Application of Importance Sampling Simulation
to
CDMA systems

by

Sanjay Nagpal

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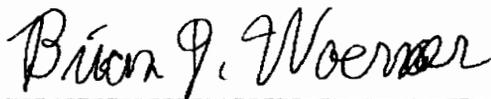Virginia Polytechnic Institute and State University

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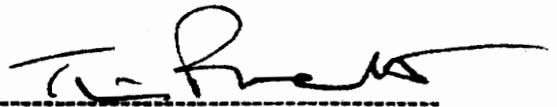
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(ABSTRACT)

The wireless revolution has taken the telecommunication industry by storm. The convenience provided by wireless in the day to day activities is the driving force behind it's popularity. With the increasing demand for such systems, research in multiple access techniques has received much interest. CDMA has been proposed as a next generation multiple access technique for cellular systems. The performance capabilities of a CDMA system are gauged by a variety of methods including analytical studies and simulations.

Simulation studies are the most reliable and popular performance measurement techniques. This thesis studies the application of Importance Sampling to the simulation of the IS-95 CDMA standard. Importance Sampling techniques help to achieve the simulation results by sending fewer bits and thus reduce the simulation time by a significant factor. Different versions of Importance Sampling techniques have been discussed and applied to the system. The results of Importance Sampling have been compared with the original results for the Bit Error Rate and Frame Error Rate to prove the validity and the effectiveness of Importance Sampling Techniques.

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1. INTRODUCTION

1.1 Wireless Communication

In recent years, there has been much interest in the development of wireless systems. [Rapp 93]. Wireless communications holds forth the possibility of communicating between two points without any physical connection (hard wire) between them. Wireless systems use radio frequency waves to signal between the transmitter and the receiver. Commonly used wireless devices are paging sets, police radios, land mobile radio and car phones. The FCC is allocating new frequencies for a planned ubiquitous personal communication service.

1.1.1 Cellular Telephone Systems

Cellular Telephony introduced to the public for the first time, the possibility of using telephony during motion. The word 'mobile' in the term 'mobile communications' has been derived from the fact that the transmitter or the receiver or both could be in motion (mobile) during the communication process. Conventional land mobile telephone systems suffer from many drawbacks like limited coverage, poor service performance and inefficient frequency spectrum utilization. [Lee 89]. Cellular phone systems are able to overcome many of these limitations.

Cellular Systems are so called as they are based on the concept of segmenting coverage area into regions called cells. These cells may have different geometries like circular, hexagonal or other shapes. Coverage studies have shown that the hexagonal honey-comb cell geometry provides best frequency reuse in an idealized environment, but practical cells have irregular shapes based on terrain. A cell generally comprises of a transmitting base station and a number of mobile users who subscribe to the system. The frequency path or channel from the transmitting base station to the mobile user is called forward path and from the mobile to the base station is called the reverse path. The key advantage of cellular systems is that frequency may be reused in cells separated by sufficient distance. Figure 1.1 below shows the hexagonal honeycomb cell distribution

hexagonal honeycomb cell distribution

enlarged cell

base station

○ → mobile users

Figure 1.1 - Hexagonal Cell Geometry

base station antenna

reverse path

forward path

mobile antenna

mobile unit

BASE STATION

Figure 1.2 - Forward And Reverse Channels In A Cellular System

1.2 CDMA For Cellular Telephone

The FCC is the central body that allocates frequency to different systems in the United States. A bandwidth of 62.5 MHz in the 800 MHz band has been allocated for cellular systems. The boom in the cellular business has led to the situation of a large number of users in a frequency limited system. Thus, the efficient use of the available frequency spectrum has become one of the foremost considerations in the design of cellular systems. This has led to the development of new digital cellular telephone systems which make efficient use of frequency spectrum. These systems include both the IS-54 based Time Division Multiple Access (TDMA) [IS-54] standard and the IS-95 based Code Division Multiple Access (CDMA) [IS-95] standard. Because of the potentially higher capacity and the unique difficulty in simulating CDMA systems, this thesis is focussed on simplifying the simulation of these systems using Importance Sampling techniques.

f1 = The original bandwidth

f2 = The spread bandwidth

PROCESSING GAIN = f2 / f1

Figure 1.3 - Processing Gain In Spread Spectrum Systems

The idea behind spread spectrum is to increase or spread the bandwidth available for transmission in order to accomodate more users in the system. This extra bandwidth is available for protection against interference. The factor by which the bandwidth is spread is called the SPREADING GAIN or the PROCESSING GAIN.

1.2.1 Types Of Spread Spectrum Systems

Spread Spectrum Systems were initially developed for secure communications problems such as preventing an enemy from trying to intercept or jam communications during war. As equipment costs declined, spread spectrum became commercially useful for multipath rejection and multiple access applications. There are two main categories of Spread Spectrum Systems:

Frequency Hopped Spread Spectrum (FH/SS)

The basic principle underlying frequency hopping is that the frequency of a user is hopped or changed frequently in a random manner. A random number generator determines the hopping frequency. Since the random number generator generates numbers in a random fashion, the frequency of each user keeps changing in a random way. There is very little probability that at a given instant, the frequency of two different users will be the same. If however, such a case arises, there could be a collision. The probability of such a collision is very low. The data sent is bursty in nature. Even if a collision occurs, error correction coding can be used to protect data. The chances of collisions can further be reduced if the random sequences are orthogonal to each other. Frequency hopping has been proposed for use with the TDMA GSM system to give it some of the advantages of spread spectrum [Eriksson 92].

Consider a system in which there are deep Rayleigh fades. In a frequency hopped system, the Rayleigh fade will occur for a much shorter time than any other system if the hopping rate is greater than the fading rate. The average fade is thus reduced. In fact, a 20 dB fade in a simple communication system can be significantly reduced to 2-3 dB fade after implementing Spread Spectrum techniques.

Direct Sequence Spread Spectrum (DS/SS)

The idea behind this form of spreading is to create a bit stream by the modulo two addition of two different bit streams and then transmit the combined version. One bit stream is the information signal and the other is the one generated by a random number generator. Since the spreading code (sequence) for each signal is different, at the receiver end, only the correct signal is despread back to its original form. DS/SS has become very popular and is used in many spread spectrum systems. The following figure [Calhoun 88] illustrates the process:

Figure 1.4 - Direct Sequence Spread Spectrum System

A DS/SS signal has a number of important characteristics. For a DS/SS signal, the transmission bandwidth greatly increases from the narrowband signal by a factor equal to the processing gain. The spread signal may be received by correlating with a replica of

the spreading code. Multiple access capability is achieved by assigning a unique spreading code to each potential user. The IS-95 system [IS-95] uses a form of DS/SS, and we focus on this technique in this thesis.

1.2.2 Concept Of CDMA

Code Division Multiple Access or CDMA is the multiple access technique for spread spectrum systems. Each user has his own code which is different from the code of others. The advantage of increased capacity is one of the greatest advantages of CDMA over conventional TDMA or FDMA systems.

Comparison with TDMA and FDMA systems

TDMA or Time Division Multiple Access is based upon the idea of different users using the same channel at different times. A time slot is provided for each user and the entire channel can be used by the user. Due to the restriction of the amount of time available to access the channel, the data transmitted is bursty in nature. The following figure [Calhoun 88] shows the concept of TDMA. The entire frequency channel f1 can be accessed at different time slot (slot 1, slot 2,etc.) by different users.

frequency f1 | slot 1 | slot 2 | slot 3 | slot 4 |

frequency f2 | slot 1 | slot 2 | slot 3 | slot 4 |

frequency fn | slot 1 | slot 2 | slot 3 | slot 4 |

TIME →

Figure 1.5 - Time Slots In A TDMA System

FDMA or Frequency Division Multiple Access is based on the concept of dividing a particular frequency channel into smaller blocks of frequency. Each user may use a particular slot of frequency for the entire time. The figure below explains in detail, the concept of FDMA:

f11	f12	f13	f14	freq f1
f21	f22	f23	f24	freq f2
fn1	fn2	fn3	fn4	freq fn

frequency

Figure 1.6 - Frequency Slots In An FDMA System

Unlike FDMA or TDMA which allows either the frequency to be shared or the access time to be shared respectively, CDMA allows the use of the same frequency slot at the same time for different users. The users are however distinguished on the basis of their different codes. The figure below explains this concept.

	f1	t1f1	t2f1	t3f1	t4f1	t5f1	t6f1
	f2	t1f2	t2f2	t3f2	t4f2	t5f2	t6f2
	f3	t1f3	t2f3	t3f3	t4f3	t5f3	t6f3
	f4	t1f4	t2f4	t3f4	t4f4	t5f4	t6f4
	f5	t1f5	t2f5	t3f5	t4f5	t5f5	t6f5
	f6	t1f6	t2f6	t3f6	t4f6	t5f6	t6f6
		t1	t2	t3	t4	t5	t6	time

freq

Figure 1.7 - Time And Frequency Slots In A CDMA System

In the above figure, slot t1f1 represents frequency f1 being used at time t1.

A detailed comparison of TDMA, FDMA and CDMA is given in [Calhoun 88]. Some of the important points of comparison are:

Like TDMA, CDMA involves the transmission of bursty data. FDMA differs from the other two techniques as it involves transmission of continuous data.

FDMA is limited in capacity. This is because the frequency spectrum is divided into smaller slots and the user has access to only a particular smaller frequency slot. The capacity of TDMA systems is increased as the entire spectrum may be used by a user though for a limited time slot. CDMA, proposed as the next generation multiple access technique, has a theoretical capacity of 4-6 times that of TDMA [Gilhousen 91]. This capacity increase is not true for analog systems as TDMA and CDMA techniques apply to digital systems only.

Hand-Off is a major concern in FDMA systems due to the continuous nature of transmissions. TDMA and CDMA systems involve small bursty data transmission and hence, hand-off is not a major problem when switching to another cell frequency.

In TDMA and CDMA systems, the same radio channel is shared by a number of users. As a result, the cell-site equipment cost is shared by different users. The cost is relatively much more in FDMA systems due to the single-channel-per-carrier nature of FDMA systems.

1.3 Performance Evaluation Of Communication Systems

There are many ways to determine the performance of communication systems. Of these, analytical and computer simulation methods are most common [Bert 92]. Analytical methods involve the study of the system using statistical techniques. Much work has been done in this area over the last few years. Bello and Nelin [Bel 62], Liu and Feher [Liu 90] and Chuang [Chu 91] are noteworthy contributors in this field. Computer simulation involves the testing of the system performance using computer simulation tools. Computer simulation methods allow modeling of complex systems.

1.3.1 Monte Carlo Simulation

The Monte Carlo technique is a simple and very popular simulation technique. It is based on the principle of transmitting lots of bits in random and comparing the received stream with the transmitted one for detecting errors. A model of the system transmitter, the medium or channel and the system receiver is first made. The bits are transmitted at a specified bit rate. After going through the channel, the received bits are compared to a threshold value. Depending on whether they exceed the threshold value or not, the decision is made at the receiver. The next step is to compare each received bit with the corresponding transmitted bit and then declare if the bit is in error. The Bit Error Rate (BER) of the system is determined by dividing the number of erroneous bits by the total number of bits sent.

info. bits

compare to see if
bit is in error

transmitter | channel | receiver

decision/threshold

device

Figure 1.8 - Block Diagram Of A Simple Monte-Carlo Simulation Method

For example. if 200 bits out of 10,000 transmitted bits are in error, the BER of the system is given by

$$BER = \text{Num. of bits in error} / \text{Num. of transmitted bits}$$
$$= 200/10000$$
$$= .02$$

The Monte Carlo method is simple and applicable for any communication system. However, if a system has a very low BER, Monte Carlo method becomes impractical due to the large number of bits required to simulate the system. Consider a simple baseband communication system with a BER of 10^{-6} i.e. 1 bit in every 10^6 bits sent is in error. In other words, a minimum of 10^6 bits must be sent on an average to obtain a single bit in error, and many more in order to obtain an accurate estimate of the true BER of the system. Thus extensive simulation time is required [Shan 80].

1.3.2 Importance Sampling

The problem described above for Monte Carlo systems led to the birth of Importance Sampling, a technique to determine very low values of BER for communication systems. Importance Sampling, as the very name suggests, samples data at important points only and yet estimates the true BER of the system. It is one of the primary methods adopted for the simulation of systems with a Gaussian or Rayleigh noise distribution. The aim of Importance Sampling is to bias or modify the probability distribution function in such a way as to generate more errors with fewer bits. Using an unbiasing factor called weights, it then determines the BER of the system after multiplying the received bits in error with their respective weights. The weight is determined by taking the ratio of the distribution before biasing to the value after distribution. A detailed procedure to determine the weights is given in section 3.1.2. There are different versions of Importance Sampling that are applicable to communication systems. These have been described in length in section3.2. It has been seen that Importance Sampling provides reduction in simulation time of the order of 3 to 8.

1.4 Literature Survey

1.4.1 Previous Work

There are different approaches to obtain the performance results for CDMA systems. Some researchers have used analytical or statistical techniques to evaluate the performance of communication systems in the past few decades. The primary contributors to the prediction of bit error rates have been Bello and Nelin [Bel 62]. Their studies dealt with fading channels and the problem of intersymbol interference. Liu and

Feher [Liu 90] studied more complicated systems and analyzed the performance of systems using $\pi/4$ DQPSK modulation.

However, the most prominent method adopted nowadays is computer simulation. Software tools allow researchers to build models of the real world system and then use software tools to predict the performance of these systems. With powerful PCs and workstations, it is now easy to implement intricate propagation simulation software and get very accurate results [Seidel 90]. The Mobile & Portable Radio Research Group (MPRG) at Virginia Tech has been a leader in the development of software tools like Bit Error Rate Simulator (BERSIM) [Thoma 92], Simulator for Indoor Radio Channel Impulse Measurement (SIRCIM) [Seidel 90] and other similar packages. Shanmugam [Shan 88] provides an overview of the state of the art in software packages for simulation of communication systems.

Importance Sampling is a technique to simulate the Monte Carlo system using much fewer bits. The Importance Sampling technique was implemented on the Qualcomm CDMA system which had originally been developed by Yingjie Li [Li 93] at the MPRG at Virginia Tech.

