOTH receiver and WLAN packets transmitter, which is the main interference source. The third parameter is the WLAN transmission types. The distance between the BLUETOOTH transmitter and the BLUETOOTH receiver will be set as 1 meters first, which is the nearest distance among them. Then we consider the BLUETOOTH system in the following situations:

1) Only the piconet interference is available
2) A WLAN interference device is put in the area of BLUETOOTH transmission.
3) Both the WLAN and the piconets interference are considered

Finally we consider those situations if the distance of the BLUETOOTH transmitter and the BLUETOOTH receiver are 2 meters and 3 meters in each situation.

4.1 The piconet Interference

If several piconets consist of a SCATTERNET, the interference among them cannot be avoided. In this section, a method of analysis will be introduced. MATLAB coding will implement the math formulas and display them in Figures.

From eqn (3.11) and the assumptions in Section 2.7, let the number of channel be *M*, let the number of interference sources be *K*, let *Ph* be the probability that at least one is at present in the desire frequency slot, then *Ph* is:

$$Ph = 1 - \left(1 - \frac{1}{M}\right)^{K-1} \approx \frac{K-1}{M} \quad . \tag{4.1}$$

Let P_{pico} be the probability of error when K piconets are at present, let Pe (in eqn (3.11)) be error probability of single piconet using GFSK modulation, from equation of [Rapp96] we have

$$P_{pico} = P_e * (1 - P_h) + o.5 * P_h \quad . \tag{4.2}$$

Then, put eqn (3.11) into eqn (4.2),

$$P_{pico} = \int_0^\infty e^{-\frac{\gamma}{2}} \left(0.5 I_0(ab) + \sum_{k=1}^{\infty} \left(\frac{a}{b} \right)^k I_K(ab) \right) * \frac{1}{\Gamma} * \exp\left(-\frac{\gamma}{\Gamma} \right) d\gamma * (1 - P_h) + 0.5 P_h \cdot \tag{4.3}$$

Therefore, the error probability of BLUETOOTH signals, which go through a fading channel, and the piconets interference, is as shown in eqn (4.3). BER Analysis result is shown in Figure 4.1 below.

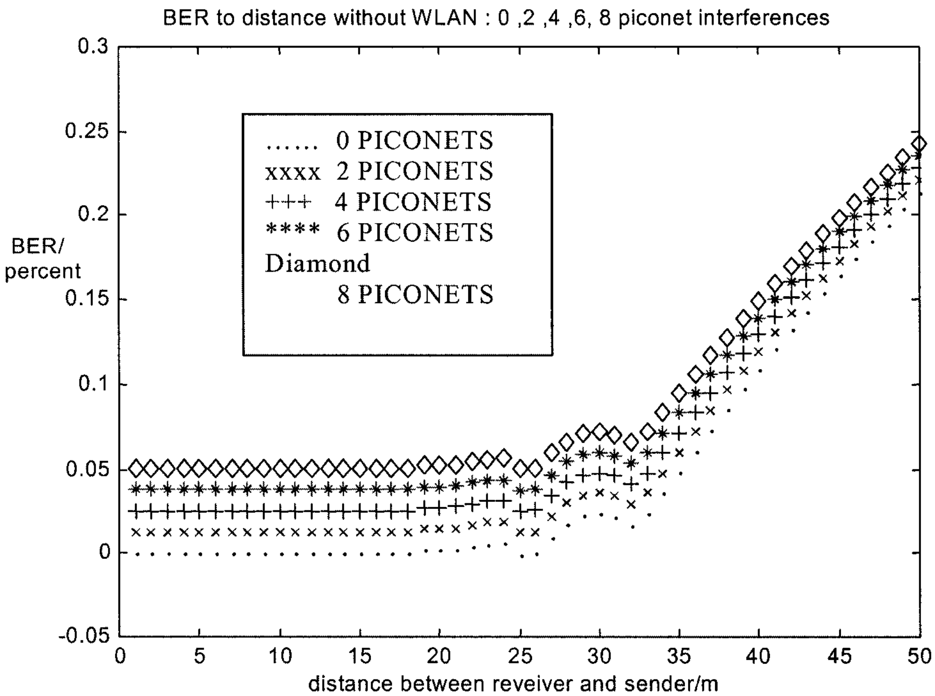
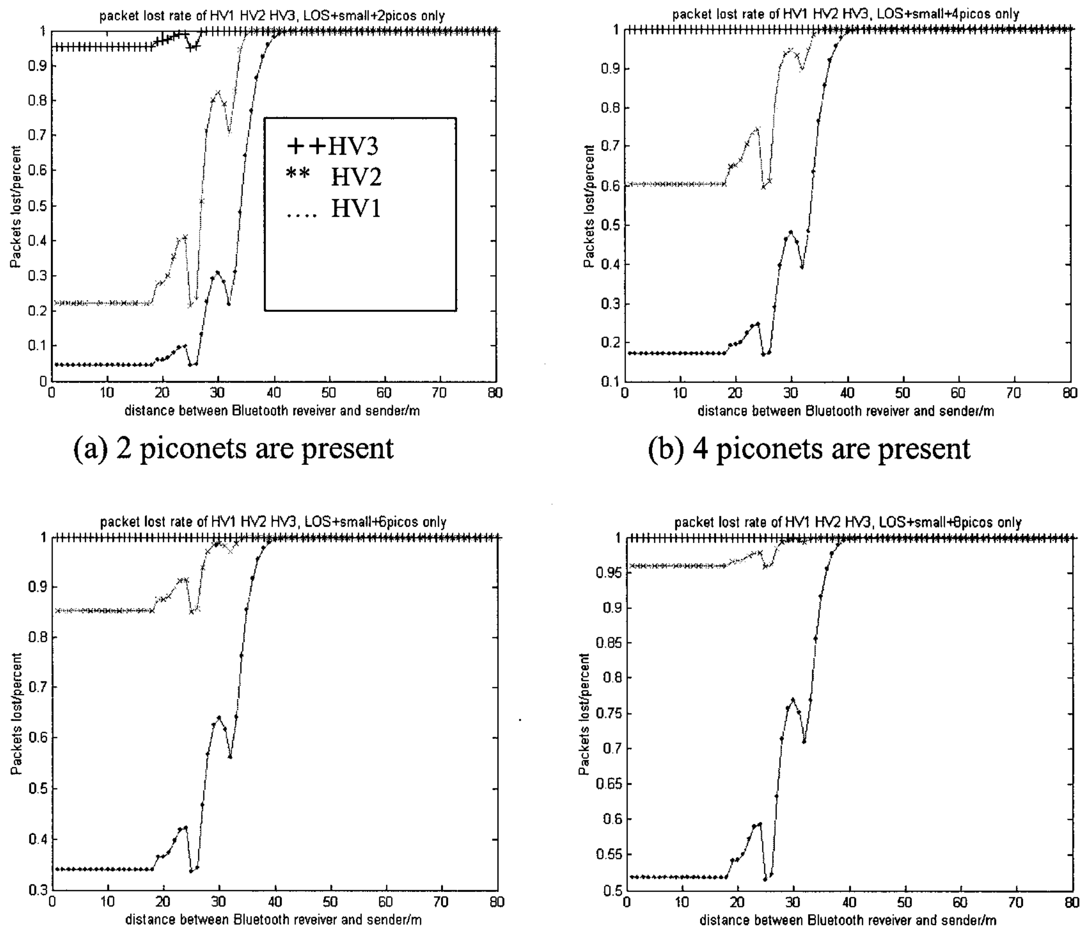


Figure 4.1 BER via distance between BT transmitter and BT receiver (0-8 piconets interference considered)

Refer to Figure 4.1, when no WLAN interference sources are present, the curve shows the tendency of BER via the distance between a BLUETOOTH transmitter and a BLUETOOTH receiver. When 8 piconets interference sources are at present, The BER will remain above 5% no matter what kind of situations they are in. When 2 piconets are there, the BER will stay above 1.5% around.

According to the analyses done in Section 3.2 and this section, HV1, HV2 and HV3 have difference packet loss rates when difference numbers of piconet interference are at present



(a) 2 piconets are present

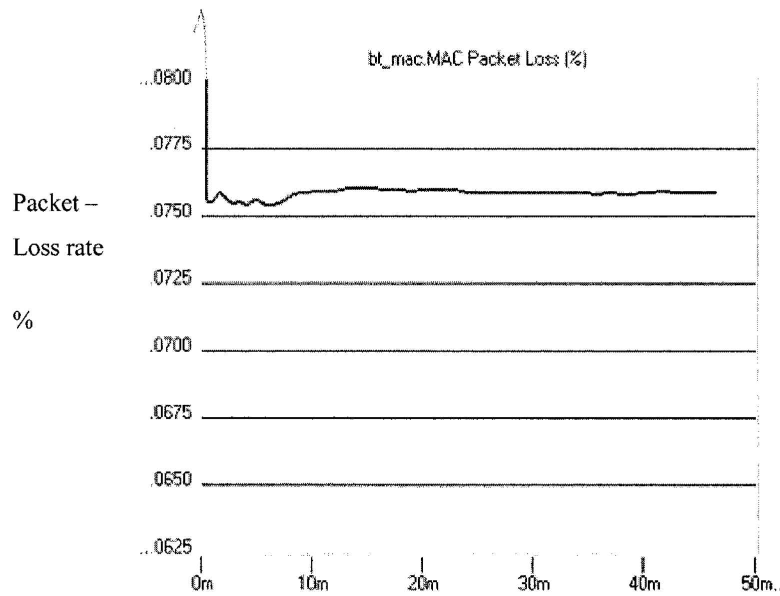
(b) 4 piconets are present

(c) 6 piconets are present

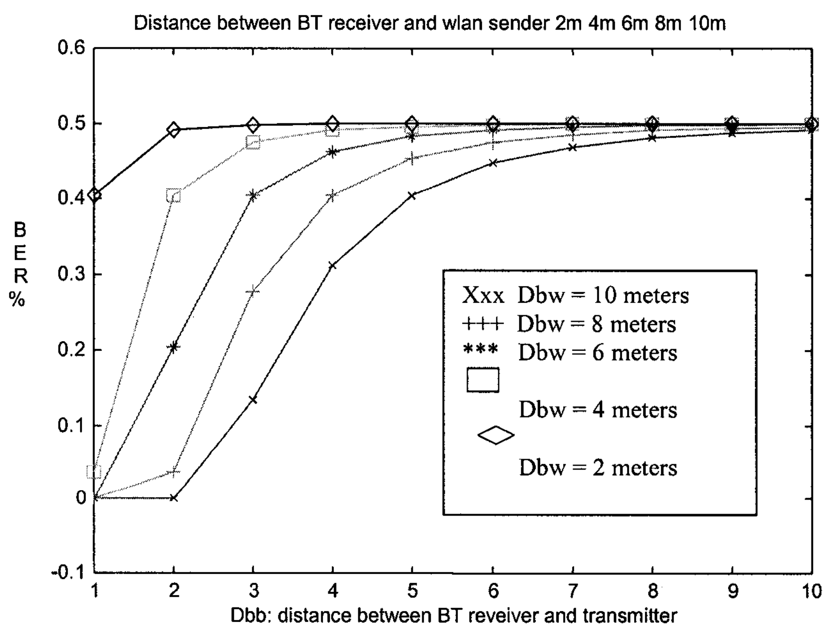
(d) 8 piconets are present

Figure 4.2 Packet-loss-rate with 0-8 piconets interference

Figure 4.2a, shows the packet loss performance as a function of the separation distance between the BLUETOOTH transmitter and the BLUETOOTH receiver (*Dbb*) when two piconets are present. Three curves shows the performance of packet type HV1, HV2 and HV3. For example, the packet loss rate of HV1 (Bottom curve) remains stable when *Dbb* is below 20 meters. But the packet loss rate becomes unstable when *Dbb* is 20–40 meters. The reason is that the BER of packets is an unstable in this range (Figure 4.1) and this kind of BER leads to its packet loss in unstable manner. When the range is over 40 meters, the packet loss rate will remain high since signal is fading over distance too much. In 4.2a, the probability of error will stay below 4% for HV1 packets, 20% for HV2 and 90% for HV3 within an area of 20-meter range. That is to tell that we cannot choose HV3 as voice packets type when there are two piconets interference sources there. Other curves in Figure 4.2 also display the similar trend of changes. But the packet loss rate of HV3 remains higher than 70% no matter how many piconets we choose.