There has been a great deal of previous study of Importance Sampling techniques although very little of it has focussed on CDMA systems. A major contribution to the study of IS techniques has been made by Shanmugam and Balaban [Shan 80]. Their studies deal with the determination of BER over fading channels and choosing the optimum number of samples to get accurate performance of IS techniques. Jeruchim [Jeru 84] and Hahn [Hahn 89] have studied the application of IS techniques to satellite systems. In [Hahn 89], the studies show that IS techniques can be applied straight forward to systems with distributed noise sources i.e. to n-hop systems. The results were proved with different C/N values for each hop. In [Jeru 84], similar results have been obtained for a satellite system. The diagram below shows a simplified block diagram of the satellite system:

Figure 1.9 - Data Transmission And Reception In A Satellite Link

Devetsikiotis and Townsend [Dev 90] obtained time reduction factors of the order of 3 to 8 and derived the results for near-optimal set of biasing parameters. Later, in 1992, they combined with Wael A. Al-Qaq [Wael 92] and applied IS methods to communication links characterized by time-varying channels and using adaptive equalizers. Theses adaptive equalizers adapt to the noise for a duration equal to the memory of the system. A very detailed study of different approaches to IS techniques has been provided in [Jeru 84]. The work explores the suitability of different techniques like tail extrapolation theory, quasi-analytical methods and extreme value theory.

1.4.2 The Bit Error Rate Simulator (BERSIM)

The Bit Error Rate Simulator (BERSIM) is a software tool developed by the Mobile & Portable Radio Research Group (MPRG) at Virginia Tech. It is used to explore the properties of high data rate wireless mobile and portable communications links [Thoma 92]. The first version of BERSIM was BERSIM 1.1 developed by Victor Fung [Fung 91], a graduate student at the MPRG. It has now been modified to BERSIM Version 2.0 and

can be run on the SUN workstation and on the IBM personal computer. The flow chart [Thoma 92] for Its operation is shown below:

```
              ┌─────────┐
              │  start  │
              └─────────┘
                   │
                   ▼
          ┌──────────────────┐
          │      enter       │
          │   parameters     │
          └──────────────────┘
                   │
                   ▼
            ◇ C/I > 100dB ◇ ──────────┐
                   │                   │
                   │ N                 │
                   ▼                   │
          ┌──────────────────┐         │
          │  gen cochannel   │         │
          │   interference   │         │
          └──────────────────┘         │
                   │◄──────────────────┘
                   ▼
          ◇  check           ◇  outdoor   ┌──────────────┐
          ◇  channel type    ◇ ──────────►│ run tworay.exe│──────┐
                   │                       └──────────────┘       │
                   │ indoor                                       ▼
                   └──────────────►┌──────────────┐      ┌──────────────┐
                                   │ run indoor.exe│────►│     run      │
                                   └──────────────┘      │    BERSIM    │
                                                          └──────────────┘
                                                                 │
                                                                 ▼
                                                          ┌─────────┐
                                                          │  stop   │
                                                          └─────────┘
```

Figure 1.10 - Flow Chart For BERSIM 2.0

Like any other communication system, BERSIM consists of a transmitter, channel and a receiver. Its basic structure is shown [Thoma 92] below

STRUCTURE OF BERSIM 2.0

Figure 1.11 - Structure Of BERSIM 2.0

In this thesis, BERSIM Version 3.0 has been used which simulates a 1.25 MHz CDMA system.

The characteristics of BERSIM 3.0 are given in a tabular form below [Li 93]

TABLE 1.1 - Characteristics Of BERSIM 2.0

PARAMETERS	OPTIONS
Modulation	Π/4 DQPSK,BPSK,FSK
Data Rate	0 to 10 Megabaud
Carrier frequency	unlimited
Channel	two-ray,flatRayleigh, SIRCIM,SMRCIM, user defined
Symbol timing recovery	perfect timing jitter
Interference	white Gaussian noise, co-channel interference
Input	parameters, random or user supplied data, channel definition file, internally generated channel
Output	bit error rate, outage rate, bit error pattern, eye pattern
Computer supported	PC compatible, SUN workstation. X-windows user interface
Hardware component	installs in standard PC/AT expansion slot, replays bit error pattern in real time on user's baseband data (upto 15 Mbps)

1.5 Research Objective And Outline Of Thesis

1.5.1 Research Objective

The purpose of this research is to incorporate Importance Sampling in the simulation of the IS-95 CDMA standard. The 1.25 MHz CDMA system has been pioneered by Qualcomm Inc., and is expected to become the next generation multiple access scheme for cellular systems. BERSIM 3.0 is used to perform the simulation study.

The need to incorporate Importance Sampling arose due to the large amount of time originally taken (24 hours) to simulate the system. Such a large delay in the simulation process is unacceptable for practical applications. Importance Sampling had been earlier applied to other communication systems which were much simpler. The challenge for this work was to understand the entire working of the CDMA system and then successfully implement Importance Sampling into the system in ordered to speed it up. The success of this implementation is evaluated by comparing the results with those of the original system. This work is unique because it represents the first implementation of Importance Sampling techniques for complex spread spectrum systems with memory. (The concept of memory is explained later in Chapter 3).

1.5.2 Organization Of Thesis

Chapter 2 describes in detail the components of the Qualcomm CDMA system. Chapter 3 describes the different forms of Importance Sampling. Chapter 4 describes the simulation approach and the reasons for choosing a particular type of Importance Sampling. Chapter 5 describes the results obtained with Importance Sampling (demonstrates the curves for BER using BERSIM and the tables of values for different values of Eb/No). Chapter 6 concludes the thesis and indicates possible future work that could be done. Appendix A gives a list of references used in the thesis. Appendix B contains the code and explains how different programs have been linked and compiled to achieve the results.

2. The CDMA Model Used In The Simulation

The CDMA System used is the one specified by Qualcomm Inc. and is described in detail in the IS-95 CDMA standard [Qual 92]. It describes in detail, the system model and components for forward (base station to mobile) channel and reverse (mobile to base station) channel. It gives an elaborate list of system parameters. The simulation of the system using simple Monte Carlo simulation was done by Yingjie Li, a former student at the Mobile & Portable Radio Research Group (MPRG) at Virginia Tech. A block diagram of the system is given below

Figure 2.1 - Block Diagram Of The CDMA System Components

A brief description of the different parts is given below. For detailed descriptions, one may refer to the IS-95 manual [Qual 92].

2.1 Requirements For CDMA Operation

2.1.1 Power Control And Output Power Levels

Necessity Of Power Control

Power control is used to minimize the impact of the fading of the received signal [Cameron 93]. Power control allows efficient transmission of power since the minimum required amount of power is transmitted. This helps reduce battery consumption. In CDMA systems, power control is a primary concern.

Measurement studies have shown that the power received falls off inversely with the distance. For free space, the received power is inversely proportional to the square of the distance through which the signal propagates.

$$P \propto \frac{1}{d^n} \qquad (2.1)$$

where n = 2 for free space.

In a cellular system, the forward and reverse channel are depicted in the following figure [Cameron 93]:

Figure 2.2 - Forward and Reverse Channels

In the forward channel, the mobile units receive power from the base station (transmitter). The mobiles which are further away (mobile 1) will receive lesser power due to the greater distance of separation from the base station. The closer mobiles (mobile 2) will have a stronger reception of signal. Thus the near mobiles do not need as much power to maintain a required BER as is required by the mobiles which are farther away.

In the reverse channel, the mobiles transmit power to the base station. For mobiles that are farther, more power is required (to compensate for the fading and propagation loss due to distance) than is required for the mobiles closer to the base station.

Mobile stations are classified into class I, class II and class III depending on the range of maximum power transmission [Qual 92].

Class I:	1.25 watts < ERP at maximum output < 6.3 watts
Class II:	0.50 watts < ERP at maximum output < 2.5 watts
Class III:	0.20 watts < ERP at maximum output < 1.0 watts

The power control bits are implemented in the data stream after the data scrambling. The data stream with the position of the power control bit is shown below:

Figure 2.3 - Power Control In IS-95 CDMA System

As seen from the above figure, the power control bit can occupy 16 possible start positions. Each start position corresponds to the one of the first 16 modulation symbols shown [Qual 92]. There are 24 bits that are used for data scrambling. The 4-bit binary number with values from 0 to 15 is formed from bits 23,22,21 and 20 to determine the location of the power control bit. In the above example, the 4-bit binary number has the value 10 and hence, the power control bit starts from position 10.

The power control bit is transmitted from the base station to the mobile (forward channel) and indicates how much power the mobile must increase or decrease in order to meet the requirements of the system. A '0' or a '1' is transmitted, the '0' indicating that the mobile is not sending enough power and should increase Its power output and the '1' indicating that the mobile should decrease Its mean output power level. The base station estimates the received signal strength from the mobile station and accordingly assigns a '0' or a '1' to the power control bit.

2.1.2 Channel Frame Structure

The following figure shows the forward traffic channel frame structure. Each data frame contains upto 172 data bits plus CRC bits for error detection and 8 bits which represent the tail of the convolutional encoder. This data frame represents 20 ms of human speech.

F = Frame quality indicator (CRC)
T = Encoder tail bits

Figure 2.4 - Forward Traffic Channel Frame Structure

2.2 Transmitter

* The transmitter contains the following components:
* The data generator
* The convolutional encoder
* The block interleaver
* The PN sequence generator
* The modulator
* The filter

We discuss these below.

2.2.1 The Data Generator

The IS-95 standard requires generation of data at variable rates of 9600, 4800, 2400 and 1200 bps. These bits are generated using a random number generator. User specified data can also be input by reading the data from specified files. Currently, a varaible rate vocoder is being implemented in the IS-95 CDMA system in order to provide binary data at the variable data rates specified above. In the simulation, a data rate of 9600 bps has been assumed.

2.2.2 The Convolutional Encoder

Encoding is done using a convolutional encoder. The encoder has a constraint length of 9 and a data rate of 1/2 for the forward channel and 1/3 for the reverse channel. Generator vectors are used to generate 2 (3 for reverse channel) output symbols for each input symbol using modulo 2 addition. The encoder used for the forward channel is shown below

The convolutional encoder for the forward channel (Rate = 1/2)

Figure 2.5 - K=9 & Rate = 1/2 Forward Channel Convolutional Encoder

Here K=9 is the constraint length, Co and C1 are the output symbols for an input symbol. g0 and g1 are the two generator functions used to determine the coded symbols. Thus for every input bit into the encoder, two encoded bits are output.

The reverse channel encoder has rate 1/3 and constraint length 9. The reverse channel uses a more powerful code, because the sequences are non-orthogonal and power control may be a problem.

In the figure below, C0, C1 and C2 are the three output symbols generated for each input symbol using generator functions g0, g1 and g2.

Figure 2.6 - K=9 & Rate = 1/3 Reverse Channel Convolutional Encoder

2.2.3 The Block Interleaver

Most well known codes increase the reliability of transmission of information when errors are independent. However, in many cases, the problem of bursty errors is acute and such a case is very common in channels subjected to multipath and fading. Signal fading due to multipath causes the signal to fall below the threshold level of the detection device and thus cause a large number of errors to occur. Block interleaving is a technique to convert the bursty channel into one with independent errors [Proakis 89]. The interleaver is implemented after the channel encoder. A simple communication system with the location of the block interleaver is shown below:

```
input
 ──────┌──────────┐      ┌──────────┐      ┌──────────┐
       │ channel  │──────│interleaver│──────│modulator │───┐
       │ encoder  │      └──────────┘      └──────────┘   │
       └──────────┘                                        │
                                              ┌────────────────┐
                                              │ C H A N N E L  │
                                              └────────────────┘
output
 ──────┌──────────┐      ┌──────────────┐    ┌──────────┐   │
       │ channel  │──────│deinterleaver │────│demodulator│──┘
       │ decoder  │      └──────────────┘    └──────────┘
       └──────────┘
```

Figure 2.7 - Block Diagram Showing Interleaver And Deinterleaver Stages

The interleaver can be of two types: Block interleaver or Convolutional interleaver. A block interleaver is used in the current system. A Block interleaver stores the data in the form of a matrix comprising of m rows and n columns. The degree of a block interleaver is the number of rows it contains. The bits are read out column wise. The deinterleaver stores the received data in the same form but reds it out row wise.

After being encoded, the data symbols are interleaved by a block interleaver which is a 24 x 16 array. Block interleaving is an additional measure to prevent the possibility of errors and is particularly important in case of bursty errors. The block interleaver input for a data rate of 9600 bps for the forward channel is shown;

TABLE 2.1 - Block Interleaver Input Data

1	25	49	73	97	121	145	169	193	217	241	265	289	313	337	361
2	26	50	74	98	122	146	170	194	218	242	266	290	314	338	362
3	27	51	75	99	123	147	171	195	219	243	267	291	315	339	363
4	28	52	76	100	124	148	172	196	220	244	268	292	316	340	364
5	29	53	77	101	125	149	173	197	221	245	269	293	317	341	365
6	30	54	78	102	126	150	174	198	222	246	270	294	318	342	366
7	31	55	79	103	127	151	175	199	223	247	271	295	319	343	367
8	32	56	80	104	128	152	176	200	224	248	272	296	320	344	368
9	33	57	81	105	129	153	177	201	225	249	273	297	321	345	369
10	34	58	82	106	130	154	178	202	226	250	274	298	322	346	370
11	35	59	83	107	131	155	179	203	227	251	275	299	323	347	371
12	36	60	84	108	132	156	180	204	228	252	276	300	324	348	372
13	37	61	85	109	133	157	181	205	229	253	277	301	325	349	373
14	38	62	86	110	134	158	182	206	230	254	278	302	326	350	374
15	39	63	87	111	135	159	183	207	231	255	279	303	327	351	375
16	40	64	88	112	136	160	184	208	232	256	280	304	328	352	376
17	41	65	89	113	137	161	185	209	233	257	281	305	329	353	377
18	42	66	90	114	138	162	186	210	234	258	282	306	330	354	378
19	43	67	91	115	139	163	187	211	235	259	283	307	331	355	379
20	44	68	92	116	140	164	188	212	236	260	284	308	332	356	380
21	45	69	93	117	141	165	189	213	237	261	285	309	333	357	381
22	46	70	94	118	142	166	190	214	238	262	286	310	334	358	382
23	47	71	95	119	143	167	191	215	239	263	287	311	335	359	383
24	48	72	96	120	144	168	192	216	240	264	288	312	336	360	384

2.2.4 The PN Sequence generator

PN (pseudo-noise) spreading code allows assignment of a unique code to each user. The bits are spread over PN chips using a randomly generated code. Thus at the receiver end, the despreading code would despread only that bit which had been spread using that code.

This is how a CDMA spread spectrum systems allow the use of a large number of users to use the same frequency band. The PN sequence for the forward channel is generated based on the following polynomial:

$$p(x) = x^{42} + x^{35} + x^{33} + x^{31} + x^{27} + x^{26} + x^{25} + x^{22} + x^{21} + x^{19} +$$

In the process of spreading, each bit is spread over 128 chips. The PN sequence repeats itself after 2(42) -1 chips. The PN generator is initialized with a '1' followed by 41'0's'. This generator polynomial produces an extremely long sequence with a period of over 10 years.

2.2.5 The Modulator

The next step after data scrambling is the spreading of each symbol by 64 Walsh symbols. The modulation used is a combination of binary phase shift keying (BPSK) and quadrature phase shift keying (QPSK). The I and Q channels are spread using different PN sequences. PN sequence for I channel is

$$P_I(x) = x^{15} + x^{13} + x^9 + x^8 + x^7 + x^5 + 1$$

and for the Q channel is

$$P_Q(x) = x^{15} + x^{12} + x^{11} + x^{10} + x^6 + x^5 + x^4 + x^3 + 1$$

For the forward channel, the output of the spread symbols is matched with the phase using the following table

TABLE 2.2 - Output And Phase Matching In I And Q Channels

I	Q	Phase
0	0	$\Pi / 4$
1	0	$3\Pi / 4$
1	1	$- 3\Pi / 4$
0	1	$-\Pi / 4$

The signal constellation for the forward channel is shown below:

Figure 2.8 - Signal Constellation For Forward CDMA Channel

For the reverse channel, the corresponding figure is drawn below

Figure 2.9 - Signal Constellation For Reverse CDMA Channel

2.2.6 The Filter

The next step after modulation is filtering. Baseband filters are used. The sampling interval of the filters is 1/4 th the duration of a PN chip i.e. each PN chip is sampled 4 times.

TABLE 2.3 - Coefficients Of The Bandpass Filter

K	h(K)
0,47	-0.025288315
1,46	-0.034167931
2,45	-0.035752323
3,44	-0.016733702
4,43	0.021602514
5,42	0.064938487
6,41	0.091002137
7,40	0.081894974
8,39	0.037071157
9,38	-0.021998074
10,37	-0.060716277
11,36	-0.051178658
12,35	0.007874526
13,34	0.084368728
14,33	0.126869306
15,32	0.094528345
16,31	-0.012839661
17,30	-0.143477028
18,29	-0.211829088
19,28	-0.140513128
20,27	0.094601918
21,26	0.441387140
22,25	0.785875640
23,24	1.0

The frequency response of the filter has a flat spectrum with a passband of 1.25 MHz.

2.3 Channel

Channel is the path between the transmitter and the receiver. The channel characteristics are very important in the performance of a system. A rapidly fading or changing channel is a greater challenge to deal with than a slow fading channel. The channel is the portion where the original signal undergoes distortion and different forms of interference and causes Its received form to differ from Its original form and thus is a major contributor to the error. The major problems in the mobile radio channel environment are multipath, co-channel interference, intersymbol interference, fading (log-normal and Rayleigh) and noise. The channel noise may be used to bias the entire distribution to obtain more frequent errors. The channel noise becomes a great concern if it exceeds a certain unknown limit. This belief forms the backbone of this thesis and Importance Sampling is applied to the channel noise.

2.3.1 The Gaussian Noise

The most common form of channel noise in cellular systems is Additive White Gaussian Noise (AWGN) for which

$$Y = X + G$$

where G is a zero mean gaussian random variable with variance σ^2 and $X = x_k$, k=0,1,....,q-1. For a given X, it follows that Y is Gaussian with mean x_k and variance σ^2. That is,

$$P(y\, /\, X = x_k) \qquad \frac{1}{\sqrt{2\Pi}\sigma}\ \ e^{-(y - x_k)^2\, /\, 2\sigma^2} \qquad \text{[Proakis 89]}$$

The Gaussian noise (G) has a probability distribution which is shown below

Figure 2.10 - Probability Distribution For Gaussian Noise

Importance Sampling determines the nature of this Gaussian noise and weighs Its importance in the contribution of BER. From the above figure, we see that the Gaussian noise in the current system is one with zero mean and unit standard deviation (stddev). The larger the standard deviation of this distribution, the greater the amount of noise in both the sides and hence the greater the chances of an error being introduced. Thus, the Eb/No is reduced if Eb is kept constant. Thus the value of stddev used in the system actually depends on the value of Eb/No. The distribution of the Gaussian noise can be varied by changing Its mean or variance. This process called biasing is dealt with in greater detail in the following chapter.

The channel used in the simulations is a multipath channel. We use measured impulse response data which is typical in cellular environment. We use this so that we can make comparisons with the results not using Importance Sampling [Li 93].

2.4 Receiver

The receiver contains the same blocks as the transmitter. These blocks are the filter, the demodulator, the deinterleaver and the viterbi decoder. Both hard decision and soft decision decoding may be used. The actions of these components is the compliment of their counterparts in the transmitter stage. The symbols after passing through the channel, are filtered, demodulated, deinterleaved and finally decoded. A threshold detection method determines if the received signal strength is above or below a fixed threshold value and decides whether a '1' or a '0' has been received. On comparing with the corresponding transmitted bit, errors are detected and hence the BER of the system is determined. The entire process is repeated a number of times to estimate the BER. Also, the simulations are repeated for different parameter settings.

2.5 Rake Receiver

The term RAKE has been borrowed from the rake, an instrument used in the garden to collect things. The Rake receiver is a special form of receiver used in the mobile radio environments subjected to multipath fading.

Multipath components are caused by the reflections of the transmitted signal from different man made or natural obstructions in the path between the transmitter and the receiver. These multipath components reach the receiving antenna at different times and with different strengths. The strength of a particular component depends on the channel characteristics for that particular component. The components may add destructively (intersymbol interference) and hence cause the signal strength to reduce. These multipath components therefore represent the lost signal energy. In a conventional receiver, only the strongest component is selected as the received signal. Some receivers use the first component as the received signal. The current CDMA system developed by Qualcomm Inc. can use different techniques to determine the received signal. The possibility of using

the energy in the different multipath components constructively to increase the received signal strength gives rise to the rake receiver.

The working of the rake receiver is based on the principle that signature sequences have low autocorrelation properties if their relative separation is greater than one chip period [Cameron 93]. Therefore, if a multipath component arrives with greater delay than one chip period, it will have low correlation with the desired component. If another correlation receiver with a delay equal to that of the above mentioned component is used, it will have better correlation with this component than with any other component. Based on this phenomenon, the rake receiver consists of a number of correlation receivers. These correlation receivers are weighted by a weighting factor the magnitude of which is proportional to the amount of fade in the corresponding component. Therefore, each correlation receiver correlates with only one of the strongest components. Similarly, the other correlation receivers output strong signals. In the figure below, $Z1$, $Z2$, ..., Zm are the decision statistics for the m correlation receivers and $w1$, $w2$,....,wm are the weighting factors. $r(t)$ is the received signal.

Figure 2.11 - Block Diagram Of A Rake Receiver

The IS-95 transmission standard has been proposed for use in a large number of cellular telephone and PCS systems world wide. We have described the important features of this system. Because of Its widespread use, there is a great deal of interest in accurate techniques for performance evaluation of this system. The usefulness of simulation techniques has been limited by the computational complexity. In the remainder of this thesis, we explore the use of Importance Sampling to reduce the simulation time for CDMA systems.

3. Importance Sampling

3.1 Introduction To Importance Sampling

Importance Sampling is a technique to reduce the amount of time required for Monte Carlo simulations. The basic principle is to make the events of interest occur more frequently than they normally do [Beau 90a]. It achieves this by making an accurate estimate of the performance of a system with fewer bits required than in standard simulation. The method creates more errors for a given number of bits. Although the errors are generated more frequently, BER is converted to known values by multiplying by a known correction factor. In Monte Carlo simulation, the minimum number of bits required to estimate the performance of the system is at least 10/BER where BER is the bit error rate of the system. The assessment of bit error rate performance of a digital communication system via computer simulation has been the traditional manner chosen for Monte Carlo simulation. For systems with very low BER values, this would require a very large number of bits to be simulated [Jeru 87]. For example, for a system with a BER of 10^{-8}, the minimum number of bits required by Monte Carlo method would be 10^9 [Baker 93]. With Importance Sampling, a reduction factor of the order of 3 to 8 can be achieved. This helps to determine the performance of the same system with many fewer bits within a desired level of accuracy. Importance Sampling has become a popular technique and is used in most simulation work done in the industry. Simulations that originally took long hours or days can now be done in a much shorter time. The amount of time reduction depends on the system to which the method is applied.

3.1.1 Biasing The System

Importance Sampling is a modified form of Monte Carlo simulation. It reduces the total number of bits to be simulated by biasing the system in order to generate more errors. In other words, it generates the same number of errors as in the case of Monte Carlo simulation for a smaller number of bits sent. The biasing is accomplished by modifying the probability density function. For example, in a communication system with Additive White Gaussian Noise (AWGN), the probability density function of Gaussian Noise is modified or biased in such a manner so as to generate a large number of errors. This

increases in the number of errors is then scaled for at the receiver to accurately determine the BER of the system. This is called unbiasing the system.

Consider a simple baseband binary communication system. Let x(t) represent the signal and n(t) the Gaussian noise added to it. The received signal is x(t) + n(t). The system can be represented by the following figure [Jeru 87]

signal samples
x(t)

SYSTEM

output samples
y(t)

noise samples
n(t)

Figure 3.1 - Block Diagram Of A Simple Communication System

The input signal x(t) has a probability density function shown below

Figure 3.2 - Probability Distribution For Input Signals

To determine the BER of the system, we count the number of received signals above (or below) a threshold voltage and divide by the total number of signals sent. This process is repeated many times in order to verify the results. Also, it can be repeated for different values of Signal to Noise Ratio (SNR) and a plot of the BER vs. SNR can be obtained. The Gaussian noise added to the signal has a probability distribution function shown below

Figure 3.3 - Probability Distribution For Gaussian Noise In The Channel

The x-axis represents the magnitude of the noise and the y-axis represents the probability density of the noise. It can be argued that the larger the magnitude of noise, the greater the probability that it will cause a bit/signal to be in error. There is thus an unknown threshold value of the noise magnitude which if exceeded, would cause an error. This threshold is unknown. Importance Sampling attempts to choose noise samples from the region for which the magnitude of the noise exceeds this unknown threshold. This region may be termed as the Important Region. By modifying the probability distribution to generate noise samples of a larger magnitude, Importance Sampling causes more errors to be generated at the receiver end. This explains the biasing procedure. The biasing may be achieved in different ways and thus we have different forms of Importance Sampling. These forms are explained in detail in a later section of the chapter.

3.1.2 UNBIASING THE SYSTEM AND THE CONCEPT OF WEIGHTS

Let us consider the same baseband binary system described in the above section. The output random variable (x(t) + n(t)) can be mapped to the input random variable x(t) i.e. for every input signal x(t), we have a corresponding output signal y(t) = x(t) + n(t). The probability density function (p.d.f.) of the output is similar to the p.d.f. of the input. Let T represent the threshold which if exceeded indicates that the received bit is in error. Let n be the number of bits received in this region and N be the total number of bits sent. The BER of the system is given by :

$$BER = n/N \qquad\qquad (3.1.1)$$

Figure 3.4 - Threshold Detection And Important Region

For a biased system, the weight/unbiasing factor for all the bits in the Important Region is given by

$$W_{av[i]} = \frac{1}{n_i} \sum_{k=1}^{ni} 1/B(x_{ki}) \qquad (3.1.2)$$

where n_i is the number of bits in error, $B(x_{ki})$ is the biasing factor for the sample x_{ki} and $W_{av[i]}$ is the average weight or unbiasing factor.

This weight has an average value much less than 1.

The BER is now given by

$$BER = \lim_{N \to \infty} \frac{n_i \times W_{av[i]}}{N} \qquad (3.1.3)$$

Thus, though a much larger number of erroneous bits are detected, yet the small value of the weights prevents the BER from getting very large.

The weight for the above system can be determined by different methods. The accuracy by which the weights compensate for the biasing determines the accuracy of the method and is a measure of the performance of Importance Sampling. Hence, determination of weights is crucial in Importance Sampling.

3.2 TYPES OF IMPORTANCE SAMPLING

3.2.1 Monte Carlo (MC)

Monte Carlo simulation technique is also called error counting technique [Jeru 84]. It works on the simple principle of observing the number of bits in error and dividing this number by the total number of bits sent to determine the BER of the system. [Jeru 84] has derived an expression for the confidence interval in which the BER would lie.

Consider that a +1 volts is transmitted. The p.d.f. of the received signal is given by $f_1(V)$. If the received signal falls below threshold V_T, the bit is in error.

Figure 3.5 - Threshold Detection For Monte-Carlo Systems

Similarly, if a 0 volts signal is transmitted and the received signal p.d.f. is $f_0(V)$, the bit received would be in error if the received voltage exceeds V_T.

Figure 3.6 - Threshold Detection For Positive Tail Of Distribution

Thus by setting a particular threshold for detection, the Monte Carlo method simply works on counting signals above or below the fixed threshold and uses this number to evaluate the BER of the system. As pointed out earlier, in case of systems with very small values of BER, this method is inefficient as it requires a large number of bits to be simulated.

3.2.2 Scaling Importance Sampling

$$No = 4\sigma^2 \qquad\qquad (3.2.1)$$

where No is the Noise density and σ^2 is the variance.

In the following figure, f(x) is the p.d.f. of the gaussian noise x. A new gaussian variable y can be generated by a simple relation

$$y = ax \qquad\qquad (3.2.2)$$

where a is a constant . The p.d.f. of y is given by f*(x). The increase in variance causes the distribution to be flatter maintaining the area under the curve as 1.

Figure 3.7 - Scaling Importance Sampling

The bias factor in this case is

$$B(x) = f^*(x)/f(x) \text{ [Shan 80]}. \tag{3.2.3}$$

The corresponding value of unbiasing factor or weight of the system is

$$W(x) = 1/B(x) = f(x)/f^*(x). \text{ [Shan 80]}. \tag{3.2.4}$$

As seen from the figure, more noise samples are drawn from the tail (important region) of the noise distribution. Since the amplitude of noise is larger in the tail region, the greater the increase in variance (greater the value of constant a), the greater the number of errors generated. It must be remembered though that an increase in variance and hence in the signal noise means a decrease in the SNR for the system. In order to have results for the same value of SNR, the signal power must also be increased with an increase in the variance. The amount of improvement achieved depends on the choice of the constant a. It is assumed that a value of 0.5 for a is a good choice to start with.