(a) Packet loss rate via time



(b) BER curve via Dbb

Figure 4.3 BER via BT distance with WLAN

Figure 4.2b shows the same performance curves when four piconets are present. Similar performance is observed except that the value of packet loss rate to each packet type is higher than those in Figure 4.2a. From Figure 4.2b, only HV1's packets loss rate can be less than 20%, which is acceptable rate for the voice transmission. If there are more than 4 piconet interference sources, the voice transmission could be distorted too much to hear. (Figure 4.2c & d)

Conclusion is that piconet interference could be an important factor to the BLUETOOTH voice transmission.

4.2 Wireless LAN interference

In this section, WLAN is considered as the sole interference source to the BLUETOOTH transmission. Signal to Noise ratio (SNR) becomes signal to interference. (SNI). As in eqn (3.11), the probability of error (BER) can be obtained from SNR. According to fading analysis in Section 3.1.4, Figure 4.3 can be explained as below.

If the distance between a BLUETOOTH receiver and a WLAN transmitter is too close (top curve), the BER is very high even if the BT transmitter and the BT receiver are close to each other. On the other hand, if the distance between a BT transmitter and a BT receiver is greater than 4 meters, the BER will hit 30%, which leads to an unbearable quality of voice. Therefore, we could only set this parameter as 1 meter, 2 meters, and 3 meters only. Since a BLUETOOTH packet and a WLAN packet are randomly positioned in the same frequency and time domains, the packet loss rate can only be obtained from simulation. Generally, the closer between Bluetooth devices and WLAN device, it is larger to the BER of Bluetooth packets. The closer between Bluetooth devices, it is smaller to the BER of Bluetooth packets.

Figure 4.3(a) displays the typical time evolution of packet-loss-rate via time when the parameters of Blutooth and WLAN system are set at: Dbb=1meter, Dbw=4meter, WLAN spreading method =11 Mhz and no piconet. The packet loss rate performance is stable with a small fluctuation between 6% and 8%. The packet-loss-rate is the accumulative time average, Therefore, the rate is high in the beginning due to a small number of sample. Figure 4.3(b) show the bit error rate as a function of the separation distance between the BLUETOOTH transmitter and the BLUETOOTH receiver (*Dbb*). This Figure has five curves corresponding to the five kinds of distance (*Dbw*). The top curve, for example, depicts a tendency of the BLUETOOTH BER over *Dbw* = 2 meters. It shows the BER is higher than 0.4 when WLAN interference is near the BLUETOOTH transmitter. The other curves show the correspondent BER performance. When *Dbw* is 10 meters, the interference from WLAN is the lowest and the BER of the BLUETOOTH is the highest.

4.2.1 Collision Scenario

We have the assumption on Section 2.6 that WLAN 's traffic load is 100%.

Following Figure 4.4 shows the collision map under the assumption, which is that the WLAN device is transmitting packets all the time. In other words, the traffic load of the WLAN IEEE802.11b is 100 percent. The reason why we choose 100 percent traffic load is that the packet loss rate of BLUETOOTH is proportional to the traffic load of IEEE802.11b.

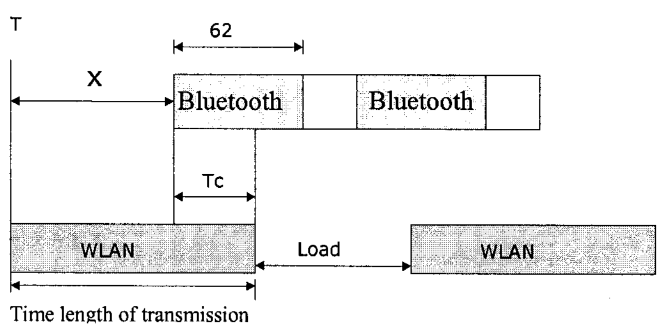


Figure 4.4 Collision scenario of WLAN and BLUETOOTH packets

Items 1: X from 0-Time length of transmission uniform

Items 2: Collision BER = Pc

Load time could be DIFS plus time of backoff window. If the BLUETOOTH packets are drop in lead-time of WLAN, there will be no collision. Only if the bits of the BLUETOOTH packet overlap with WLAN packet, can the bit error rate of overlapping bits of BLUETOOTH be increased to a level that we discussed in the previous sections.

4.2.2 Parameters

Using basic access pattern, we set the parameters as follow:

Table 4.1 WLAN Basic Accesses

	Slot time (us)	Data rate (Mbs)	DIFS (us)	SIFS (us)	Contention winsize
802.11 FHSS	50	1 & 2	128	28	16-1024
802.11b DSSS	20	1 & 2 & 5.5 &11	50	10	32-1024

In WLAN, we have two communication methods, FHSS and DSSS. They use different values of parameter. But we can use a mean channel BASIC ACCESS pattern like Figure 2.3. A typical packet transmission time includes:

Table 4.2 WLAN Parameters

	Frame bits	Length of physical head	Transmission time
frame payload	8000	N/A	8000/data rate
ACK/FHSS(data rate 1Mbps)	112	128	112 us +128us =240us
ACK/DSSS (data rate 1Mbps)	112	192	112us+192us = 304us

From all information above, we can set the WLAN packet transmission scenario.

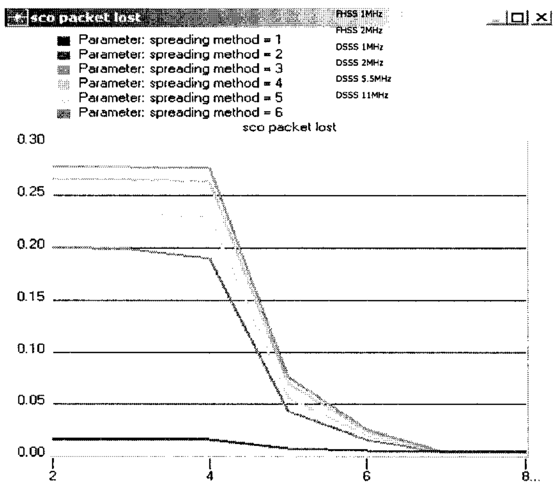
4.2.3 Packet Loss Rate Performance over WLAN (HV1)

The BLUETOOTH packet's format is shown in Figure 3.4. Since the payload of HV1 uses the most powerful error correction method, which is (1/3) repetition code, among these three packets types, the HV1 has the best voice-performance and the lowest packet loss rate. In this section, the simulation results are shown based on the following situations.

1. Distance between the BT transmitter and the BT Receiver is 1 meter
2. Distance between the BT transmitter and the BT Receiver is 2 meter
3. Distance between the BT transmitter and the BT Receiver is 3 meter

We will see the curve of the packet-loss-rate against the distance between the BT receiver and the WLAN transmitter. Also we set the third parameter as hopping pattern of WLAN, which is FHSS 1 Mhz, FHSS 2Mhz, DSSS 1Mhz, DSSS 2Mhz, DSSS 5.5Mhz and DSSS 11Mhz separately.

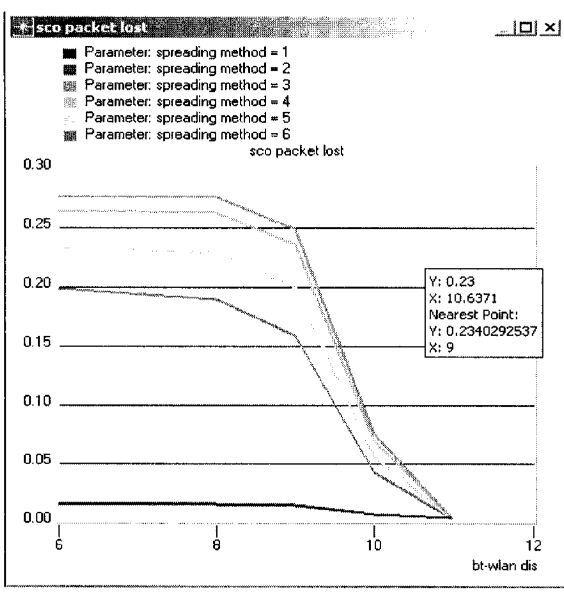
Also we will run these simulations and show the simulation results under the interference of piconets. The WLAN spreading method (FHSS and DSSS) and transmission rate can be seen in Chapter 2.1.



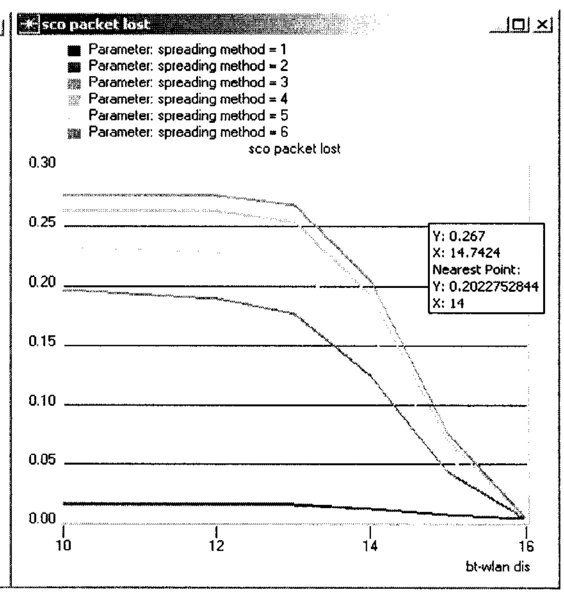
(a) *Dbb*=1 meter

Spreading method =1	means	WLAN use FHSS	1	MHz
Spreading method =2	means	WLAN use FHSS	2	MHz
Spreading method =3	means	WLAN use DSSS	1	MHz
Spreading method =4	means	WLAN use DSSS	2	MHz
Spreading method =5	means	WLAN use DSSS	5.5	MHz
Spreading method =6	means	WLAN use DSSS	11	MHz

(b) WLAN's 6 kinds of spreading methods



(C) *Dbb* =2 meter



(d) *Dbb* =3 meter

Figure 4.5 Packet-loss-rate of HV1 via distance between BLUETOOTH and WLAN

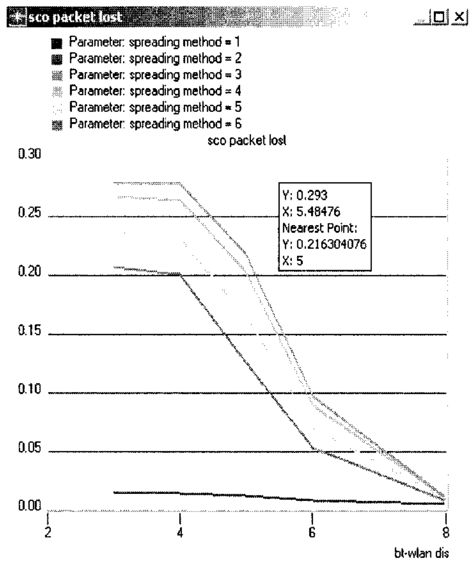
Fig 4.5a shows the BLUETOOTH packet loss rate as a function of the separation distance between the BLUETOOTH transmitter and the WLAN transmitter (*Dbw*) when only the WLAN is present. This Figure has six curves corresponding to the six kinds of

WLAN transmission rate. The top curve, for example, depicts a tendency of the BLUETOOTH packet loss rate over WLAN DSSS 1MHz. It shows 27% packet loss rate of BLUETOOTH when *Dbw* is lower than 4 meters. This loss rate has a sharp decrease to below 2.5% when *Dbw* is larger than 7 meters. The reason is that the fading of WLAN becomes larger and larger when the WLAN transmitter is far away. This fading leads to an increase of SNR and a drop of BER. Figure 4.5c shows the same performance curves when the distance of BLUETOOTH and WLAN (*Dbw*) is less than 12 meters. Similar observation is observed except that the packet loss rate begins to decrease when *Dbw* is larger than 12 meters. In our simulations, *Dbw* is an integer parameter. Therefore, the performance curves in the Figures are not very smooth. All following curves show similar trend.