3.2.3 Improved Importance Sampling

In this version of Importance Sampling, the mean of the p.d.f. of the distribution is shifted in the direction of the important region [Baker 93]. In case of a binary baseband communication system, if a +1V is sent, the mean of the p.d.f. of the Gaussian noise is shifted towards the negative tail and in case a -1V is sent, the mean is shifted towards the positive tail. Consider the case when a +1V is sent

Figure 3.9 - Mean Shifted In Other Direction For Improved Importance
Sampling [Beau 90a].

Let us consider a simple baseband system in which 10000 bits are sent and 20 bits are in
error. The BER in case of Monte Carlo method would be 20/1000 i.e. 0.02 or 2%. Let us
assume that in case of Improved Importance Sampling, 20 bits are observed to be in error
by sending just 100 bits. Let the average weight of a bit be 0.01. The BER of the system
would be

$$BER = 20 \times .01 / 100 = 0.02 \text{ or } 2\%$$

which is the same as the value obtained in Monte Carlo simulation. Thus, the performance was evaluated by sending 1/100 th of the total number of bits. However it is to be noted that the above example only illustrates the concept of Improved Importance Sampling. The actual value is determined by using the following relation

$$BER = W_{av[i]} \times n_i^*/N = 1/N \sum_{k=1}^{ni^*} 1/B(x_{ki}) \qquad (3.2.5)$$

where n_i^* is the number of weighted bits in error.

In [Shan 80], the expression for the weight of a bit is given by

$$W_i = (\prod_{m=1}^{M} B_{mi})^{-1} \qquad (3.2.6)$$

where M is the memory of the system.

The total weight of the system is

$$W = \sum_{i=1}^{n} W_i / N. \qquad (3.2.7)$$

where n is the number of observed bits in error and N is the total number of bits sent.

The details of Improved Importance Sampling (determination of the Optimum Shift point) are dealt with in more detail in Section 4.2.

3.2.4 Sub-Optimum Importance Sampling

Sub-Optimum Importance Sampling works on similar lines as Improved Importance Sampling. A detailed discussion of the application of this technique to the Gaussian tail and the Rayleigh tail is given in [Beau 90]. The technique to generate the bias function is the same. However, in this method, a threshold point T in the gaussian p.d.f. is assumed. This is the unknown threshold value of the noise which if exceeded, would cause the bit to be in error. If this threshold was known, the significance and very purpose of Importance Sampling would be killed. This is because if the threshold was known, only noise samples with values greater than the threshold would be used in the simulation i.e. the modified p.d.f. has a region that is zero, a region that is similar in shape to the original p.d.f. and a region of transition between these two regions.

$$f^*(x) = \begin{cases} f(x)/q & \text{for } x > T \\ 0 & \text{otherwise} \end{cases} \qquad (3.2.8)$$

where q is the q-function value by which the biased distribution probability is divided to make the area under the curve 1.

In [Wang 87], a detailed mathematical derivation to estimate the important region is given.

Figure 3.10 - Sub-Optimum Importance Sampling

In Sub-Optimum Importance Sampling, an estimate of the above threshold is made and only those noise samples of value greater than the threshold are used. The closer the estimate to the actual unknown value of the threshold, the better the performance of this method. There is a method to know when the threshold value has been exceeded. Let us assume that a threshold value has been assumed. Noise samples of values greater than the threshold are used. Let 20 out of 100 bits observed be in error. If the value of assumed threshold is increased in steps, a stage will be reached when every bit sent would be in error. This is because the assumed threshold is so large that every noise sample has a

large enough value to cause a bit to be in error. If the assumed threshold is further increased, the number of erroneous bits does not increase (as it has reached Its maximum value) but the BER decreases as the value of the weight $f(x)/f^*(x)$ gets more and more smaller as we move more and more towards the tail end of the p.d.f. Thus the point or threshold value after which the BER never increases could be assumed to be pretty close to the actual optimum threshold value of the noise.

In short, two possible cases arise when a threshold value is assumed:

Case 1: The assumed threshold value is smaller than the actual value i.e. the assumed important region is larger than or contains the actual important region

Figure 3.11 - Assumed Important Region Is Greater Than Actual
Important Region [Beau 90].

It has been shown that the time saving in the simulation, i.e. the reduction in the number of bits to be simulated, is directly dependent on how close the assumed threshold is to the actual threshold.

Case 2: The assumed threshold value is larger than the actual value i.e. the assumed important region is smaller than or is contained in the actual important region

Figure 3.12 - Assumed Important Region Is Smaller Than Actual Important Region[Beau 90]

In this case, since all noise samples are drawn from the actual important region, all the bits observed would be in error. This is a case of overbiasing and the results obtained would be erroneous.

Thus, it is suggested that the guess for the threshold should be made in such a way that the assumed important region is large enough to contain the actual important region but small enough to keep the difference in the regions small.

3.2.5 Composite Importance Sampling

Composite Importance Sampling includes features of both Improved Importance Sampling and Sub-Optimum Importance Sampling [Baker 93]. It assumes a threshold like the Sub-Optimum method and it uses the technique of shifting the mean of the gaussian p.d.f. like Improved Importance Sampling. Let x be the original random variate with a p.d.f. shown as f(x). Let x be translated to a new value x' by the relation

$$x' = |x| + M \qquad\qquad (3.2.9)$$

where M is the amount of shift applied to the mean of the distribution. Assuming that the shift M is a good estimate of the threshold for the translated value x', the modified p.d.f. of x' is given by f*(x) where

$$f^*(x) = \begin{cases} 2f(x-M) & \text{for } x >= M \\ 0 & \text{for } x < M \end{cases} \qquad\qquad (3.2.10)$$

Figure 3.13 - Composite Importance Sampling

The performance of this method improves as M is made closer to the actual threshold point T. This method is also called Composite Importance Sampling.

3.3 Importance Sampling Parameters

Though there are a large number of parameters involved in the use of Importance Sampling, some of these outweigh the others in importance. The most important of these parameters are the memory of the system and the amount of shift in case of Improved Importance Sampling, Sub-Optimum Importance Sampling and Absolute Value Importance Sampling. The parameters are interdependent in nature which means that the importance of a particular parameter may increase or decrease depending on the amount

of influence the other parameters have for a particular set of values. It is the understanding of the behavior of these crucial parameters that helps in implementing Importance Sampling successfully. Such an understanding is achieved primarily by experience which in turn is achieved by running simulations with other parameters constant and varying only one parameter. The individual behaviors change by a certain degree when the joint effect of all of them is observed.

3.3.1 Memory Of The System

The memory of the system may be defined as the number of previous samples that influence the decision on the current bit. The memory of the system may be known or unknown. Several methods have been used previously to determine system memory. In case of complex systems like CDMA or other systems using Viterbi Decoders, the system may have infinite memory.

If a system has memory length K, the input samples that contribute to a particular output sample are designated x_{ij} where j = 1,2,3,......,K [Davis 86].

Certain authors like Shanmugam [Shan]have suggested that in such a case, a cut-off value for the system memory should be assumed and the technique should be implemented using this cut-off value for system memory. From [Beau 90a], if memory length being used is greater than the actual memory length, accuracy is not affected much. However, if it is smaller than the latter, there would be a degradation of performance.

It is seen that the larger the system memory, the lesser the significance of Importance Sampling. Larger the system memory, grater the number of samples. Experience has shown that this tends to lower the BER of a system. If a particular bit is sampled only once, there is a greater probability that it could be detected in error than if it was sampled 100 times. This explains why the BER reduces slightly when system memory is increased.

The following table illustrates how the effectiveness of Importance Sampling deteriorates with increasing memory [Beau 90a]

TABLE 3.1 - Effect Of System Memory On Sample Size Savings Factor (SSSF)

SYSTEM OF MEMORY LENGTH = 1	SYSTEM OF MEMORY LENGTH = 5
saving factor = 45	saving factor = 7
saving factor = 300	saving factor = 30
saving factor = 2800	saving factor = 170
saving factor = 25500	saving factor = 1000

Here, saving factor is the ratio of the number of bits originally sent/simulated to the number of bits required with Importance Sampling.

3.3.2 THE AMOUNT OF SHIFT

In case of Importance Sampling methods using the mean shift method (Improved Importance Sampling, Sub-Optimum Importance Sampling and Absolute Value Importance Sampling), the amount of shift applied to the mean of the p.d.f. is of paramount importance. As the shift is increased towards the tail region of the p.d.f. (important region), the number of bits in error keeps increasing. The BER should also increase. However, the weight reduces as we move towards the tail region of the p.d.f.. The two effects oppose each other and the net effect on the BER depends on the relative change on the two forces acting against each other. It is observed that with a few bits sent, if the shift is too small initially, no errors are detected. This means that the noise samples have a magnitude much lower than the actual threshold. However, as the shift is increased, the errors increase and the BER increases. Close to the optimum point, the weight starts becoming a significant contributor and the BER stabilizes for some time for different values of the shift. If the shift is further increased, the actual unknown optimum shift positioned is crossed and it is observed that though the number of errors is still increasing, the weights get so small that the overall BER reduces. Further increase in shift will lead to a stage when all bits are in error. After this stage, the number of erroneous bits has reached Its maximum (equal to number of bits sent) and the weights become the dominant factor. The weight keeps decreasing for every small increase in the shift. Thus

the BER after biasing taken into account, will reflect the true BER of the system until the optimum shift is exceeded. After this point, the BER produced by Importance Sampling will no longer be valid.

3.3.3 Reasons For The Choice Of Improved Importance Sampling

In order to implement IS in the given CDMA system, an intensive literature survey followed by a detailed theoretical study was done on the different versions of IS. The method of implementing each of these versions was explored to and then the suitability of each method for the particular system was weighed. Then the codes for each of these versions was written and tested on a simple communication system to study the pros and cons and to finally choose the best suitable match for the system. The method of shifting the mean (Improved Importance Sampling) was chosen as the most suitable method due to the following reasons

Increasing the variance (Scaling Importance Sampling) worked successfully. The bias function as seen before is given by

$$B(x) = \frac{f^*(x)}{f(x)} \qquad (3.3.1)$$

In case of Scaling Importance Sampling (also called Conventional Importance Sampling), the above expression can also be written as

$$B(x) = \frac{c}{[f(x)]^{\alpha}} \qquad (3.3.2)$$

where c is so chosen as to keep the area under the curve equal to unity. The value of c can be given by

$$c = \sqrt{(1-\alpha)/(2\pi)^{\alpha}} \qquad (3.3.3)$$

A conservative choice for α is 0.5. The improvement in simulation time i.e. the SSSF depends on α. This method is used for biasing noise density functions. However, it was proved later that Improved Importance Sampling could yield greater amount of reduction in the simulation time. In [Shan 80], a detailed comparison of the two methods shows that IIS consistently outweighs and outperforms SIS [Baker 93]. So this method was ruled out due to Its diminishing importance when compared to other IS techniques.

Sub-Optimum and Composite Importance Sampling were also implemented. However, the results were not correct. The reason was that the weights for individual samples exceeded 1 on many occasions resulting in an overall weight greater than 1 in many cases. This observation denied the theory behind IS that the weight should be less than 1. This is because with increasing shift, the number of errors increased and their weights also became greater than 1. As a result, there was a possibility of the Bit Error Rate (BER) or the Frame Error Rate (FER) to exceed 1. This is impossible in actual practice and so the method was ignored. Due to lack of literature on the application of such processes on spread spectrum systems, the reason for the weight exceeding 1 could not be conjectured.

The implementation of Improved Importance Sampling was very encouraging. The results were in near total agreement with the expected values. The results yielded weight values over a large range but the average value of the weight was always less than 1. The results were true for different values of Eb/No and for different number of samples per bit also (i.e. for different memory values). Thus, Improved Importance Sampling was chosen as the most suitable technique.

4 IMPORTANCE SAMPLING APPLIED TO THE CDMA SYSTEM

The application of Importance Sampling to memoryless systems is found in a number of studies. Most of these studies have indicated a time reduction factor of 3 to 8 orders of magnitude for such systems. The systems described are simple to study and do not involve large memory values.

The application of Importance Sampling to a communication system involves the detailed study of the entire system and an understanding of the functionality of each component. This is because the application of the Importance Sampling procedure involves changing the system noise distribution and hence affects the performance of the system. No previous study has indicated the possibility of implementing Importance Sampling in a spread spectrum system. The implementation of Importance Sampling techniques to the CDMA problem is the first of its kind. Also, there are different versions or types of Importance Sampling that can be applied. The search for the best IS scheme is clearly a difficult problem, especially for coded systems [Chen 90].

4.1 The Complexity Of The CDMA System

The Qualcomm CDMA system to which the technique of Importance Sampling was applied is highly complex. A detailed description of the system components has been given in Chapter 2. The first step was to determine the memory of the system. The memory of the system has been defined as the number of previous bits or samples on which the decision of the current bit or sample depends. For a memoryless system, this number is zero indicating that the bits are independent. In the current CDMA system specified by Qualcomm Inc., the decision on any one bit or sample depends on a large number of previously transmitted bits. Each bit is encoded into 2 symbols for the forward channel and into 3 symbols for the reverse channel. The encoded symbols are interleaved, modulated and then spread over Walsh chips. The baseband filter then samples the symbols at the rate of 4 samples per symbol. The total number of samples per bit in both the forward channel as well as the reverse channel case is 512.

Forward CDMA Channel

Figure 4.1 - Forward CDMA Channel

In this chapter, we focus first on a simple model of a CDMA system, to develop the basic Importance Sampling method. In chapter 5, we apply Importance Sampling to the full CDMA system.

Determination Of Frame Error Rate Instead Of Bit Error Rate

Importance Sampling is based upon the assumption of the bits being independent of each other. However, the highly dependent nature of bits in a spread spectrum system violates this assumption. To avoid this intricate problem, the Frame Error Rate (FER) of the system was determined instead of the BER. The frames are independent of each other. Each frame in the current system has 192 bits and each bit is sampled 512 times. Though the bits within a frame are not independent of each other, yet the frames as a whole are

independent in nature. The weight of each sample was determined. The weight of one bit in a frame is the product of the weights of the 512 samples for that bit.

$$W_b = \prod_{i=1}^{i=512} w_i \qquad (4.1.1)$$

where w_i is the weight of a sample of a bit.
The weight of the entire frame is

$$W_f = \prod_{b=1}^{b=192} W_b \qquad (4.1.2)$$

where W_b is the weight of a bit.
Combining the above two equations

$$W_f = \prod_{i=1}^{i=192 \times 512} w_i \qquad (4.1.3)$$

where w_i is the weight of a sample for a frame. (A frame has a total of 192 x 512 samples).