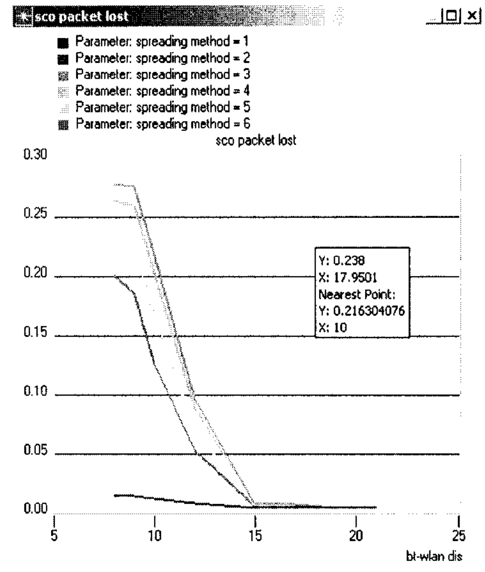
From Figure 4.5 above, we can summarize the observations

1) When *Dbw* is 1 meter, HV1 has the best performance.
2) Its BT-rate (BLUETOOTH packet-loss-rate) will be 1-2% if only considering the WLAN FHSS as the interference source. For example, when *Dbw* (distance between BLUETOOTH transmitter and WLAN) is 7 meters, BT-rate will decrease to below 1% when *Dbw* is above 7 meters (Figure 4.5a).
3) BT-rate will be 20-30% if considering the WLAN DSSS transmitter as an interference source. As example in Figure 4.5a, when *Dbw* is 7 meters, BT-rate of HV1 will decrease to below 1% when the distance is above 7 meters. The WLAN DSSS transmitter has the wide frequency band (22 MHz) and it leads to the increasing of collision possibility between the BT and WLAN packets. Due to the increment of the distance, the WLAN transmitter has less power to affect the BT transmitter.
4) When the WLAN adopt DSSS 11 MHz as its spreading method, the BLUETOOTH have the least packet loss rate comparing with other DSSS methods. The reason is that packet length of WLAN will be the shortest at this situation.
5) The larger the distance between BLUETOOTH and receiver, the higher the packet loss rate.

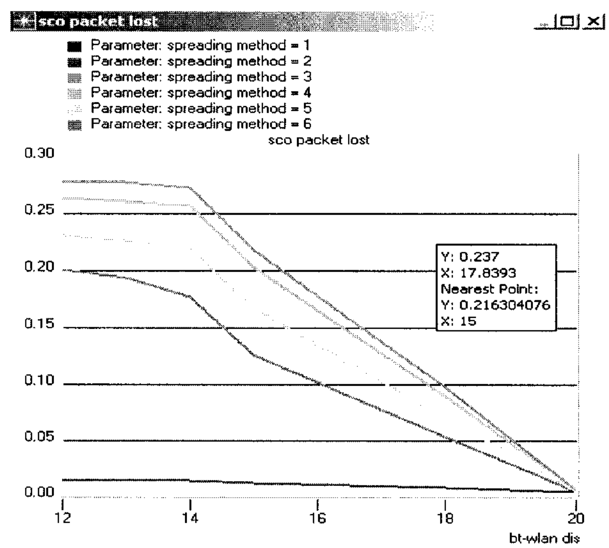
4.2.4 Packet Loss Rate Performance over WLAN (HV2)



(a) *Dbb* =1 meter



(b) *Dbb*= 2 meters



(c) *Dbb* = 3 meters

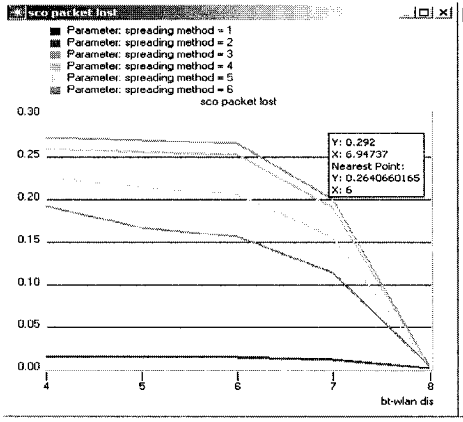
Figure 4.6 Packet-loss-rate of HV2 via distance of BLUETOOTH and WLAN

The BLUETOOTH performance is shown in Figure 4.6 when HV2 packet type is used. Figure 4.6 also show the BLUETOOTH packet loss rate of HV2 as a function of separation between the BLUETOOTH receiver and WLAN transmitter when only WLAN is present. HV2's performance is worse than that of HV1 because of its worse FEC. Comparing to Figure 4.5; Figure 4.6 shows the similar performance curves but different values where the HV2 packet loss rate begins to decrease. In both Figure 4.5c and Figure 4.6b as for an example, the *Dbb* is all set to 2 meters. The packet loss rate of HV1 starts to decline when *Dbw* is more than 8 meters, but it is 10 meters instead for HV2. The FEC of HV1 is more effective than HV2's one. The performance differences between HV1 and HV2 can be summarized as follow.

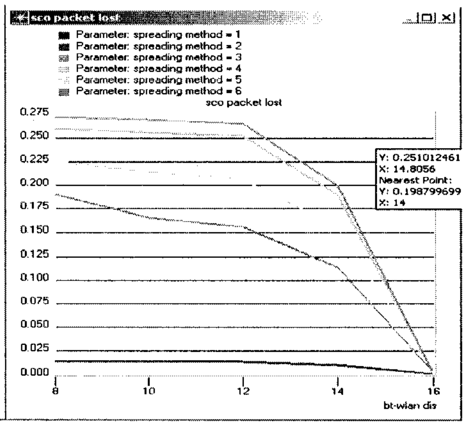
1) The packet loss rate of HV2 begins to decrease at a large *Dbw* value
2) The slope of this decrease is smaller than that of HV1.

4.2.5 Packet Loss Rate Performance over WLAN (HV 3)

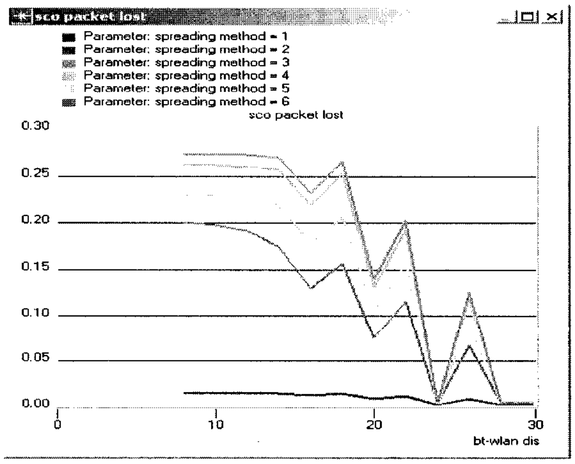
For HV3 packet type, we only consider the situation without piconet interference because BT-rate will be at least as high as 90% with 2 piconets at present. (See Section 3.)



(a) *Dbb* = 1meter



(b) *Dbb* = 2 meter



(c)*Dbb* =3 meter

Figure 4.7 HV3's Packet-loss-rate via distance between BLUETOOTH and WLAN

Figure 4.7 shows the BLUETOOTH packet loss rate of HV3 as a function of separation between the BLUETOOTH receiver and the WLAN transmitter. Comparing to Figure 4.6, Figure 4.7 shows the similar tendency of packet loss rate except when the distance between the BLUETOOTH transmitter and receiver is set as 3 meters away, the packet loss rate of it shows a kind of very large unstable status. When running the simulation of Figure 4.7, the parameter of distance between the BLUETOOTH and WLAN is set as 20,22,24,26,28,30 meters separately from 20 to 30 meters. Because HV3 has no error correction FEC in its packet payload and BER of it shows random changes in this area, the packet loss rate of HV3 also shows a kind of unstable change. It is very sensitive to be affected by the WLAN transmission. Only after the WLAN device is far away enough, can packet loss rate become stable. Other Figures in later sections probably show similar situations and the reason is the same as above.

4.2.6 The Performance Comparisons of HV1, HV2 and HV3 :

This section will do the comparison of different packets using table explanation. The basic parameters are still the BT-rate and *Dbw*. We let BT_rate be the packet loss rate, let *Dbb* be the distance between the BLUETOOTH transmitter and BLUETOOTH receiver. Let "BT-rate starting to decline" be the distance of BLUETOOTH receiver and WLAN transmitter when the packet loss rate is starting to decrease. Let "BT-rate of DSSS is lower than 10%" be the distance of the BLUETOOTH receiver and WLAN transmitter when packet loss rate is less than 10 percent. Let "BT-rate be lower than 1%" be the distance of the BLUETOOTH receiver and WLAN transmitter when packet loss rate is less than 1 percent.

Table 4.3 Performance Comparison

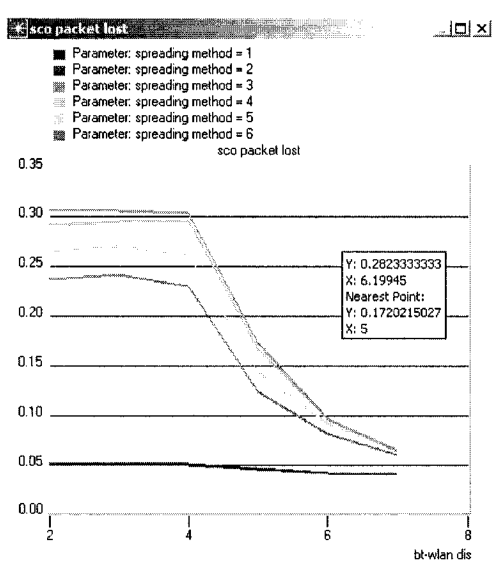
No piconets interference	BT-rate starting to decline	BT-rate of DSSS is lower than 10%	BT-rate is lower than 1%
HV1 (*Dbb*=1m)	4meters	5 meters	7 meters
HV2 (*Dbb*=1m)	4meters	6 meters	8 meters
HV3 (*Dbb*=1m)	4meters	7.5 meters	8 meters
HV1 (*Dbb*=2m)	8meters	10meters	11meters

HV2 (*Dbb*=2m)	8meters	12meters	15meters
HV3 (*Dbb*=2m)	8meters	15meters	16meters
HV1 (*Dbb*=3m)	13meters	15meters	16meters
HV2 (*Dbb*=3m)	12meters	18meters	20meters
HV3 (*Dbb*=3m)	12meters	>22meters	>22meters

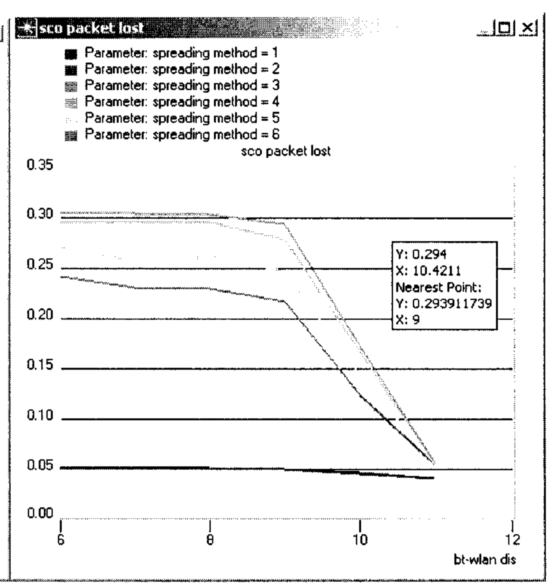
The above Table shows the resulting simulation with three different situations, in which *Dbb* is 1 meter, 2meters and 3 meters separately. When *Dbb* is set as 1 meter, their performances of BT-rate do not have a large difference. But with increasing of this value, we can see the various performances.

4.3 Performance Evaluation under WLAN and piconet

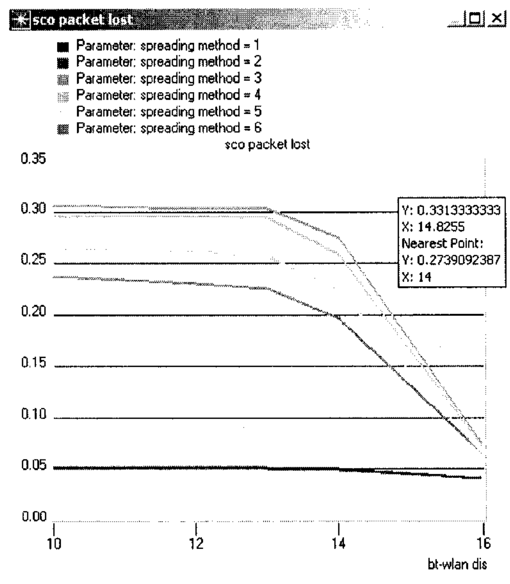
In this section, the performance evaluation will be done considering that both WLAN and piconets interferences are at present in a fading channel. By applying equation in Section 4.2 and 4.3 on OPNET, the evaluation is divided into three categories, HV1, HV2 and HV3 as follows:



(a) BT_BT= 1 meter



(b) BT_BT= 2 meter



(c) BT_BT= 3 meter

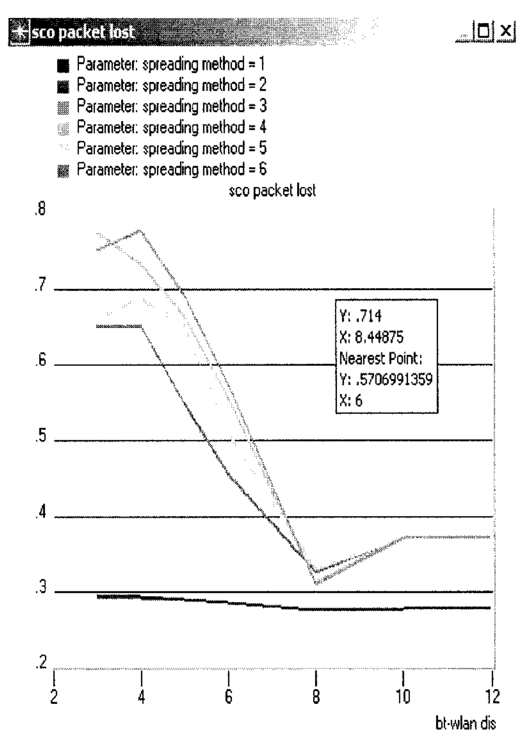
Figure 4.8 HV1's performance with two piconets and WLAN

Figure 4.8 shows the BLUETOOTH packet loss rate of HV1 as a function of separation between the BLUETOOTH receiver and WLAN transmitter when both piconet and WLAN are present. The Figure has six curves corresponding to six different WLAN transmission rate. Similar observation of tendency is observed with Figure 4.3 except the following observations.

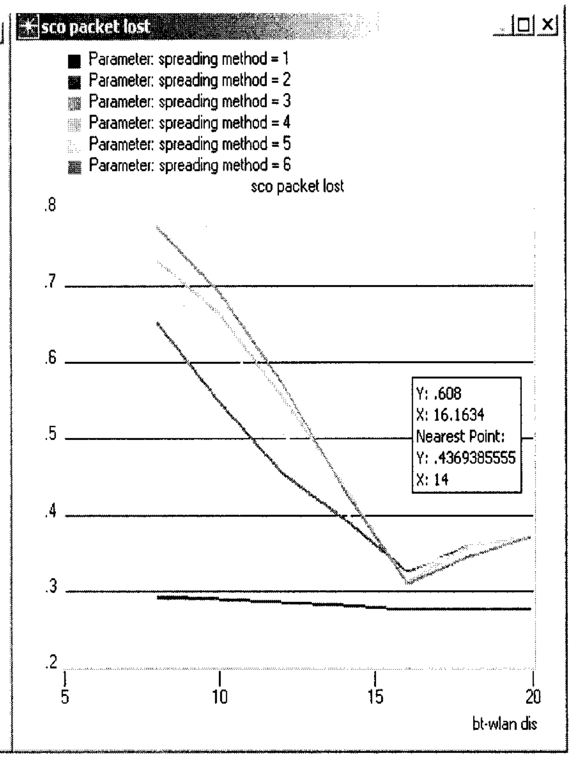
1) When WLAN uses FHSS hopping method as its hopping pattern, the packets loss rate will be around 5%.

2) When WLAN uses DSSS as it spreading pattern, the packet loss rate will gradually decrease to 5% with increasing the distance between WLAN and BLUETOOTH.

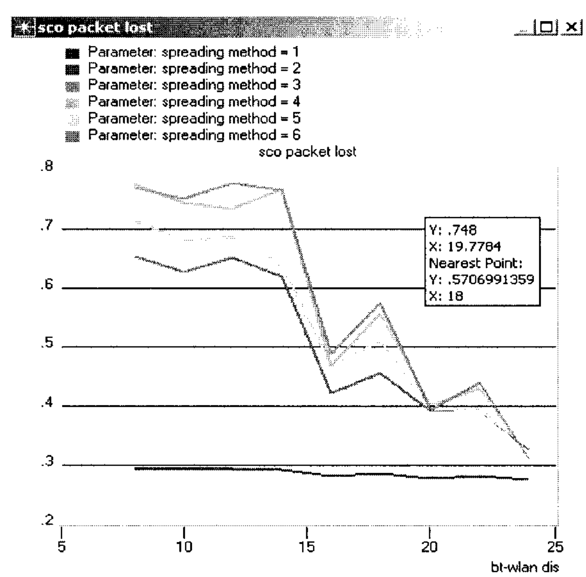
3) The distance between the BLUETOOTH transmitter and receiver will greatly affect the performance of BLUETOOTH transmission. For example, 4.6(a), (b) and (c) display that when this distance is set as 1 meter, 2 meters and 3 meters respectively.



(a) BT_BT= 1 meter



(b) BT_BT= 1 meter



(C) BT_BT= 1 meter

Figure 4.9 HV2's performance with two piconets and WLAN

Figure 4.9 also shows the BLUETOOTH packet loss rate of HV2 as a function of serration between the BLUETOOTH receiver and WLAN transmitter. HV2's performance is worse than HV1 because of its worse FEC. Comparing to 4.8; Figure 4.9

shows the similar performance curves but different values where the HV2 packet loss rate begins to decrease. It can be summarized as follow.

1) When WLAN uses FHSS, the packet loss rate of BLUETOOTH is around 30%, which is not acceptable to voice transmission.

2) Those curves display an unstable status. The reason is that the correction ability of FEC of HV2 is not strong enough to overcome bit error rate of packets and packets loss rate is very 'sensitive' to any errors happened in packets. Similar explanation can be seen in the explanation of Figure 4.7.

For HV3's performance, when two piconets are at present, performance of BLUETOOTH transmission is the worst one since no FEC on HV3's payload part. No matter how close the BLUETOOTH transmitter and the receiver are, packet loss rate will be higher than 80%. Most of information bits are lost.

Therefore, only the packet type HV1 can be chosen when there is piconets interference at present.

4.4 A Proposal to Improve The Performance of System

Based on our performance in the simulation and evaluation, we would like to improve the system performance based on the following observations.

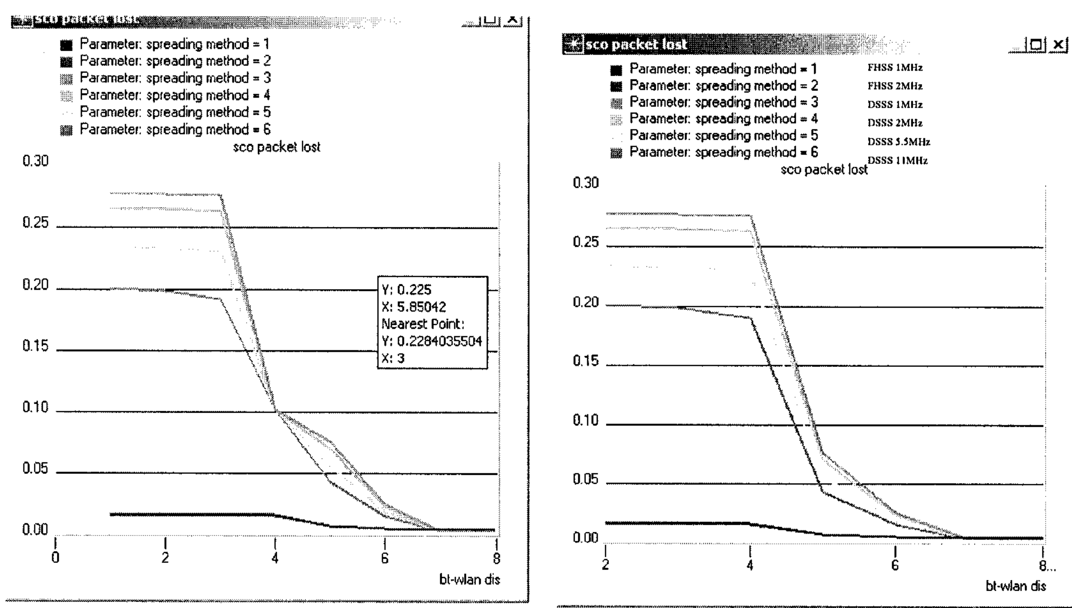
Table 4.4 Power classes

Power Class	Maximum Output Power (Pmax)	Nominal Output Power	Minimum Output Power[1)]	Power Control
1	100 mW (20 dBm)	N/A	1 mW (0 dBm)	Pmin<+4 dBm to Pmax Optional: Pmin[2)] to Pmax
2	2.5 mW (4 dBm)	1 mW (0 dBm)	0.25 mW (-6 dBm)	Optional: Pmin[2)] to Pmax
3	1 mW (0 dBm)	N/A	N/A	Optional: Pmin[2)] to Pmax

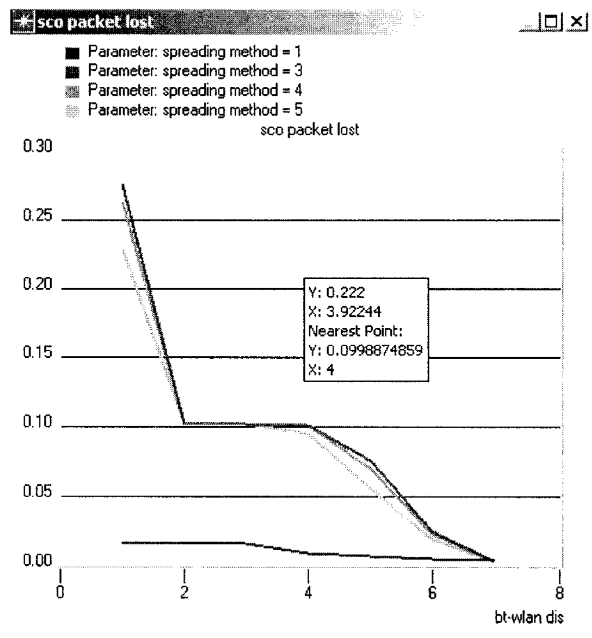
Referring to Table 4.4 above are three power classes that are defined by BLUETOOTH specification. Since BLUETOOTH devices are generally designed for short-range applications, it is not practical to increase the power assumption of a small and portable devices to 100 mw, so the Power Class 3 is the main option for most of current BLUETOOTH devices. This is used in all of the performance evaluations of this thesis.

Power Class 2 may be another good choice to improve the performance of BLUETOOTH voice and data transmission. The principle is simple. Let us say that a threshold is set at 10 percent of packet loss rate. Whenever the packet loss rate is above 10%, the power of BLUETOOTH transmitter will be increased to 2.5 mw from 1mw. Such change can improve the signal to noise ratio, improve the bit error rate and therefore reduce the packet loss rate. Under the normal situations of packet loss rate below 10 percent, power level reset back to 1 mw to save the battery energy of the devices.