If a frame is in error (if three or more bits are in error within a frame in the current system), the frame weight is used to determine the FER of the system.

$$FER = \frac{\sum_{f=1}^{f=NE} W_f}{N} \qquad (4.1.4)$$

where NE is the number of frames in error and N is the total number of frames simulated.

4.2 Application Of Importance Sampling To A Simple Communication System

Due to the complexity of the CDMA system (discussed later in the chapter), Importance Sampling was first applied to a simple baseband system in order to understand the exact nature of the technique. The method of shifting the mean was applied to a binary baseband system. The system was simple in nature and did not take into account different stages in a communication system like encoding, interleaving and modulation which were present in the actual system. This simplified system was being used as a test bench to verify the authenticity of Importance Sampling and to study the effect of important parameters. The code was developed in ANSI C. The simple baseband system consisted of a source to generate random data. If a +V volts is sent, the mean is shifted down or made less positive and if a -V volts is transmitted, the mean is shifted up or made more positive. The data was sent through a channel with AWGN characteristics. The noisy data bits were received and the method of threshold detection was applied to determine the received bits. The received bits were compared with the originally transmitted bits and the number of bits in error was determined. Each of the erroneous bits had a weight associated with it (the determination of weights has been dealt with in a later section of this chapter). The BER of the system was finally determined by adding the weights of the erroneous bits and dividing the sum of the weights by the number of bits sent. Figure 4.2 below shows a simple baseband communication system

AWGN ----- Additive White Gaussian Noise

Figure 4.2 - Simple Baseband Communication System

The results obtained for the system were very accurate. An improvement factor of 10 was achieved. The BER values of the system before and after implementing Importance Sampling were in close agreement. The results were further verified for different values of Eb/No and for different number of samples per bit. These simulation runs helped to understand the effect of different parameters involved. These results were also very encouraging. The results have been described and compared to those of the original system in chapter 5.

4.3 Application Of Importance Sampling To Spread Spectrum System

The above baseband system was modified to incorporate DS/SS technique for CDMA operation. Each bit in the original system was spread over 128 chips using a spreading code. At the receiver, the despreading code was used to recover the spread symbols. The results of the spread spectrum system were also very encouraging. The BER for different values of Eb/No and different number of samples per bit were in close agreement with the original results.

A detailed study of the effect of the different parameter settings had now been completed. It was observed that as a general trend, the number of errors increased with an increase in the amount of shift. However, the weight for each corresponding bit reduces with an increase in the shift. The two forces act opposite each other. After getting successful results with the above spread spectrum system, it was decided to implement Importance Sampling in the actual system.

4.4 BER And FER Values Of The Original CDMA System:

The original system was simulated for Eb/No = 0, 5 and 10 dB values. Note that a frame or block of data is in error if three or more bits in the frame are in error. This threshold value was assumed arbitrarily and is not specified as a fixed value for the system.

$$BER = \frac{\text{NUMBER OF BITS IN ERROR}}{\text{TOTAL NUMBER OF BITS SIMULATED}} \qquad (4.4.1)$$

$$FER = \frac{\text{NUMBER OF FRAMES IN ERROR}}{\text{TOTAL NUMBER OF FRAMES SIMULATED}} \qquad (4.4.2)$$

The results below shows the values of BER and FER for the forward channel at 1920 MHz, at a data rate of 9600 bps and using randomly generated data.

(i) Eb/No = 0 dB:
Number of bits sent = 29908
Number of bits in error = 6130
BER = 0.204962
FER = 0.641026

(ii) Eb/No = 5 dB:
Number of bits sent = 29908
Number of bits in error = 3244
BER = 0.108466
FER = 0.474359

(iii) Eb/No = 10 dB:
Number of bits sent = 29908
Number of bits in error = 3072
BER = 0.102715
FER = 0.448718

Figure 4.3 - BER/FER and Number of errors vs. Eb/No Of Original CDMA System

The above curve shows the trend of the number of errors and the BER/FER values vs. Eb/No values. The number of errors in the above curve have been normalized by a factor of 10^3. It is seen that the curve flattens out above 5dB value for Eb/No. This is because the errors are caused not only due to the channel noise but also due to the interference from multiple users. At Eb/No value greater than 5dB, the channel noise is not a significant contributor to the errors generated. As the number of users is the same, the BER is not much affected by the noise at higher values of Eb/No.

The number of errors increases with a decrease in the Eb/No value. Due to the increase in number of errors, the BER and FER increase. This is expected because as the Eb/No value increases, the signal power increases and hence lesser is the chance for a bit to be in error.

4.5 IS Techniques Applied To A Simple Baseband Communication System:

In order to understand the working of IS techniques, a simple baseband communication system was developed and IS was implemented on it. The code for the baseband system is provided in the chapter 8. A simple threshold detection mechanism was used to determine if a bit was in error.

The BER results of the original system without using spread spectrum techniques are given in the following paragraphs. The problem was handled in different ways:

4.5.1 BER Values For Baseband System Without Importance Sampling:

The following results for the BER were obtained for simulating a simple baseband communication system. The results have been computed for different values of the standard deviation σ. It should be remembered that No $= 4\sigma^2$. The results are provided for different number of samples per bit.

Number of bits sent = 10000.
Number of samples per bit = 2, 3 & 4.
Values of standard deviation (sigma) = 0.6, 0.7, 0.8, 0.9 & 1.0

Relation between BER and standard deviation sigma:

Table 4.1 below shows the values of BER obtained by simulating the original system using Monte Carlo method. The results have been obtained for different values of number of samples per bit.

TABLE 4.1 - BER Values For Corresponding Values Of Standard Deviation

Number of samples per bit	Standard deviation sigma	BER or original system
2	.6 .7 .8 .9 1.0	0.0090 0.0209 0.0391 0.0584 0.0774
3	.6 .7 .8 .9 1.0	0.0024 0.0067 0.0163 0.0290 0.0443
4	.6 .7 .8 .9 1.0	0.0003 0.0020 0.0057 0.0121 0.0212

Figure 4.4 - BER vs. Standard Deviation σ for original system

From the trend of the curve, it is obvious that the BER increases with an increase in the value of sigma (σ). This is expected as the noise power is directly proportional to σ^2 and hence increases with an increase in σ. The value of Eb/No falls and hence, the value of BER is expected to increase. Also, the BER decreases with an increase in the number of samples per bit.

4.5.2 Application Of Composite IS To The System:

As discussed earlier, Composite Importance Sampling deals with shifting the mean of the PDF of the noise distribution similar to the method of Improved Importance Sampling.

By doing so, an unknown threshold value is exceeded and the received bits are in error. Composite IS is based upon the principle of choosing samples from the Importance Region only. The Important Region is formed after assuming a threshold value for the noise. An important measure to be taken is to divide the value of $f^*(x)$ by the Q-function value at the assumed threshold point. This is done in order to keep the area under the biased curve equal to unity.

(I) The first approach was to think that the threshold bears a relationship with the amount of shift. Consider the following diagram:

Figure 4.5 - Point Of Intersection = Shift/2

Let f(x) represent the original distribution of the PDF of the Gaussian noise and $f^*(x)$ = f(x-M) the biased distribution. The amount of bias or shift is denoted by M. The point of intersection of the two curves can be proved to be M/2. On one side of this point, f(x) > $f^*(x)$ for every value of x and on the other side, f(x) < $f^*(x)$ for every value of x. This led to the thought that the unknown threshold (the point beyond which all the bits are in error) could be close to the point where x = M / 2. On the other side (negative x axis), the corresponding point would be x = - M / 2. If samples are taken are taken from the tail regions (for x values >M/2 or < -M/2), the noise added would have a large magnitude and could possibly cause errors. Thus, analytical study suggested that a threshold value in the range from .3M to .5M would be a safe value to start with. The results for threshold value

equal to .5M are provided below and are compared to the actual values of the original system values.

Threshold assumed to be = .5M
Number of bits sent without IS = 10,000
Number of bits sent with IS = 1,000
SSSF = 10

TABLE 4.2 - BER Values For Corresponding Shift Values For $\sigma = 0.6$

sigma	BER of the orig. system	samples/bit	shift	BER with IS
0.6	0.009	2	0.08	0.012726
			0.09	0.012152
			0.10	0.010378
	0.0024	3	0.08	0.002697
			0.09	0.003076
			0.10	0.002141
	0.0003	4	0.08	0.000724
			0.09	0.000786
			0.10	0.000773
			0.20	0.001062
			0.30	0.002371
			0.40	0.002743

TABLE 4.2 above compares the BER values obtained after implementing IS techniques to the original values. The value of standard deviation has been fixed at 0.6. The values clearly show that the BER is in close agreement after implementing IS. This proves the validity of IS techniques. An improvement factor of 10 was obtained in the time required for the simulation run.

TABLE 4.3 - BER Values For Corresponding Shift Values For σ = 0.7

sigma	BER of the orig. system	samples/bit	shift	BER with IS
0.7	0.0209	2	0.08	0.027682
			0.09	0.027329
			0.10	0.026969
	0.0067	3	0.08	0.007477
			0.09	0.007709
			0.10	0.008271
	0.0020	4	0.08	0.002609
			0.09	0.002671
			0.10	0.002695
			0.20	0.001062
			0.30	0.007107
			0.40	0.007245

TABLE 4.3, TABLE 4.4, TABLE 4.5 and TABLE 4.6 are similar to TABLE 4.2 and show results for sigma = .7, .8, .9 and 1.0.

TABLE 4.4 - BER Values For Corresponding Shift Values For σ = 0.8

sigma	BER of the orig. system	samples/bit	shift	BER with IS
0.8	0.0391	2	0.08	0.046353
			0.09	0.047050
			0.10	0.048051
	0.0163	3	0.08	0.015197
			0.09	0.015884
			0.10	0.015957
	0.0057	4	0.08	0.006219
			0.09	0.006644
			0.10	0.006245
			0.20	0.009299
			0.30	0.013494
			0.40	0.015489

TABLE 4.5 - BER Values For Corresponding Shift Values For σ = 0.9

sigma	BER of the orig. system	samples/bit	shift	BER with IS
0.9	0.0584	2	0.08	0.063358
			0.09	0.064383
			0.10	0.064793
	0.0290	3	0.08	0.025030
			0.09	0.025813
			0.10	0.026604
	0.0121	4	0.08	0.010543
			0.09	0.011000
			0.10	0.010969
			0.20	0.015503
			0.30	0.019825
			0.40	0.019989

TABLE 4.6 - BER Values For Corresponding Shift Values For σ = 1.0

sigma	BER of the orig. system	samples/bit	shift	BER with IS
1.0	0.0774	2	0.08	0.080656
			0.09	0.082799
			0.10	0.085633
	0.0443	3	0.08	0.035692
			0.09	0.036710
			0.10	0.036927
	0.0212	4	0.08	0.017879
			0.09	0.018157
			0.10	0.018051
			0.20	0.022041
			0.30	0.025641
			0.40	0.026481

Figure 4.6 BER vs. shift for sigma = .6,.7 & .8 In A System Having 2
Samples Per Bit

Figure 4.6 above is a plot showing the difference between the BER values of the original system and those obtained after implementing IS. The values have been compared for different shift values and different values of the standard deviation sigma. Each bit is sampled 2 times in this case.

Figure 4.7   BER vs. shift for sigma = .9&1.0 In A System Having 2 Samples Per Bit

Figure 4.7 is similar to Figure 4.6 but compares values for higher values of standard deviation sigma. The curve shows that the difference betwwen the BER values increases with the amount of shift.

BER vs. shift for different values of standard deviation sigma

Number of samples per bit = 3

BER of original system with sigma = .8

BER with IS with sigma = .8

BER with IS with sigma = .7

BER of original system with sigma = .7

BER with IS with sigma = .6

BER of original system with sigma = .6

Figure 4.8   BER vs. shift for sigma = .6,.7 & .8 In A System Having 3 Samples Per Bit

Figure 4.8 above is a plot showing the difference between the BER values of the original system and those obtained after implementing IS. The values have been compared for different shift values and different values of the standard deviation sigma. Each bit is sampled 3 times in this case.

Figure 4.9   BER vs. shift for sigma = .9&1.0 In A System Having 3 Samples Per
Bit

Figure 4.9 is similar to Figure 4.8 but compares values for higher values of standard deviation sigma. The curve shows that the difference betwwen the BER values increases with the amount of shift.

Figure 4.10   BER vs. shift for sigma = .6,.7 & .8 In A System Having 4 Samples Per Bit

Figure 4.10 above is a plot showing the difference between the BER values of the original system and those obtained after implementing IS. The values have been compared for different shift values and different values of the standard deviation sigma. Each bit is sampled 4 times in this case. The BER values seem to deviate more for greater values of shift.

Figure 4.11   BER vs. shift for sigma = .9&1.0 In A System Having 4 Samples
Per Bit

Figure 4.11 is similar to Figure 4.10 but compares values for higher values of standard deviation sigma. The curve shows that the difference betwwen the BER values increases with the amount of shift.

(II) The second approach was to fix the number of samples per bit and to compute the BER values for different values of shift and thus find the shift which gives results most accurately (Optimum Shift) for a fixed number of samples per bit. The results have been computed for different values of sigma (σ).

Original System:

Number of bits sent = 10,000

Number of samples per bit = 4

System with Importance Sampling:

Number of bits sent = 100

Number of samples per bit = 4

SSSF = 100

TABLE 4.7 - BER Values For Corresponding Shift Values For $\sigma = 0.9$ In A System Having 4 Samples Per Bit

SIGMA	BER of orig. system	shift	BER with IS
		1.5	0.000000
		1.7	0.000000
		1.9	0.000000
0.9	0.012100	2.1	0.000065
		2.3	0.000487
		2.5	0.001455
		2.7	0.004698
		2.9	0.017804

In TABLE 4.7 above, the optimum shift is obtained by observing that value of shift after which the BER deviates away from the true BER value in an increasing manner. In the above case, for shifts greater than or equal to 2.9, the BER deviates from the actual value of 0.012100. Thus it can be guessed that the optimum shift lies in the proximity of a shift value of 2.9.

Figure 4.12 - BER vs. Shift For σ = 0.9 In A
System Having 4 Samples Per Bit

Figure 4.12 above shows the optimum shift position OS as at that value of shift, the BER of the system has been most accurately determined by IS techniques.