Figure 4.10 shows the BLUETOOTH packet loss rate of HV1 as a function of separation between the BLUETOOTH receiver and WLAN transmitter when WLAN are present. The Figure 4.10 has six curves corresponding to six different WLAN transmission rate. Distance of the BLUETOOTH transmitter and receiver is set as 1 meter.



(a) Power dynamic control (the Power Class 2) (b) 1mw power output (the Power Class 3)



(C) 100mw power control (the Power Class 1)

Figure 4.10 Performance of power control

Figure 4.10a depicts HV1's performance when the BLUETOOTH system uses the 2nd Power Class in Table 4.4. The power of the BLUETOOTH transmitter increases to 2.5mw from 1mw (Standard configuration) whenever the packet loss rate is higher than 10%. Therefore, the curves converge when *Dbb* is 4 meters. If this packet loss rate is less than 5%, the power of the BLUETOOTH transmitter decreases to 1 mw. Then, the quality of voice can be improved at an acceptable level. (See Chapter 5 MOS rating table) The performance of BLUETOOTH with power control is 20% better than the one without power control (Figure 4.10b). Figure 4.10b depicts HV1's performance when WLAN is at present and the 3rd Power Class in Table 4.4 is used by system. The power is fixed at 1mw.

Figure 4.10c displays curves of the 3rd Power Class. In Figure 4.10c, whenever a packet loss rate is above 10 percent, the power of transmitter will be increased until the packet loss rate is below 10%. Since the maximum of the 1st Power Class is 100 mw, the packet loss rate decreases to 10 % very quickly and is stable when *Dbw* is 2 to 5 meters. Then it decreases slowly.

The following comparison table can give us reference to see their differences. Let the packet loss rate be P_loss, let *Dbw* be the distance between WLAN and BLUETOOTH.

Table 4.5 Comparison of power control

WLAN DSSS 11MHz	*Dbw* when P_loss start to decline	*Dbw* when P_loss is lower than 10%	*Dbw* when P_loss is lower than 2%
The 1st Power Class (100mw)	1meter	2meter	7 meter
The 2nd Power Class (2.5mw)	3 meter	4 meter	7 meter
The 3rd Power Class (1mw)	4 meter	5 meter	7 meter

Definitely, the dynamic power control (100mw) has the best performance among them. But it needs portable BLUETOOTH devices with the correspondent battery facility. Hence it will increase the burden of these devices. Probably, Power Class 2 is realistic to be adopted by the BLUETOOTH devices.

4.5 Concluding Remark

When the interference and fading issues are considered together, the following designed issues have been implemented in the simulation.

1) Distance: The BLUETOOTH devices are working in a small area (~10 meters). Since WLAN devices use more powerful class (25mw), the BLUETOOTH devices can be affected within 30 meters range. The largest distance between the BLUETOOTH receiver and the WLAN transmitter is set to 30 meters.
2) Traffic load: In order to investigate the worst interference scenario, the traffic load with 100% of WLAN is set. Therefore, a WLAN transmitter is continually sending packets to affect the BLUETOOTH transmission. Since the BLUETOOTH packet loss rate is proportional to this traffic load, it is not necessary to investigate those patterns with different traffic load.
3) The WLAN spreading methods and speed: WLAN 802.11b has six kinds of transmission rate (1, 2, 5, 11MHz) and two spreading methods (FHSS, DSSS).

Therefore, the BLUETOOTH performance curves have been drawn by different spreading methods and transmission rate of WLAN.

4) piconets interference: The network is capable of measuring interference from muti- piconet nodes but no real piconet nodes are put on the BLUETOOTH network. A parameter of it is put on the proposed network instead. This kind of interference can be displayed in the simulation sets through math calculation.

5) The power solution in Ch4.4 can improve the QOS of Bluetooth, but it will be limited to use since more increasing power of BLUETOOTH devices will lead to more interference to WLAN transmission.

Analysis in this chapter displays that the interference from WLAN and other piconets can affect greatly to the BLUETOOTH voice performance evaluation. Two more piconets will highly degrade the performance of BLUETOOTH. But some methods can used to improve the performance. As for example, the BLUETOOTH system using HV1 packet can have a better performance than the one using other packet types; dynamic power control can improve the system performance.

Ch5. Voice Performance

After evaluating the performance of BLUETOOTH system in CH3 and CH4, We need to know now how those parameters can affect the quality of voice in a BLUETOOTH system. The MOS rating (Mean Opinion Score) will be introduced and be the main tool to evaluate the performance of voice under the different perspective conditions.

5.1 Voice System & MOS rating

Human voice is recorded as a .wav file by windows recorder using PCM speech coding technique. With the help from MATLAB software, we can get analog information that how MATLAB digitized voice. Thereafter, applying CVSD speech coding technique, which is used by the BLUETOOTH system as its coding technique, we made an A/D converter that converted analog information into digital bits format. Those bits information will be the input of the BLUETOOTH system on the OPNET platform.

Rapport [Rapp96] recommends a reference system. The most popular ranking system is known as the mean opinion score or MOS ranking. This is a five-point quality-ranking scale with each point associated with standardized descriptions: bad, poor, fair, good, and excellent. Next Table will show this:

Table 5.1 MOS Quality Rating [Rapp96]

Quality Scale	Score	Listening Effort Score
Excellent	5	No effort required
Good	4	No appreciable effort required
Fair	3	Moderate effort required
Poor	2	Considerable effort
Bad	1	No meaning understand with reasonable

5.2 CVSD-Speech Coding

Of the several speech coding methods available, CVSD is chosen here because it has obvious advantages over PCM and ADPCM and it is chosen in specification [BSIG99]. A/D and D/A conversions will be made based on this speech-coding algorithm. Using PCM voice recorder in windows, an analog voice file is sampled at 64k per second frequency. Wave-read function in MATLAB can dismantle this voice into a double data-array whose values is from –1 to +1. Let it times 2^{15} as in the following Table.

5.2.1 CVSD Parameter

Table 5.2 CVSD Parameters

Parameter	Value
h	$1-\frac{1}{32}$
β	$1-\frac{1}{1024}$
J	4
K	4
δ_{min}	10
δ_{max}	1280
y_{min}	-2^{15} or $-2^{15}+1$
y_{max}	$2^{15}-1$

All the CVSD parameters are in Table 6. [BSIG99] In the decoding pipeline stage, if the 4 (J or K) Previous bits are the same, we need to increase or decrease the delta = delta + 4*delta (min). Delta (min) = 10. Maximum and minimum values are 2^{15} and -2^{15} separately. When delta is lager than 1280, delta should be set as 1280. If the 4 previous respecting bits are not the same, value of delta and y will be reduced according to fading factor 1/32 and 1/1024.

5.2.2 CVSD Algorithm

Since the resources in MATLAB can help me to do A/D conversion, CVSD conversion m-file on MATLAB is made according to the specifications of BLUETOOTH.

CVSD, the speech coding of the BLUETOOTH system, uses 64 kb/s (generally at least 32k) log PCM format as its input to create a relatively more robust binary output format. The latter format applies an adaptive delta modulation algorithm with syllabic commanding. The voice coding on the line interface should have a quality equal to or better than the quality of 64 kb/s log PCM, but can save half number of bits for transmission. Detail can be seen in Appendix B.

5.3 Quality of Voice (Listening Test on MOS)

Quality of voice will be evaluated in this section at the MOS level, which should be done by human ears. Here we have 5 people in a group, who made their MOS evaluations to voice file with different packet-loss-rate from 0.28-40% as shown in the following Table. The average result will be the MOS reference for evaluation. The students BJ, CJ, LH, QY and MG are students who participated in my MOS rating experiment.

Table 5.3 MOS Rating

	Students						
BT-rate %	BJ	CJ	LH	QY	MG	Total	Average
0.28	4.9	4.8	4.9	4.9	5	24.5	4.9
0.7	4.7	4.7	4.8	4.8	4.8	23.8	4.76
1	4.6	4.6	4.7	4.7	4.7	23.3	4.66
1.4	4.6	4.5	4.6	4.6	4.7	23	4.6
3	4.4	4.5	4.5	4.5	4.6	22.5	4.5
6	4.2	4	4	4	4.5	20.7	4.14
10	4	3.7	3.6	3.5	3.7	18.5	3.7
15	3.5	3.5	3.5	3	3.6	17.1	3.42
22	3	3.5	3	2	3	14.5	2.9
28	2.6	3	2	1.5	2	11.1	2.22
34	1.7	2	1.4	1	1.6	7.7	1.54
38	1.3	1.5	1	1	1.5	6.3	1.26
40	1	1	1	1	1	5	1

The above Table 5.3 shows the results of these five people who have done the evaluation of voice on MOS rating. Therefore, we can convert data of the packet loss rate from previous chapter into MOS rating in order to let people understand the quality of voice in an easier way.

From previous chapter, we have the following parameters to evaluate the performance of the BLUETOOTH voice into interference environment:

1) MOS rating
2) *Dbb*
3) *Dbw*
4) The spreading types of the WLAN transmission:
   Spreading method 1: FHSS 1Mhz
   Spreading method 2: FHSS 2Mhz
   Spreading method 3: DSSS 1Mhz
   Spreading method 4: DSSS 2Mhz,
   Spreading method 5: DSSS 5.5Mhz
   Spreading method 6: DSSS 11Mhz

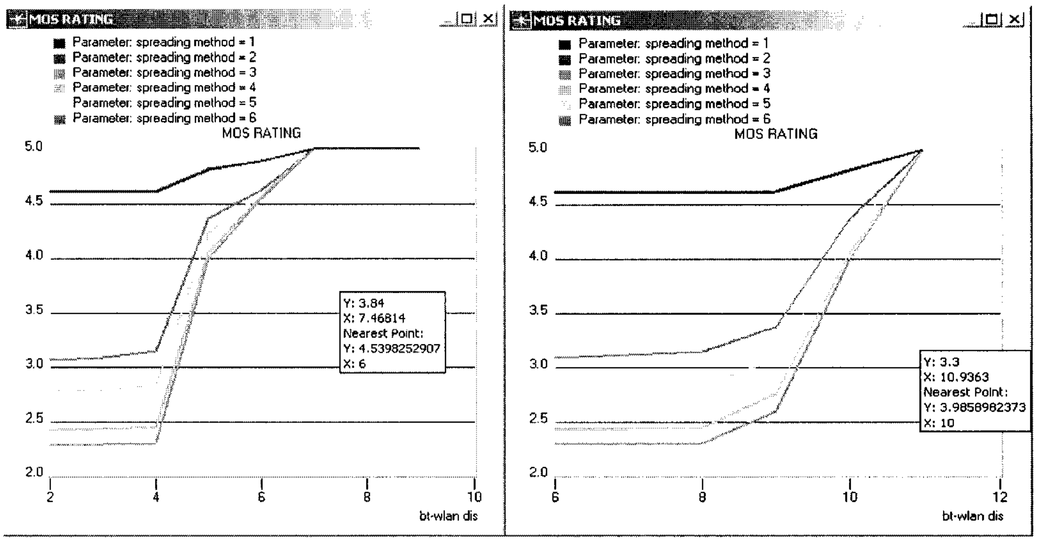
The relative positions among BLUETOOTH receiver, BLUETOOTH transmitter and WLAN interference device are very important to lead to the difference of the BLUETOOTH packet loss rate. Our Figure curves show that the MOS rating via *Dbw* and the third parameter is spreading types of WLAN interference. Here we set *Dbb* as 1meter, 2meters and 3meters to see the different performance.