TABLE 4.8 - BER Values For Corresponding Shift Values For σ = 1.0 In A System Having 4 Samples Per Bit

SIGMA	BER of orig. system	shift	BER with IS
1.0	0.021200	1.5	0.000000
		1.7	0.000000
		1.9	0.000000
		2.1	0.000041
		2.3	0.000331
		2.5	0.000997
		2.7	0.003229
		2.9	0.012206
		3.1	0.054555

TABLES 4.8, 4.9 and 4.10 are similar to TABLE 4.7 and compare results for different values of sigma.

Figure 4.13 - BER vs. Shift For σ = 1.0 In A System Having 4 Samples Per Bit

TABLE 4.9 - BER Values For Corresponding Shift Values For $\sigma = 1.2$ In
A System Having 4 Samples Per Bit

SIGMA	BER of orig. system	shift	BER with IS
1.2	0.046000	1.5	0.000000
		1.7	0.000000
		1.9	0.000000
		2.1	0.000032
		2.3	0.000153
		2.5	0.000498
		2.7	0.001612
		2.9	0.006028
		3.1	0.026697
		3.3	0.139988

Figure 4.14 - BER vs. Shift For σ = 1.2 In A System Having 4 Samples Per Bit

TABLE 4.10 - BER Values For Corresponding Shift Values For σ = 1.5 In
A System Having 4 Samples Per Bit

SIGMA	BER of orig. system	shift	BER with IS
1.5	0.088800	1.5	0.000000
		1.7	0.000000
		1.9	0.000000
		2.1	0.000017
		2.3	0.000068
		2.5	0.000230
		2.7	0.000735
		2.9	0.002693
		3.1	0.011645
		3.3	0.059562
		3.5	0.359984

Figure 4.15 - BER vs. Shift For σ = 1.5 In A System Having 4 Samples Per Bit

Figures 4.13, 4.14 and 4.15 are similar to Figure 4.12 and demonstrate the procedure to locate the Optimum Shift point OS in the IS procedure.

All the above results were very encouraging. The next step was to try out Improved Importance Sampling and then finally check for the suitability of one method on a spread spectrum system.

4.5.3 Application Of Improved Importance Sampling To The System

After successfully implementing Sub-Optimum Importance Sampling, Improved Importance Sampling was implemented. The following data shows the results for IIS applied to the baseband communication system. The data below shows values for the Optimum shift only which was obtained in the same way as described in the previous case.

Since the number of samples per bit in the actual system is very large (512), the results were computed for much larger values of the number of samples per bit.

Original System:
Number of bits sent = 1000 (10,000 if BER < 10^{-3}).
Number of samples per bit = 100, 200, 300, 400 & 500
Values of Eb/No = 0, 1, 2 & 5 dB.

System with Importance Sampling:
Number of bits sent = 100
Number of samples per bit = 100, 200, 300, 400 & 500
Values of Eb/No = 0, 1, 2 & 5 dB.
Sample Size Savings Factor (SSSF) = 100

TABLE 4.11 - BER Values For Improved Importance Sampling

Eb/No(dB)	Samples/bit	BER w/o IS	BER with IS
0	100	0.0270	0.026950
0	200	0.0240	0.024180
0	300	0.0300	0.029800
0	400	0.0270	0.026850
0	500	0.0250	0.025290
1	100	0.0170	0.016880
1	200	0.0130	0.013330
1	300	0.0180	0.017750
1	400	0.0170	0.017140
1	500	0.0130	0.012810
2	100	0.0090	0.008960
2	200	0.0080	0.007790
2	300	0.0090	0.008450
2	400	0.0110	0.008920
2	500	0.0080	0.007730
5	100	0.0002	0.000210
5	200	0.0002	0.000195
5	300	0.0003	0.000302
5	400	0.0001	0.000110
5	500	0.0000	0.000001

Table 4.11 compares the BER values for the system with and without IS techniques applied to it for different values of Eb/No. For each value of Eb/No, the results for large number of samples per bit (100, 200, 300, 400 and 500) have been provided.

The curves for the above values are given in Figures 4.16, 4.17, 4.18, 4.19 and 4.20.

Figure 4.16 - BER vs. Eb/No In A System Having 100 Samples Per Bit

Figure 4.16 shows the variation of BER with Eb/No in a system with 100 samples per bit. From the curve, we see that BER reduces with increasing Eb/No. This is expected as the greater the value of Eb/No, the less is the noise power relative to the signal strength and thus lesser is the chance of the transmitted bit to be in error. Therefore, the BER would be lower in value.

Figure 4.17 - BER vs. Eb/No In A System Having 200 Samples Per Bit

Figure 4.17 above is similar to Figure 4.16. It plots the values for the same system with 200 samples per bit. The BER again reduces with an increase in Eb/No as expected.

Figure 4.18 - BER vs. Eb/No In A System Having 300 Samples Per Bit

Figure 4.18 plots BER values for different values of Eb/No for the system with 300 samples per bit.

The number of samples per bit were incremented to larger values to study the complexities that could arise in the real IS-95 CDMA system which has 512 samples per bit.

Figure 4.19 - BER vs. Eb/No In A System Having 400 Samples Per Bit

Figure 4.19 plots BER vs Eb/No values for 400 samples per bit.

Figure 4.20 - BER vs. Eb/No In A System Having 500 Samples Per Bit

Figure 4.20 above displays BER vs Eb/No for 500 samples per bit. The success of IS in case of such a large value was encouraging and the next approach was to apply IS to the IS-95 CDMA system.

4.5.4 Application Of Improved Importance Sampling To Spread Spectrum System

The next and perhaps the most important step was to analyze the performance of IS techniques on spread spectrum systems. The original baseband system was modified to implement DS/SS and Improved Importance Sampling . The following results were

computed for 512 samples per bit (equal to the number in the actual CDMA system) and for different values of Eb/No.

Original Spread Spectrum System:
Number of bits sent: 1000 (10,000 for cases when BER < 10^{-3}).
Number of samples per bit = 512

Spread Spectrum System with Improved Importance Sampling:
Number of bits sent: 100
Number of samples per bit = 512
SSSF = 10-100

TABLE 4.12 - BER vs. Eb/No For 512 Samples Per Bit

Eb/No (dB)	Samples/bit	BER without IS	BER with IS
0	512	0.02299	0.02297
1	512	0.01299	0.01296
2	512	0.00610	0.00600
5	512	0.00060	0.00057

The number of samples per bit was increased to 512. This is the value for the IS-95 CDMA system. This large value was next used to obtain results in the case of the simple system in order to familiarize with expected problems that could be faced in a complex spread spectrum system. However, as shown by the results in TABLE 4.12, IS techniques approximated the BER for the system accurately for 512 samples per bit also.

Figure 4.21 - BER vs. Eb/No For 512 Samples Per Bit

The results obtained on the implementation of IS techniques on a simple baseband system and later on a spread spectrum system were very encouraging. SSSF factors in the range of 10 to 100 were obtained. The authenticity of IS had been validated and the next step was to actually implement Improved Importance Sampling into the Qualcomm CDMA system and test for Its efficiency in that case.

4.6 Estimation Of Weights To Determine The BER And FER Of The System

Importance Sampling, as described before, is a technique to introduce a modified probability density function and eventually reduce simulation time. The smaller the variance of the estimator, the more the reduction obtained.

Consider a simple binary NRZ system. Let us consider the following two cases for the generation of errors:

Case I: A '0' is sent but a '1' is detected. In the figure below, f(x) represents the probability density function for the output random variable. The '1' is detected due to the fact that the output threshold exceeded the value T in the figure below (Vt in the equations that follow)

Figure 4.22 - Threshold Detection To Detect Errors

The probability of error is given by [Baker 93]

$$P_0 = \int_{Vt}^{\infty} f_0(v)dv \qquad (4.6.1)$$

$$= \int_{-\infty}^{\infty} h_0(v).f_0(v)dv \qquad (4.6.2)$$

where
$$h_0(v) = \begin{cases} 1 & v >= Vt \\ 0 & v < Vt \end{cases} \qquad (4.6.3)$$

Case II: A '1' is sent but a '0' is detected. The '0' is detected for all values below Vt

The probability of error is given by [Baker 93]

$$P_1 = \int_{-\infty}^{Vt} f_1(v)dv \qquad (4.6.4)$$

$$= \int_{-\infty}^{\infty} h_1(v).f_1(v)dv \qquad (4.6.5)$$

where
$$h_1(v) = \begin{cases} 1 & v < Vt \\ 0 & v >= Vt \end{cases} \qquad (4.6.6)$$

Let us assume that we know of a new output probability density function (PDF) which reduces the variance of the estimator (and thus reduces the computation time). Let $f(x)$ be the original output PDF and $f^*(x)$ be the modified PDF.

Eq. (4.4.2) can also be written as

$$P_0 = \int_{-\infty}^{\infty} h_0(v).f^*_0(v).f_0(v)/f^*_0(v)dv \quad (4.6.7)$$

$$= \int_{-\infty}^{\infty} h^*_0(v).f^*_0(v)dv \quad (4.6.8)$$

where $\quad h^*_0(v) = h_0(v).f_0(v)/f^*_0(v) \quad (4.6.9)$

The probability of error can now be given by [Baker 93]

$$P^*_0(v) = \frac{1}{N} \sum_{i=1}^{N} h^*_0(v_i) \quad (4.6.10)$$

The biased or modified PDF $f^*_0(v)$ should be such that it causes more errors to occur. The output PDF $f^*_0(v)$ can be biased only if the input PDF $f(x)$ is biased. The input PDF maps into the output PDF in a certain manner. To successfully implement Importance Sampling, this manner must be known. Once this manner is known, the input random variable x can be biased in such a way as to cause more errors. For a communication system whose input random variable has a PDF denoted by $f(x)$ and the biased or modified PDF denoted by $f^*(x)$, the biasing factor is given by

$$B(x) = \frac{f^*(x)}{f(x)} \qquad (4.6.11)$$

Since the output random variable v is biased due to the biasing of the input random variable x, the unbiasing or weighting factor is given by [Baker 93]

$$W(x) = \frac{f(x)}{f^*(x)} = \frac{1}{W(x)} \qquad (4.6.12)$$

The weight calculated above is less than one. The BER is calculated by summing numbers less than one (the weights of the bits in error) and dividing by the total number of bits sent. We may consider normal Monte Carlo simulation as a form of Importance Sampling with weight equal to one.

Let us divide the output histogram into a number of rectangles called bins. Let P_n represent the probability of the output random v lies in the bin $[v_{n-1}, v_n]$. Let the number of samples in this bin be s_n. The probability may be estimated by P'_n where

$$P'_n = \lim_{N \to \infty} \frac{s_n}{N} \qquad (4.6.13)$$

and N is the total number of samples.

The average weight for the bin $[v_{n-1}, v_n]$ is given by [Baker 93]

$$W_{av[n]} = \frac{1}{s_n} \sum_{i=1}^{s_n} \frac{1}{B(x_{in})} \qquad (4.6.14)$$

where x_{in} is the ith input sample that produces an output sample in the nth bin $[v_{n-1}, v_n]$.

The biased estimate for the probability is given by

$$P^{*'}_n = \lim_{N \to \infty} \frac{s^*_n}{N} \qquad (4.6.15)$$

where s^*_n is the biased or weighted number of samples in the bin $[v_{n-1}, v_n]$ and N is the total number of samples.

Combining equations (4.6.13), (4.6.14) and (4.6.15), we can derive that

$$P'_n = W_{av[n]} \frac{s^*_n}{N} = \frac{1}{N} \sum_{i=1}^{s^*_n} \frac{1}{B(x_{in})} \qquad (4.6.16)$$

$$P'_n = W_{av[n]} \cdot P^{*'}_n \qquad \text{[Baker 93]} \qquad (4.6.17)$$

Reduction Factor In The Sample Size

It has been shown in [Baker 93] that the sample size reduction factor can be given by [Baker 93]

$$\text{Sample size reduction factor} = \frac{\int_{In} f(x)dx}{\int_{In} W_{av[n]}(x) \cdot f(x)dx} \qquad (4.6.18)$$

The above expression clearly demonstrates that the reduction factor will be larger if the denominator is smaller i.e. if the average weight $W_{av[n]}(x)$ for each sample is $<<< 1$.

Determination Of Weights For Calculating Frame Error Rates

The weight at a sample point is the ratio of the PDF of the original distribution to that of the modified or biased distribution. In the CDMA system to which Importance Sampling is to be applied, the noise added to the system has a Gaussian distribution. Let $f(x)$ denote the PDF of the Gaussian noise. In order to bias this distribution, the method of shifting the mean was chosen. Let $f^*(x)$ represent the biased PDF. The weight at any sample point x is given by

$$w(x) = \frac{f(x)}{f^*(x)} \qquad (4.6.19)$$

In the Qualcomm CDMA system, there are 512 samples per bit. The weight of a bit is the product of the weights of the 512 samples.

$$W_b = \prod_{i=1}^{512} w(x_i) \qquad (4.6.20)$$

The general procedure to determine the BER would be to see if a particular bit is in error (using threshold detection) and then divide the sum of the weights of the erroneous bits only by the total number of bits sent.

$$BER = \sum_{be=1}^{N} W_{be} \qquad (4.6.21)$$

where $W_{be} = W_b$ if the bit is in error and 0 if it is not in error and N is the total number of bits being simulated.

However, this method is based on the assumption that the bits are independent. But in the CDMA spread spectrum system, the bits are highly correlated and

cannot be considered independent at all. So the theory of determining BER was extended to Frame Error Rates (FER) as a frame (a block of 192 bits) can be considered independent of the previous or the next frame. The weight for a frame would thus be the product of the weights at 192 x 512 sample points.

$$W_f = \prod_{i=1}^{192 \times 512} w(x_i) \qquad (4.6.22)$$

According to the specifications provided by Qualcomm Inc. in the IS-94 manual, a frame would be in error if 3 or more bits within the frame are in error. The FER is then given by

$$FER = \sum_{fe=1}^{N/192} W_{fe} \qquad (4.6.23)$$

where W_{fe} is the weight of an erroneous frame and is equal to 0 if the frame is not in error. If it is in error, $W_{fe} = W_f$.

Concept Of Average Weight And Its Significance

As discussed above, the probability of error can be denoted as

$$P_e = \int_{\Re} f_V(v)dv \qquad (4.6.24)$$

where $\Re$ is the region in which the output values v cause an error.

Writing the same expression with the input random variable and noise probability density functions,

$$P_e = \int_{\Re} f(x,n)dxdn \qquad (4.6.25)$$

where $f(x,n)$ is the joint probability density function of the input random variable x and the noise n. Let us define an indicator function $H(x,n)$ given by

$$H(x,n) = \begin{cases} 1 & (x,n) \in \Re \\ 0 & (x,n) \notin \Re \end{cases} \qquad (4.6.26)$$

The probability of error can now be written as

$$P_e = \int_{x^k} H(x,n)f(x,n)dxdn \qquad (4.6.27)$$

where x^k is the region of the input space that results in an error.

Equation (4.6.27) shows that P_e is the mean of $H(x,n)$.
For Monte Carlo simulations, the estimator for this mean is

$$P'_e = \frac{1}{N} \sum_{i=1}^{N} H(x_i,n_i) \qquad (4.6.28)$$

The variance of this estimator is given by

$$\sigma^2_{MC}[P'_e] = \frac{P_e[1-P_e]}{N} \qquad (4.6.29)$$

For the case of Importance Sampling, the probability of error can be written as

$$P^{*}_{e} = \int_{x^k} H(x,n)W(x,n)f^{*}(x,n)dxdn \quad (4.6.30)$$

where $W(x,n) = \dfrac{f(x,n)}{f^{*}(x,n)}$ \hspace{2cm} (4.6.31)

The estimator for the mean in this case is

$$P'^{*}_{e} = \frac{1}{N^{*}} \sum_{i=1}^{N^{*}} H(x_i,n_i)W(x_i,n_i) \quad (4.6.32)$$

where N^{*} is the number of simulation trials.

It has been shown in [Baker 93] that the variance of this estimator can be given by

$$\sigma^2_{IS}[P'^{*}_{e}] = \frac{1}{N^{*}} \int_{x^k} H(x_i,n_i)[W(x_i,n_i) - P_e]f(x,n)dxdn \quad (4.6.33)$$

The above equation may also be written as

$$\sigma^2_{IS}[P'^{*}_{e}] = \frac{1}{N^{*}} [W' - P^2_{e}] \quad (4.6.34)$$

where the average weight W' can be defined as

$$W' = \int_{x^k} \frac{f(x,n)}{f^{*}(x,n)} f(x,n)dxdn \quad (4.6.35)$$

Equation (4.6.34) can also be written as

$$\sigma^2_{IS}[P'^*_e] = \frac{[W'/P_e - P_e] P_e}{N^*} \qquad (4.6.36)$$

Comparing equations (4.6.29) and (4.6.36), we see that the sample size saving factor (SSSF) is

$$SSSF = \frac{N}{N^*} = \frac{[P_e - P^2_e]}{[W' - P^2_e]} \qquad (4.6.37)$$

If W' can be estimated, then the variance of the IS estimator could be evaluated and the exact value of SSSF could be known. If that was possible, we could send only that number of samples that would be required to give the required SSSF. However, in actual practice, simulations are run with different values of N^* to yield different values of SSSF and also different values of W'.

In [Baker 93], it has been shown that the maximum value of the weight should exceed the true value of the probability of error being determined in order to get correct results. i.e.

$$Max[W(x,n)] \geq P_e \qquad (4.6.38)$$

4.7 Method Of Determining The Optimum Shift

In applying Improved Importance Sampling to the system, the PDF of the noise is shifted toward the tail ends causing more errors to occur. As the shift is kept on increasing, the number of errors keep on increasing. This would lead us to think that the shift could be made to increase indefinitely so as to keep generating more errors and cause the BER (or the FER) to keep increasing. Note that the greater the number of errors generated by

biasing the system, the greater the SSSF i.e. the fewer the number of samples required to be simulated. However, IS is based on determining the weights at these sample points. With increasing shift, more samples are taken from the region where $f(x) < f^*(x)$. Hence, the overall weight of a bit (or a frame) which is the ratio $f(x)/f^*(x)$ keeps reducing. Thus, the BER or the FER would tend to decrease. These two factor acting opposite each other create a point in the sampling region where the importance or the contribution of one outweighs the other. This point is called the point of Optimum Shift.

The determination of the Optimum Shift is the most critical part of implementing IS techniques.

[Baker 93] has deduced the location of the Optimum Shift based on his own observations. He points out that a trend is observed in the value of the BER obtained.

It is observed that initially, the BER increases with the amount of shift. The BER keeps increasing till it reaches a peak value after which it falls and never again increases. This is due to the fact that after a certain amount of shift, all the observed bits are in error and so the number of erroneous bits does not increase but their corresponding weights reduce thereby reducing the BER. According to [Baker 93], this point after which the BER never increases again is the point of Optimum Shift.

However, in the application of IS to the CDMA system, this trend was not considered as the guideline. The Optimum Shift was assumed to be that value of shift which yielded the BER and FER closest to the expected values.

5 RESULTS OF IMPORTANCE SAMPLING

This chapter presents the results of Importance Sampling as applied to the IS-95 CDMA system. The results have been obtained by simulating under different parameter settings. They have been verified by simulating for the same parameters several times. The effects of different parameters are also studied in this chapter. The simulation results have been obtained using the Bit Error Rate Simulator (BERSIM), a software developed at the Mobile & Portable Radio Research Group (MPRG) at Virginia Tech.

5.1 Setting The System Parameters Using BERSIM

BERSIM has been described briefly in the introductory chapter. However, this section deals with the entry of important parameters into BERSIM. A part of the original BERSIM code was integrated into the CDMA simulation code. The original BERSIM code was modified to implement specific values for the CDMA system. The different parameters that can be set using BERSIM are:

Number of users: The system was simulated for 1,10 & 20 users. In actual conditions, this is not practical and there are a large number of users in a cellular system. However, the results were obtained for a maximum number of 20 users only to verify with the original results of BER which had been obtained for a single user system. However, BERSIM allows any number of users to be simulated by just entering the desired number.

Eb/No: The results have been obtained for different values of Eb/No. The chief settings are at 5,10 and 15 dB values. BERSIM allows the use of different values of Eb/No for the system. The code for the CDMA system directly changes the value of standard deviation for a change in the value of Eb/No.

Choice Of Channel: Cellular systems consist of a forward channel from the base station to the mobile and a reverse channel from the mobile to the base station. The two channels differ from each other. For example, the reverse channel has a rate

1/3 convolutional encoder whereas the forward channel has a rate 1/2 convolutional encoder. The codes have been written separately for the two channels. By specifying in the BERSIM code the type of channel desired, the code follows the desired path for that particular channel.

Frequency: The CDMA system has been simulated for carrier frequencies of 1920 MHz. and 915 MHz as required by the IS-95 standard manual.

Data Rate: The IS-95 standard specifies a variable data rate vocoder. The four data rates to be used are 9600, 4800, 2400 and 1200 bps. The results have been compared for the maximum data rate value of 9600 bps.

Random vs. Fixed Data: The CDMA code provides a choice between using randomly generated bits and using a particular data stream as provided in a data file. The simulations have been carried out for randomly generated data.

Block Length: The system has been simulated for 192 bits per block or frame of data. The first frame has 148 bits. The total number of blocks originally simulated was 150.

Other Parameters: BERSIM allows the entry of other parameters like threshold values to determine bits in error, the amount of time delay, the presence of a RAKE receiver or a simple receiver, etc.

5.2 Results Of The Application Of IS Techniques To The IS-95 CDMA System

This section deals with the results obtained after running the IS simulations on the IS-95 CDMA system. The results are based upon channel impulse response data taken by Bell Atlantic Mobile under different environment conditions in different locations. The results have been compared with a large data of full scale simulations obtained without IS techniques to determine the accuracy of IS techniques. The simulations involve the following parameters:

Type of Environment:
* Semi-Rural
* Suburban
* Heavy Urban
* Urban

Carrier Frequency:
* 1920 MHz
* 915 MHz

Number of Users:
* 1
* 10
* 20

Eb/No values:
* 5 dB
* 10 dB
* 15 dB

The simulations were tried for forward channel only. The reverse channel runs can easily be verified by changing the input parameters to satisfy reverse channel condition. Also, only vertical polarization of antenna was considered. The results can be verified similarly for circular polarization also.

5.2.1 FER Simulation In A Semi-Rural Environment:

The data for the semi-rural environment was collected by Bell Atlantic Mobile along Route 213 - Flowers Mill Road in Langhorne, Pennsylvania. The area was characterized by some residential areas in addition to small businesses. Most of the region comprised of open space and farmland.

Table 5.1 below compares the FER values of the original system in a semi-rural environment with those obtained after the implementation of Importance Sampling.

The results have been obtained for Eb/No = 10 dB value for systems with 1 or 20 users. For 10 users, the results have been obtained for Eb/No values of 5 dB, 10 dB and 15 dB. Both 1920 MHz and 915 MHz frequencies have been tried in the simulation runs. Vertical polarization of the antenna has been used.

TABLE 5.1 - FER Results In A Semi-Rural Environment

Frequency	Number of users	Eb/No in dB	FER without IS	FER with IS
1920 MHz	1	10	0.012821	0.0103224
	10	5	0.032051	0.039869
		10	0.019231	0.0267852
		15	0.019231	0.0186005
	20	10	0.019231	0.019641
915 MHz	1	10	0.012821	0.00844471
	10	5	0.030769	0.0329498
		10	0.026923	0.0275694
		15	0.026923	0.0157003
	20	10	0.026923	0.0224971

Figure 5.1 below shows the variation of FER values with Eb/No for a cellular system in a semi-rural environment with 10 users and a carrier frequency of 1920 MHz. Figure 5.2 shows the results for a carrier frequency of 915 MHz. It is clear that the FER values decrease with an increase in the Eb/No value. The results have been obtained using vertical polarization and the forward channel has been simulated.

Fig 5.1 - FER vs. Eb/No for 10 users for forward channel in a
semi-rural environment at 1920 MHz with vertical
polarization

Fig 5.2 - FER vs. Eb/No for 10 users for forward channel in a
semi-rural environment at 915 MHz with vertical
polarization

In the figures below (Figure 5.3 and Figure 5.4), the relation between FER and the
number of users in the system has been shown for same system. Figure 5.3 shows the
results for a frequency of 1920 MHz whereas Figure 5.4 shows similar results for a
frequency of 915 MHz. The results show clearly that the FER values increase with an
increase in the number of users in the system.

Fig 5.3 - FER vs.number of users at Eb/No = 10 dB for
forward channel in a semi-rural environment
at 1920 MHz with vertical polarization

Fig 5.4 - FER vs. number of users at Eb/No = 10 dB for
forward channel in a semi-rural environment
at 915 MHz with vertical polarization

5.2.2 FER Simulation In A Suburban Environment:

The transmitter for these measurements was placed at 502 S. Lenola Road in Mepleshade, NJ, a suburb of Philadelphia. Measurements were recorded for both vertical polarization as well as circular polarization of the antenna. The region consisted mainly of residential as well as small business constructions.

Table 5.2 below compares the FER values of the original system in a suburban environment with those obtained after the implementation of Importance Sampling. The results have been obtained for Eb/No = 10 dB value for systems with 1 or 20 users. For 10 users, the results have been obtained for Eb/No values of 5 dB, 10 dB and 15 dB. Both 1920 MHz and 915 MHz frequencies have been tried in the simulation runs. Vertical polarization of the antenna has been used.

TABLE 5.2 - FER Results In A Suburban Environment

Frequency	Number of users	Eb/No in dB	FER without IS	FER with IS
1920 MHz	1	10	0.051282	0.0463552
	10	5	0.076923	0.0680001
		10	0.070513	0.0758315
		15	0.051282	0.0471553
	20	10	0.083333	0.0818273
915 MHz	1	10	0.012821	0.0168403
	10	5	0.012821	0.0125819
		10	0.012821	0.0111308
		15	0.012821	0.0196106
	20	10	0.012821	0.0124964