5.4 MOS Performance Over WLAN Interference

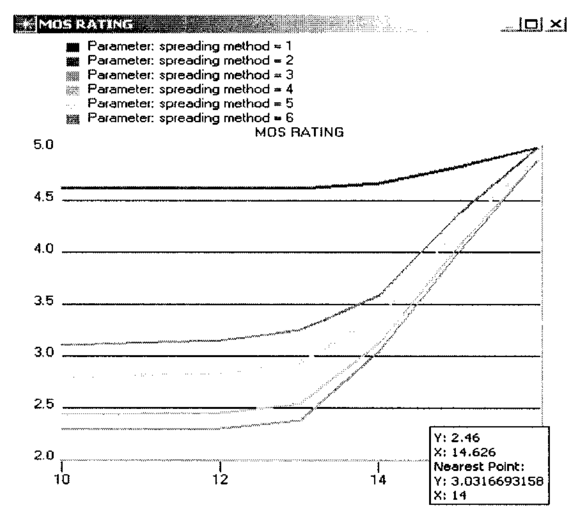
In this section, WLAN interference, as well as fading issues is considered for the MOS performance of the BLUETOOTH system. From Table 5.3, 5 students evaluated MOS ratings corresponding from 40 percent packet loss rate to zero percent packet loss rate. They are thirteen discrete MOS rating points corresponding to thirteen kinds of packet loss rate. For any specific packet loss rate among them, they can be converted into a specific MOS rating (1-5) proportionally. All Figures next will show the MOS via *Dbb*.

HV1 packets have the strongest error correction ability among the three packet types. Similar in Chapter 4, we run our simulations based on three situations: the distance between BT transmitter and BT receiver is set to 1 meter, 2meters and 3meters respectively.

5.4.1 HV1 Performance



(a) *Dbb* = 1 meter (b) *Dbb* = 2 meters



(c) *Dbb* = 3 meter

Figure 5.1 MOS performance of HV1

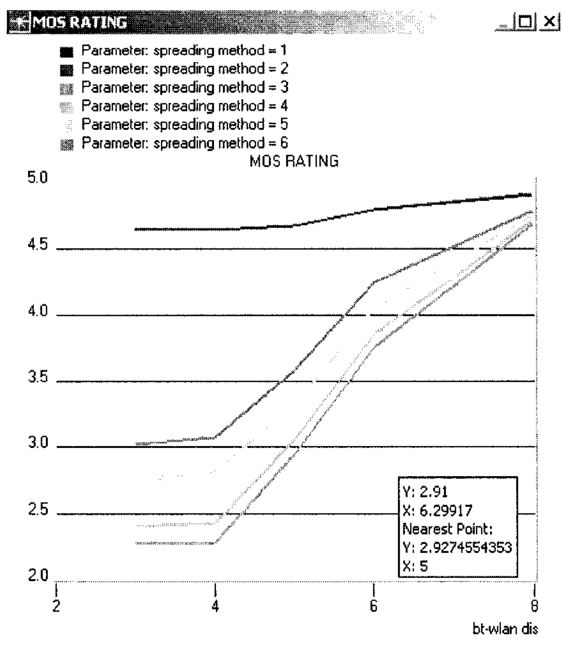
Fig 5.1a shows the MOS rating of HV1 as a function of separation between the BLUETOOTH transmitter and WLAN transmitter (*Dbw*) when only WLAN interference is present. This Figure 5.1 has six curves corresponding to the six kinds of WLAN transmission rate. The bottom curve, for example, depicts a tendency of MOS rating over WLAN DSSS 1MHz. Its MOS rating is 2.2 when *Dbw* is lower than 4 meters. This MOS rating has a sharp increase to 4.8 when *Dbw* is larger than 7 meters. The reason is that the path fading of WLAN becomes larger and larger when the WLAN transmitter is further away. This fading leads to an increase of SNR and a drop of BER. Figure 5.1b shows the same MOS performance curves when the distance of the BLUETOOTH and WLAN (*Dbw*) is less than 4 meters. Similar observation is observed except that MOS rating begins to increase when *Dbw* is larger than 8 meters. In simulation, *Dbw* is a parameter in integer value. Therefore, changing in Figures seems not smooth very much. All following curves show similar trend.

From Figure 5.1 above, we can summarize the following observations

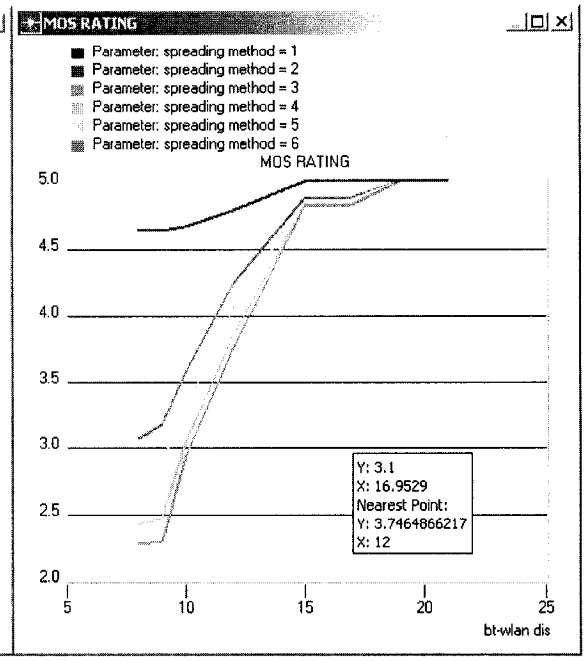
1) When *Dbb* is 1 meter, the MOS performance is the best.
2) Its MOS rating will be 4.5-5.0 if only considering the WLAN FHSS as interference source. For example, when *Dbw* (distance between the BLUETOOTH transmitter and WLAN) is above 7 meters, the MOS rating will increase above 4.8 (Figure 5.1a).
3) The MOS rating will be around 2 or 3 if considering the WLAN DSSS transmitter as an interference source. As example in Figure 5.1a, when *Dbw* is above 7 meters, MOS of HV1 will increase to above 4.5. WLAN DSSS transmitter has a wide frequency band (22 MHz) and it leads to the increasing of collision possibility between the BT and WLAN packets. Due to the increment of the distance, the WLAN transmitter has less power to affect the BLUETOOTH transmitter.
4) When WLAN adopts DSSS 11 MHz as its spreading method, the BLUETOOTH system has the highest MOS rate comparing with other DSSS methods. The reason is that packet length of WLAN will be the shortest in this situation.
5) The larger the distance of the BLUETOOTH and receiver, the higher the MOS rate.

5.4.2 HV2 Performance

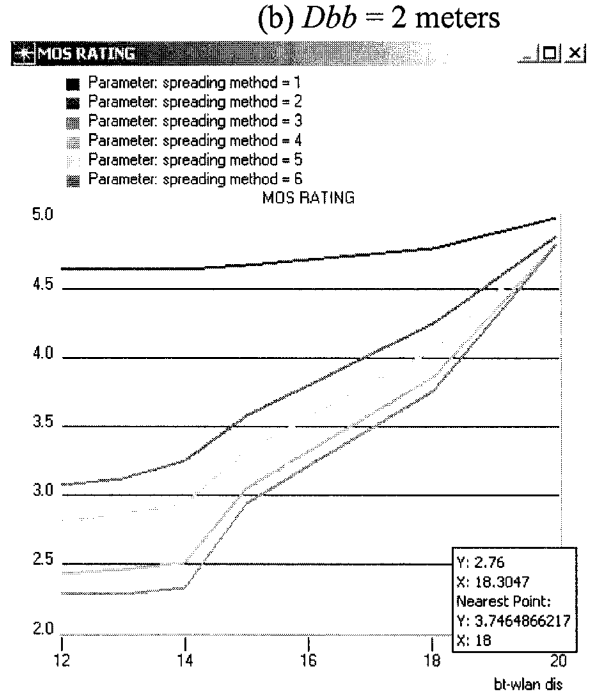
Figure 5.2 below also show the MOS rating of HV2 as a function of separation between the BLUETOOTH receiver and WLAN transmitter when only WLAN is present.



(a) *Dbb* = 1meter



(b) *Dbb* = 2 meters



(c) *Dbb* = 3 meters

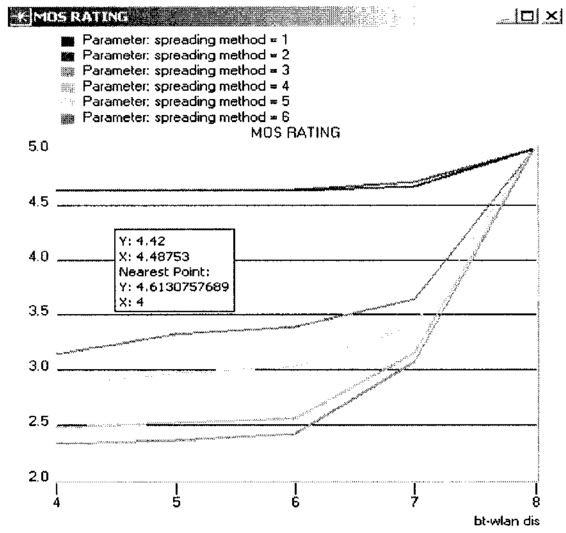
Figure 5.2 HV2 MOS performance

HV2's performance is worse than HV1 because of its worse FEC. Comparing to 5.1; Figure 5.2 shows the similar MOS performance curves but different values when MOS rating begins to increase. It can be summarized as follow.

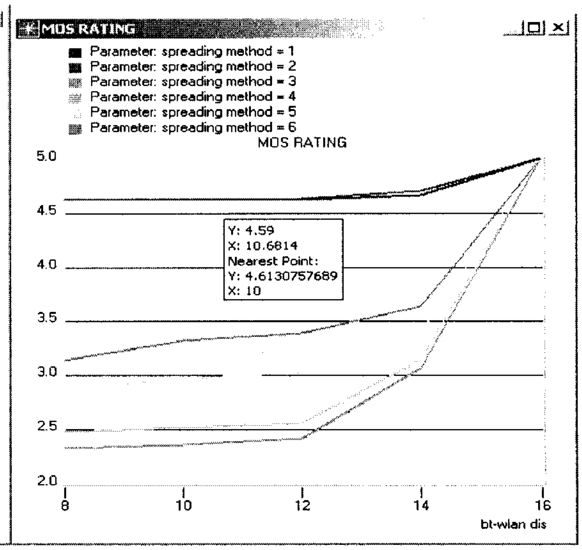
1) MOS rating of HV2 begins to increase when the *Dbw* of it is larger than that of HV1.

2) The tendency of this decrease is slower than that of HV1.

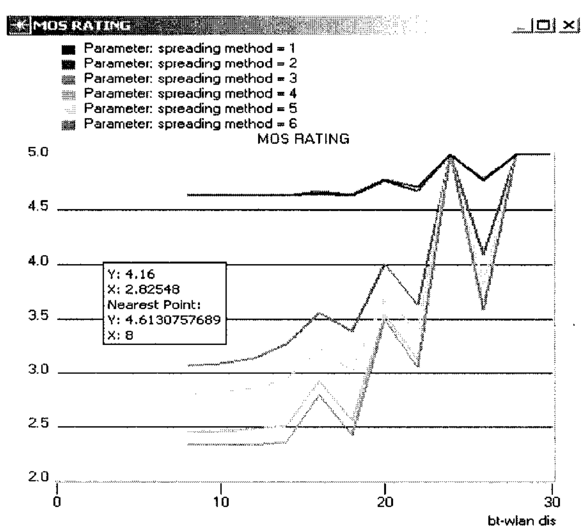
5.4.3 HV3 Performance



(a) *Dbb* = 1 meter



(b) *Dbb* = 2 meters



(c) *Dbb* = 3 meters

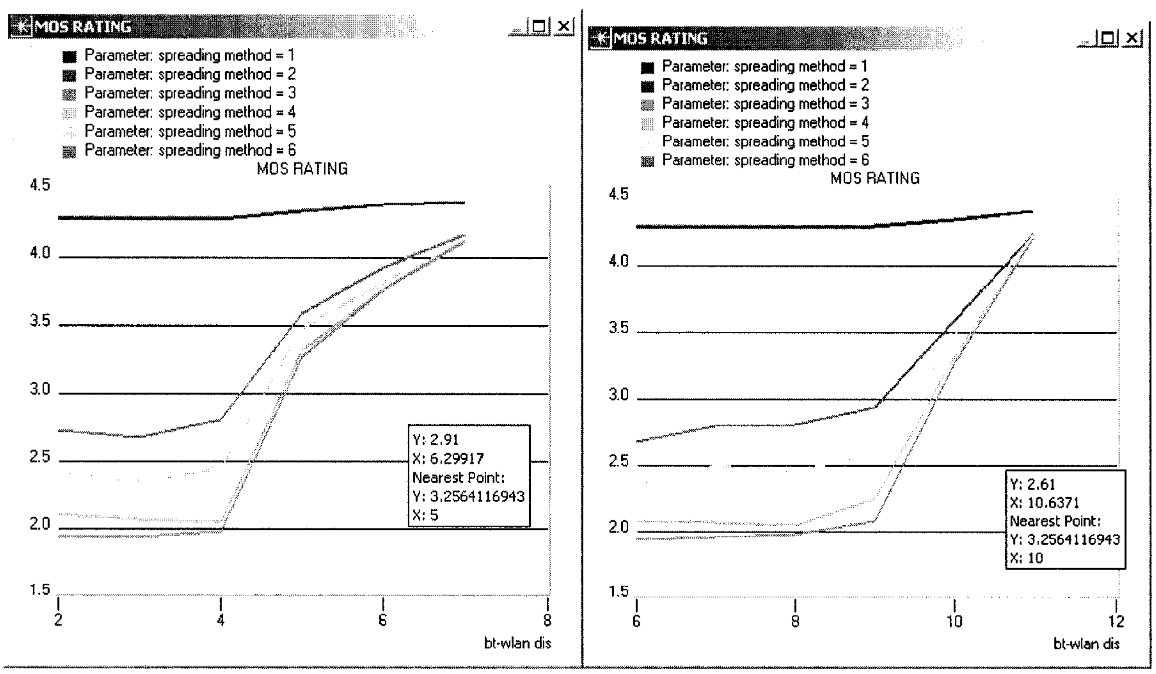
Figure 5.3 HV3 MOS performance

Figure 5.3 shows the MOS rating of HV3 as a function of separation between the BLUETOOTH receiver and WLAN transmitter when only WLAN is present. Comparing to Figure 5.2, Figure 5.3 shows the similar tendency of MOS changing except that when distance between the BLUETOOTH transmitter and receiver is set at 3 meters away, MOS rating of it shows a kind of very large unstable status. When running the simulation of Figure 5.3, the parameter of distance between the BLUETOOTH and WLAN is set as 20, 22, 24, 26, 28, 30 meters respectively from 20 to 30 meters. Because HV3 has no error correction FEC in its packet payload and BER of it shows random changes in this area, MOS rating of HV3 also shows a kind unstable change. It is very sensitive to be affected by WLAN transmission. Only after the WLAN device is far away enough, can MOS rating become stable.

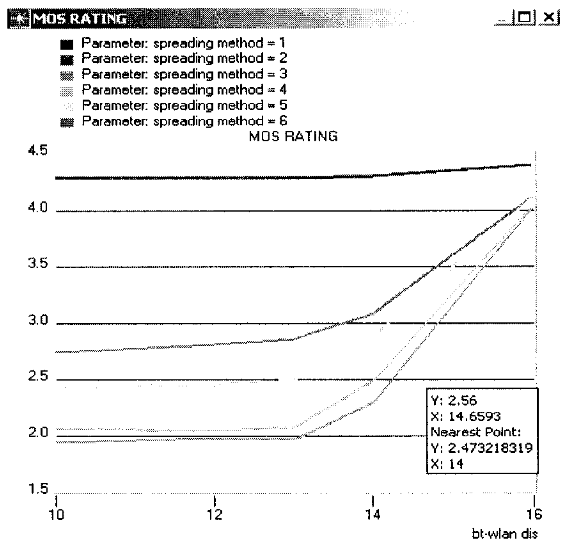
5.5 MOS Performance Over WLAN and piconet Interference

In this section, WLAN and piconet interference are considered together as well as fading issues. Two piconet interference sources are used as assumption in Section 2.7. HV1, HV2 and HV3 's MOS performance will be discussed separately when *Dbb* is set as 1, 2, and 3 meters.

5.5.1 HV1 Performance



(a) *Dbb* = 1meter (b) *Dbb* = 2 meters



(c) *Dbb* = 3 meters

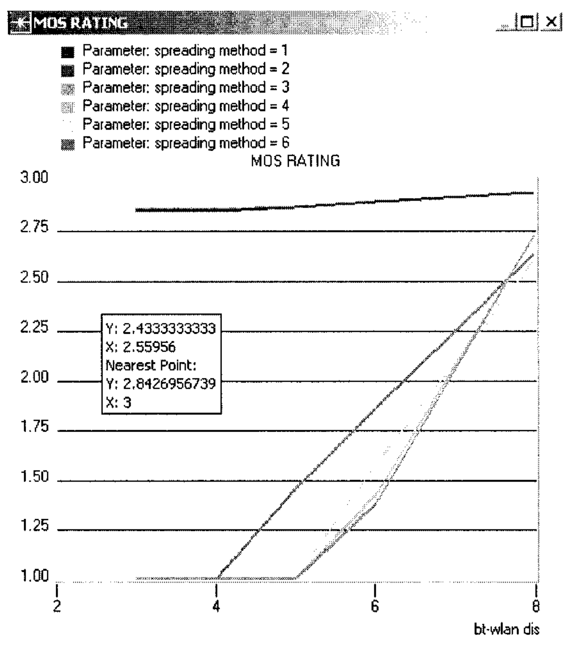
Figure 5.4 HV1 MOS via distance of BLUETOOTH and WLAN

Figure 5.4 shows the MOS rating of HV1 as a function of separation between the BLUETOOTH transmitter and WLAN transmitter (*Dbw*) when both WLAN and piconet interference are present. This Figure has six curves corresponding to the six kinds of WLAN transmission rate. The bottom curve, for example, depicts a tendency of MOS rating over WLAN DSSS 1MHz. Comparing with Figure 5.1, similar observations are observed except that the highest MOS of them is no more than 4.6. Figure 5.4 depicts that the MOS rating with 2 piconets is degraded a little bit but not much due to the thanks of strong correction ability of HV1. Since the MOS ratings of voice with WLAN DSSS 1Mhz are below 2.0 in some situations, voice is hardly to hear clearly at this time.

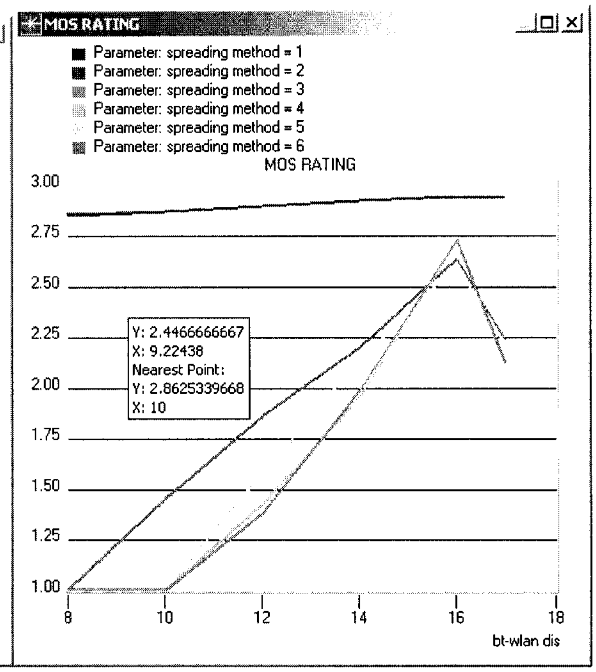
5.5.2 HV2 Performance

Figure 5.5 below shows the MOS rating of HV2 as a function of separation between the BLUETOOTH receiver and WLAN transmitter when both WLAN and piconets are present. HV2's performance is worse than HV1 because of its worse FEC. Comparing to 5.2, Figure 5.5 depicts that performance of HV2 is poor. The reason of unstable status is explained in previous chapters (Refer to explanation of Figure 4.7). The interference of piconet can greatly affect the transmission of the BLUETOOTH HV2 due to weak FEC of it.

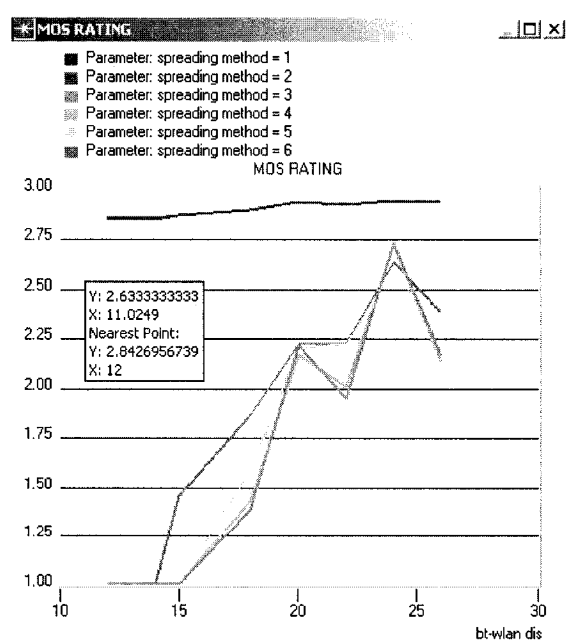
If using HV3 for BLUETOOTH transmission, piconet interference will lead to a more than 80% packet lost rate, which is obviously not acceptable for voice.



(a) *Dbb* = 1 meters



(b) *Dbb* = 2 meters



(c) *Dbb* = 3 meters

Figure 5.5 HV2 MOS performance

5.6 The Performance Comparison of HV1, HV2 and HV3:

The following Table displays the comparisons of performance information of three voice packet types. For resisting the interference from WLAN, we would better use HV1 voice packets, and try to close the distance between the BLUETOOTH transmitter and receiver.

Table 5.4 The Performance of the BLUETOOTH with WLAN interference

No piconets **interference**	**The smallest MOS**	**MOS starting to increase**	**MOS of DSSS is higher than 4**	**Where MOS is the highest**
HV1 (*Dbb*=1m)	2.3	4meters	6 meters	7 meters
HV2 (*Dbb*=1m)	2.3	4meters	8 meters	10 meters
HV3 (*Dbb*=1m)	2.3	4meters	7.5 meters	8 meters
HV1 (*Dbb*=2m)	2.3	**8meters**	**10.5meters**	**11meters**
HV2 (*Dbb*=2m)	2.3	**9meters**	**14meters**	**19meters**
HV3 (*Dbb*=2m)	2.3	**10meters**	**15meters**	**16meters**
HV1 (*Dbb*=3m)	2.3	12meters	15.5meters	16meters
HV2 (*Dbb*=3m)	2.3	12meters	19meters	22meters
HV3 (*Dbb*=3m)	2.3	12meters	>22meters	>22meters

Table 5.5 The MOS Performance of the BLUETOOTH with WLAN and piconets interference

2 piconets **interference**	**The smallest MOS**	**MOS starting to increase**	**MOS of DSSS is higher than 4**	**Highest MOS**
HV1 (*Dbb*=1m)	1.9	4meter	7 meters	4.3
HV2 (*Dbb*=1m)	1	4meter	N/A	2.8
HV3 (*Dbb*=1m)	4meters	N/A	N/A	1
HV1 (*Dbb*=2m)	**1.9**	**8meter**	**11meters**	4.3
HV2 (*Dbb*=2m)	**1**	9meter	**N/A**	2.8
HV3 (*Dbb*=2m)	**8meters**	N/A	N/A	1
HV1 (*Dbb*=3m)	1.9	13 meters	16 meters	4.3
HV2 (*Dbb*=3m)	1	14 meters	N/A	2.8
HV3 (*Dbb*=3m)	N/A	N/A	N/A	1

Conclusion of this chapter can be drawn as follows:

1) If there is a WLAN interference source only, we can use either of HV1, HV2 or HV3 based on different BLUETOOTH traffic situation. But we'd better to close the BLUETOOTH receiver to transmitter as much as we can (say 1 meter).

Therefore, we can obtain high quality of voice only if we can put the BLUETOOTH device 7 meters, 11meters and 16meters away from the WLAN source for HV1, HV2 and HV3 respectively.

2) If both WLAN and piconets interferences are there, we can only consider HV1 as the BLUETOOTH traffic carrier. Therefore, we can obtain relative high quality of voice (MOS 4.3) only if we can put the BLUETOOTH device 7 meters, 11meters and 16meters.

3) One WLAN FHSS interference source cannot give a big influence to BLUETOOTH voice transmission.

5.7 Concluding Remark

Analysis in this chapter shows that two- piconets interference affects the quality of BLUETOOTH system voice variously to different voice packet types. HV2 and HV3 are not recommended to use in the BLUETOOTH system since their FECs are not good enough to improve the quality of BLUETOOTH voice.

WLAN has certain effectiveness on the transmission of the BLUETOOTH voice. The spreading method and the transmission rate used by the WLAN transmitter make different interference levels to the BLUETOOTH voice transmission. One has to be at least 6 meters away from the WLAN transmitter in order to obtain relatively good quality of voice.

Ch6. Conclusion

This thesis has evaluated the BLUETOOTH system performance when different interference sources are present. The thesis has also analyzed the fading characteristic of wireless signal in the physical channel. As set out in Section 1.3, we have implemented BLUETOOTH and WLAN protocols, setup the voice performance comparison when different interference sources are present, and established a physical channel model. A power control method is proposed to minimize the interference based on our simulation results. Conversion is done between analog and digital signal using CVSD speech coding method.

An end-to-end simulation set has been setup to evaluate the voice performance of the BLUETOOTH system. Simulation shows that the quality of BLUETOOTH voice can be severely degraded when WLAN or piconets is at present. However, the fading factors without interference cannot affect the BLUETOOTH transmission when the BLUETOOTH devices are within a small range area (~10 meters). Even though WLAN or piconets interference is available, we can always minimize this kind of interference, such as moving the BLUETOOTH devices away from interference sources, choosing the HV1 voice packet type, and increasing the transmission power to enhance the resistance to the interference.

Two important assumptions that lead to the conclusion are (i) 100% traffic load on WLAN interference device, (ii) Rayleigh fading distribution, which is the worst small scale fading. These assumptions help us to learn the worst scenario, such as 100% traffic load of interference device, the most small scale fading.

6.1 Future Work

Our previous assumptions and results suggest more work is required on the worst scenarios. We can add more WLAN interference sources with different geological distribution and traffic intensity distribution, as well as adding more piconets interference sources. There is also need for some sort of algorithm for controlling the interference between the systems. For example, some awareness scheduling in channel access scheme can be used to detect the presence of 802.11 and to regulate channel access for both systems, thus much reducing interference.

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Appendix A: OPNET Simulation

A.1 Simulation Parameters:

BLUETOOTH parameters:

- Packet types: HV1 ,HV2 and HV3
- Distance between BLUETOOTH transmitter and receiver
- Large Fading exponent (3.5)
- Power of transmitter (1mW, 2.5mw,100mw)
- Distance between BLUETOOTH transmitter and receiver
- Temperature
- Bandwidth 1MHz/channel
- 79 channels
- Packet transmission 625 μs /packet

WLAN parameters:

- Spreading method (FHSS DSSS)
- Transmission rate(1MHz, 2Mhz, 5,5MHz and 11MHz)
- Packet length (8000bits)
- Power of transmitter (25mW)
- Large fading exponent (3.5)
- Distance between BLUETOOTH transmitter and receiver

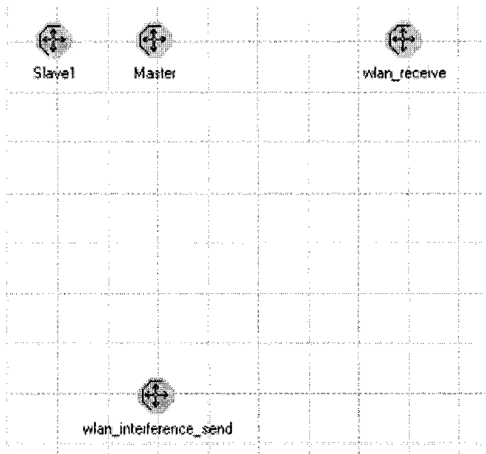
piconet

- Number of piconets

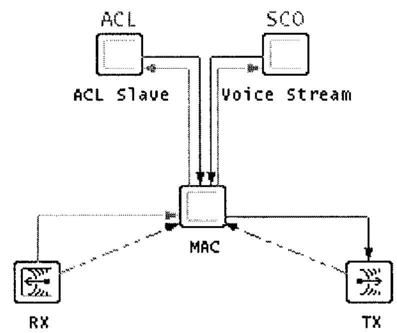
A.2 OPNET Modules

A.2.1 OPNET Simulation Module

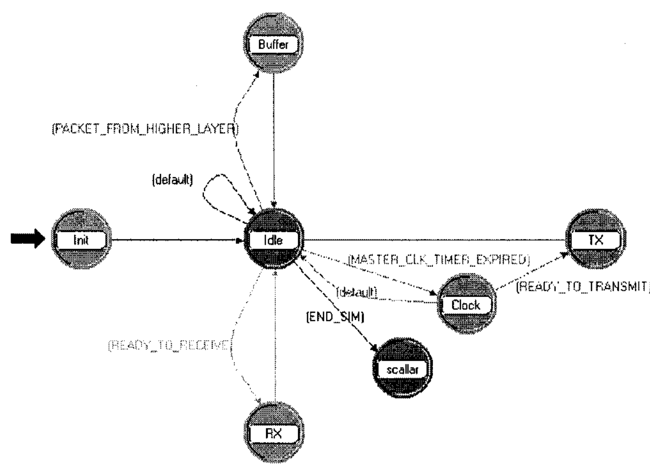
The proposed OPNET simulation model is derived from model in Section 2.4.



(a) OPNET network model



(b) OPNET node model of Master in (a)



(C) Process model of MAC in (b)

Figure A.1 General OPNET simulation model

Figure A.1 depicts three hierarchies of BLUETOOTH system. Figure A.1a displays that there are four BLUETOOTH devices are present in a small area. After clicking master in (a), Figure A.1b appears. It can tell which is creating voice packets (SCO), which is creating data packets (ACL). In MAC node, packets will be processed according to protocols. Figure A.1c is the process model of MAC to display how to manage data streams.

A.2.2 OPNET Process Modules

The following is a list of process module, which is the core part in BLUETOOTH system. They are:

Model name	Purpose
bt_sco_stream:	HV packet generator
lan_access_master:	Data packet generator
bt_mac_mast:	MAC layer of BLUETOOTH master process model
bt_mac_slave:	MAC layer of slave
wlan_mac_send:	MAC layer of WLAN transmitter
wlan_stream_resp:	Packet generator of WLAN

A.2.3 OPNET Node Modules

The following is a list of node module, which is the main part in BLUETOOTH system. They are:

Model name	Purpose
bt_device_slave	the slave of the BLUETOOTH system
bt_device_mast	the master of the BLUETOOTH system
wlan_receive	the WLAN receiver in the BLUETOOTH system
wlan_send_node	the WLAN transmitter in the BLUETOOTH system

A.2.4 OPNET Network Module

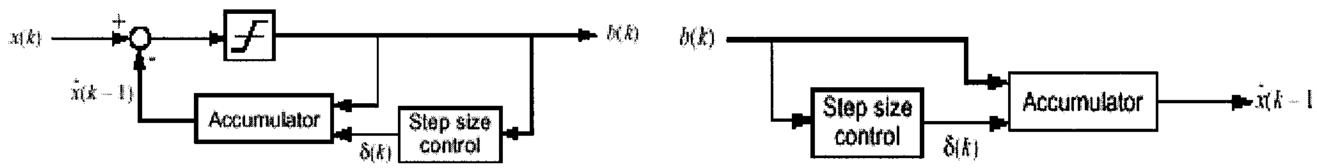
Only one Network module is available and its project name is yyy1. Detail code is listed in my project CD.

Appendix B: CVSD Algorithm

This section introduces the CVSD speech-coding algorithm that is realized in the proposed BLUETOOTH system.

B.1 CVSD Algorithm [BSIG99]

The input to the CVSD encoder is 64 k samples/s linear PCM. Block diagrams of the CVSD encoder and CVSD decoder are shown as follow:



(a) CVSD encoder (b)Decoder

Figure B.1 Step Control of CVSD

The input of CVSD is 64k samples/s PCM analog signals. Since the adjacent samples of human voice are highly correlated, we just need to compare the amplitude of them and output binary "1" or "0" . During the coding process, we will use the step control as Figure B.1 in order that this algorithm can trace delta change of signals.

$$b(k) = \mathrm{sgn}\{x(k) - \bar{x}(k-1)\} \quad (B6.1)$$

b(k) = "1" when $x(k) < \bar{x}(k-1)$ and b(k) = "0" when $x(k) > \bar{x}(k-1)$ from equation1.

Therefore, the output of encoder is a 64kbit/sec's binary format. This digital format coding will be transmitted through transmission media and transferred into analog signal through Decoder at Figure B.1. When you receive binary coding from system, you need to control the step size according to the bits format. See equation2, if the four previous bits are the same, the step size will increase as equation3.

Parameter a={ 1 when J bits in the last K output bits are the same }

{ 0 under other situation } (B6.2)

$$\text{delta}(k) = \min\{\text{delta}(k-1) + \text{delta}(\min), \text{delta}(\max)\} \quad \text{when } a=1 \qquad \text{(B6.3)}$$

$$= \max\{\text{beta} * \text{delta}(k-1), \text{delta}(\min)\} \quad \text{when } a=0$$

Beta is the decay factor of delta. If we devided the analog signal into 2^15 levels. The parameter should be like Table as follow:

Therefore, if amplitude of analog signal is more that 2^15 or –2^15, the max value will be 2^15 for positive and –2^15 for negative value.

Appendix C: WLAN

In this section, some protocols of WLAN to constitute a WLAN packet is introduced. The content of Basic Access of WLAN is also introduced.

C.1 WLAN PLCP and PMD Protocols [IEEE97]

The PLCP and the PMD protocols explain the format of WLAN packet in order to investigate how WLAN packets can affect BLUETOOTH packets.

a) A physical layer convergence function, which adapts the capabilities of the Physical Medium Dependent (PMD) system to the PHY service. This function shall be supported by the Physical Layer Convergence Procedure (PLCP), which defines a method of mapping the IEEE 802.11 MAC sub-layer Protocol Data Units (MPDU) into a framing format suitable for sending and receiving user data and management information between two or more STAs using the associated PMD system. WLAN packets use PLCP protocol to encapsulate their packets and let their packets be like Figure below. The length of packets will affect the interference level to BLUETOOTH transmission. Later in Chapter 4, we will use it as one parameter.

b) A PMD system, whose function defines the characteristics of, and method of transmitting and receiving data through, a wireless medium (WM) between two or more STAs each using the DSSS system.

C.2 Basic Access of WLAN [Bian00]

The following is a list of definition in Basic Access mechanism of WLAN. They are:

1) DIFS: is the inter frame space used for a station willing to start a new transmission, which is calculated as PIFS plus one slot time, i.e. 128 ms in 802.11.

2) SIFS (Short inter-frame space): used to separate transmissions belonging to the single dialog (Fragment-ACK) and it is the minimum inter frame space. There is, at most, one single station to transmit at any given time, therefore giving it priority over all other stations. This value for 802.11 PHY is fixed to 28 ms, time enough for the transmitting station to be able to switch back.

3) Mean back off windows: In CSMA mechanism, before a transmitter wants to transmit, he has to "listen" the medium to see if they are free. If yes, they need a 16-1024 timeslot random delay to try their best to avoid the possibility of collision in the beginning of transmission. But usually they will continue transmit several packets until all their information frames run out. Therefore, 16 time slots, a mean time, are inserted in every frame transmission.

4) Frame & ACK: time can be calculated