Figure 5.5 below shows the variation of FER values with Eb/No for a cellular system in a suburban environment with 10 users and a carrier frequency of 1920 MHz. Figure 5.6 shows the results for a carrier frequency of 915 MHz. It is clear that the FER values decrease with an increase in the Eb/No value. The results have been obtained using vertical polarization and the forward channel has been simulated.
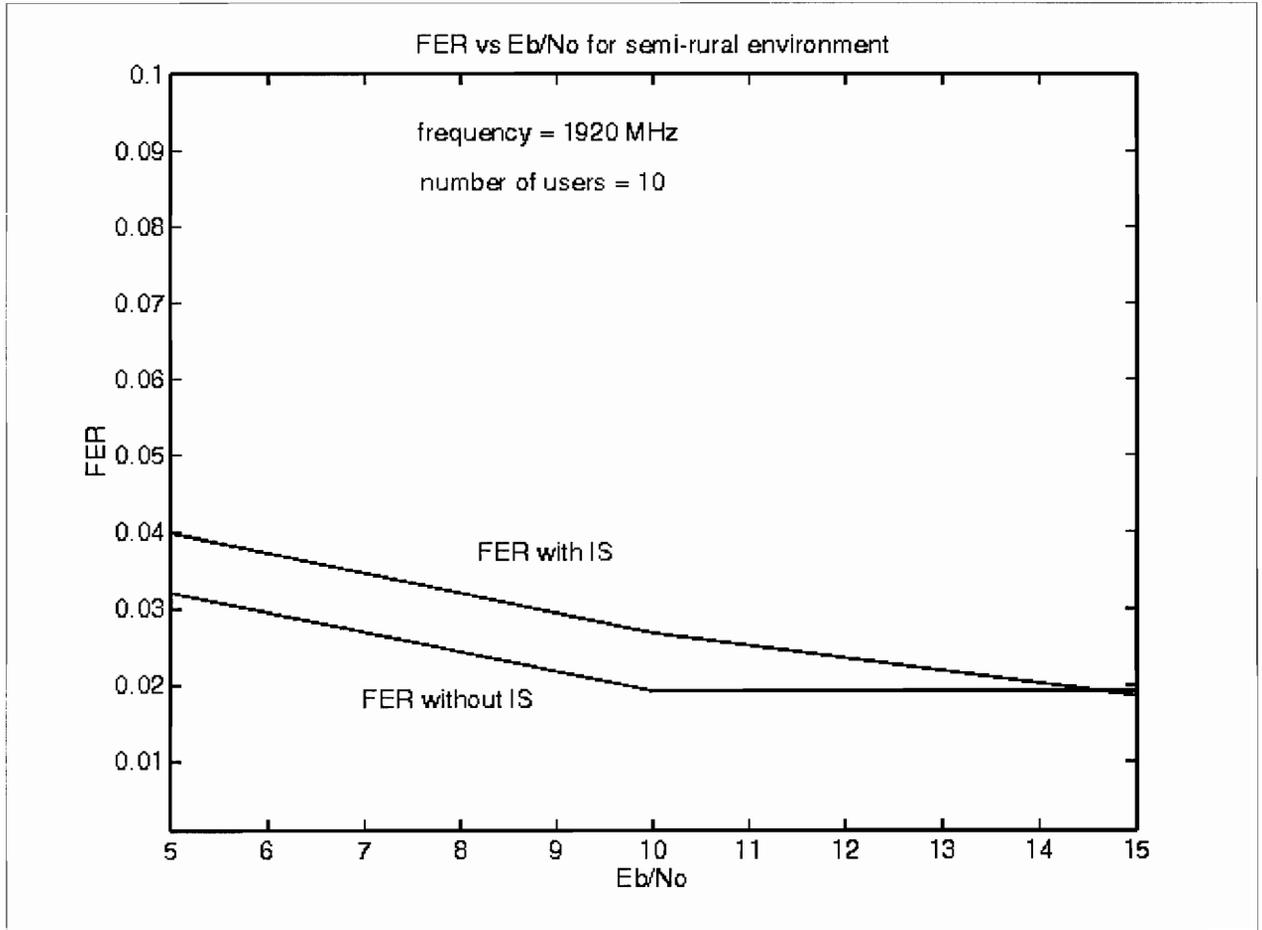
Fig 5.5 - FER vs. Eb/No for 10 users for forward channel in a
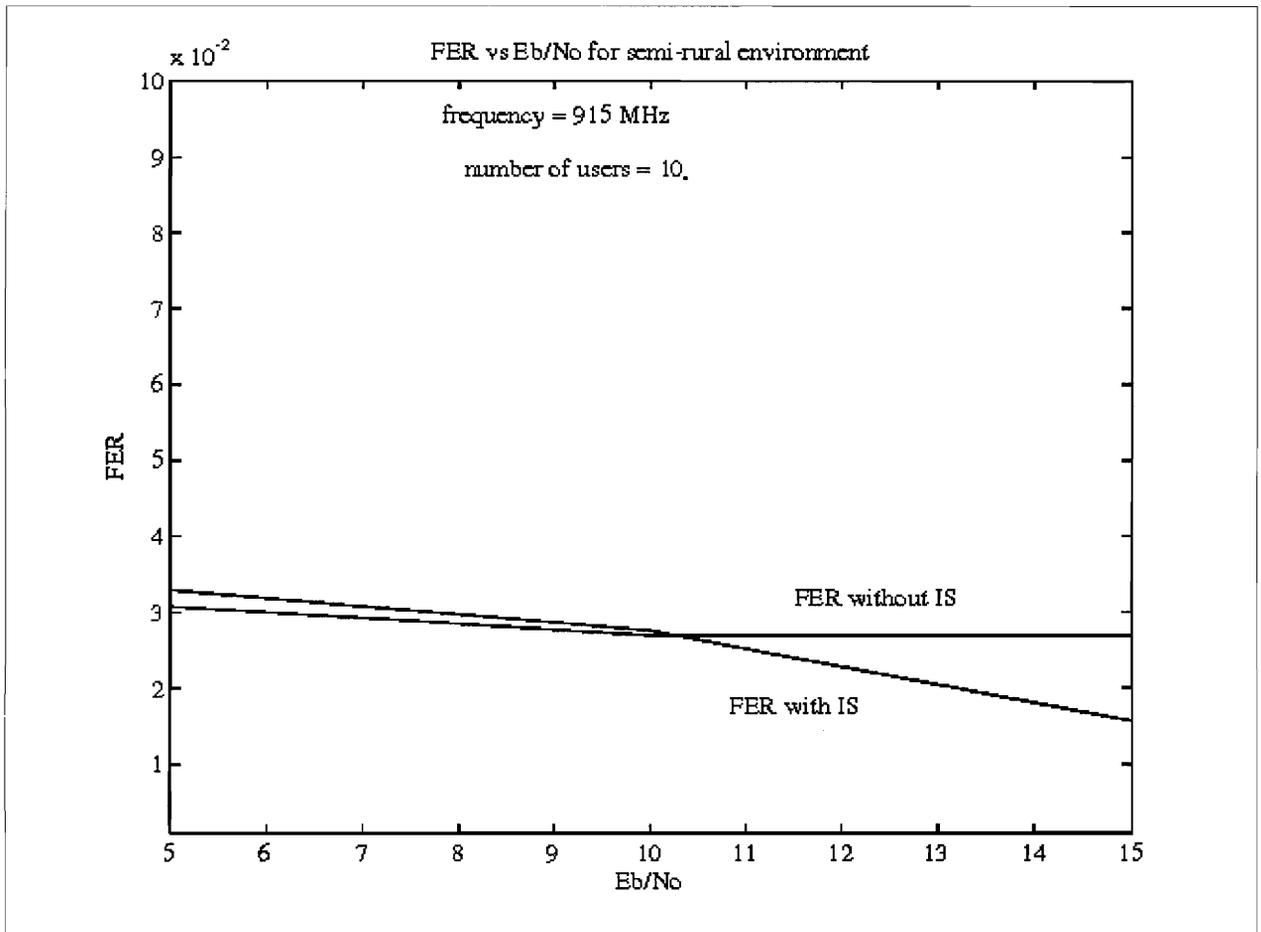suburban environment at 1920 MHz with vertical
polarization

Fig 5.6 - FER vs. Eb/No for 10 users for forward channel in a
suburban environment at 915 MHz with vertical
polarization

In the figures below (Figure 5.7 and Figure 5.8), the relation between FER and the
number of users in the system has been shown for same system. Figure 5.7 shows the
results for a frequency of 1920 MHz whereas Figure 5.8 shows similar results for a
frequency of 915 MHz. The results show clearly that the FER values increase with an
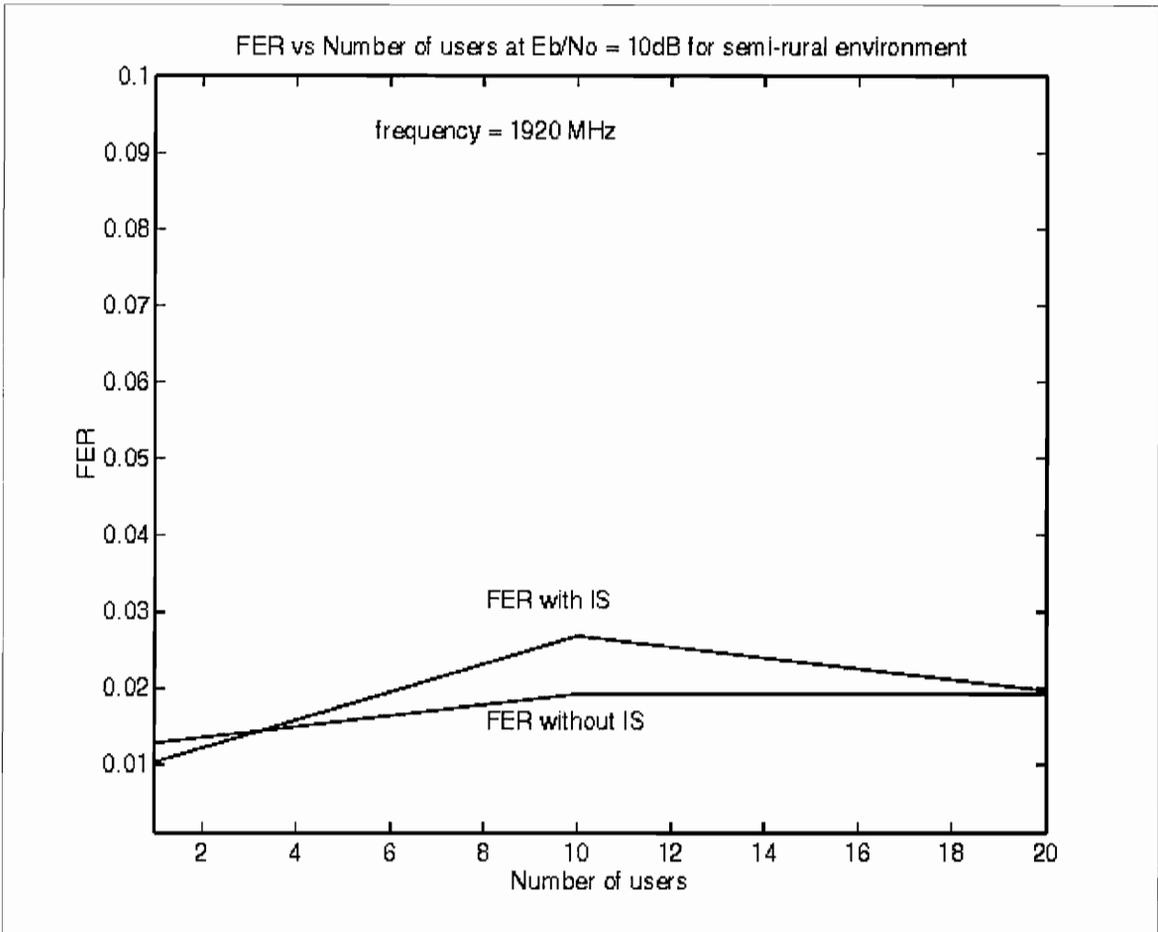increase in the number of users in the system.

Fig 5.7 - FER vs.number of users at Eb/No = 10 dB for
forward channel in a suburban environment
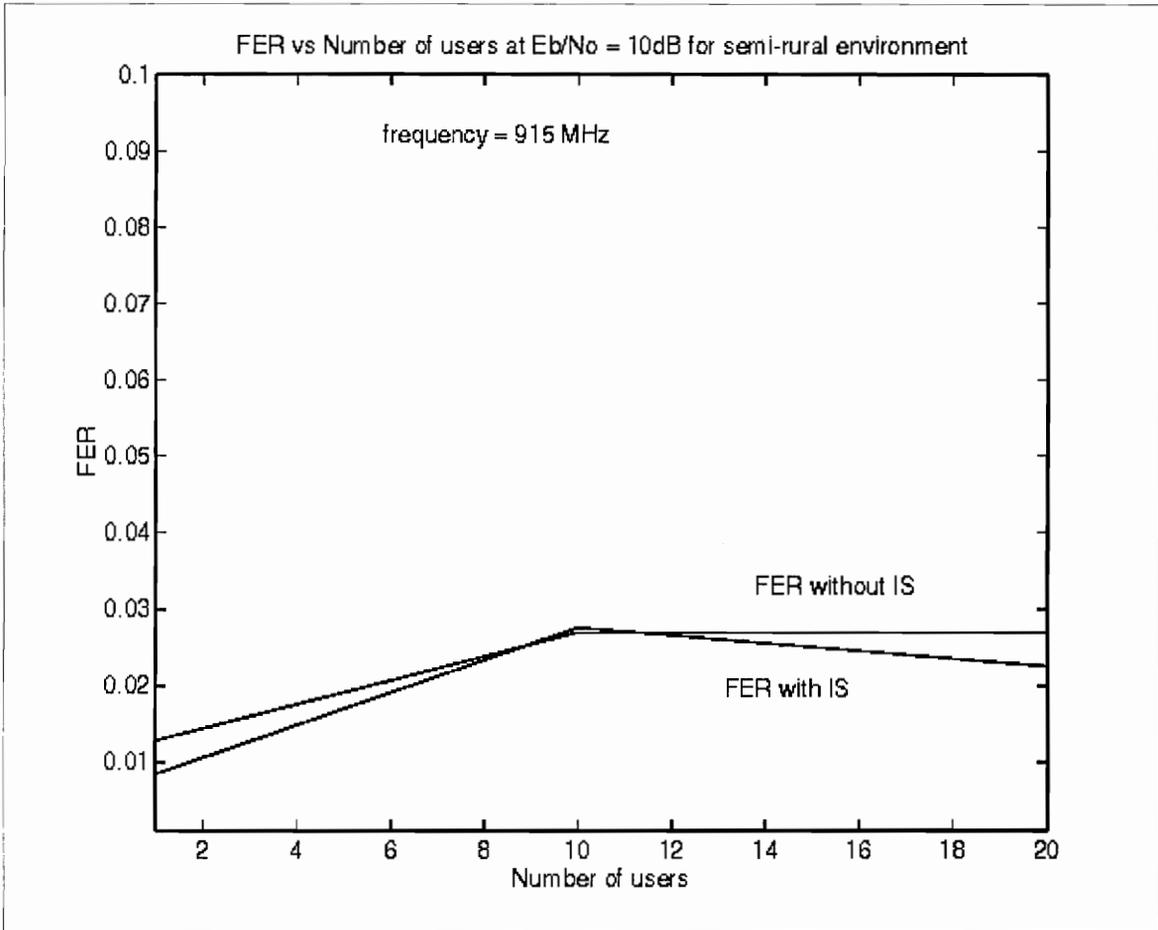at 1920 MHz with vertical polarization

Fig 5.8 - FER vs. number of users at Eb/No = 10 dB for
forward channel in a suburban environment
at 915 MHz with vertical polarization

5.2.3 FER Simulation In A Heavy Urban Environment:

The heavy urban area of 1500 Locust Street in Philadelphia, PA was used for the measurements for heavy urban environment. Most of the structures in the region were over 40 stories in the downtown area. Table 5.3 below compares the FER values of the original system in a heavy urban environment with those obtained after the implementation of Importance Sampling. The results have been obtained for Eb/No = 10 dB value for systems with 1 or 20 users. For 10 users, the results have been obtained for

Eb/No values of 5 dB, 10 dB and 15dB. Both 1920 MHz and 915 MHz frequencies have been tried in the simulation runs. Vertical polarization of the antenna has been used.

TABLE 5.3 - FER Results In A Heavy Urban Environment

Frequency	Number of users	Eb/No in dB	FER without IS	FER with IS
1920 MHz	1	10	0.025641	0.0324223
	10	5	0.064103	0.059089
		10	0.064103	0.057645
		15	0.038462	0.029771
	20	10	0.166667	0.154687

Figure 5.9 below shows the variation of FER values with Eb/No for a cellular system in a heavy urban environment with 10 users and a carrier frequency of 1920 MHz. It is clear that the FER values decrease with an increase in the Eb/No value. The results obtained are foe a vertical polarization and the forward channel.

Fig 5.9 - FER vs. Eb/No for 10 users for forward channel in a
heavy urban environment at 1920 MHz with
vertical polarization

In the figure below (Figure 5.10), the relation between FER and the number of users in
the system has been shown for same system. Figure 5.10 shows the results for a
frequency of 1920 MHz. The results show clearly that the FER value increases with an
increase in the number of users in the system.

FER vs Number of users at Eb/No = 10dB for heavy urban environment

frequency = 1920 MHz

FER without IS

FER with IS

Number of users

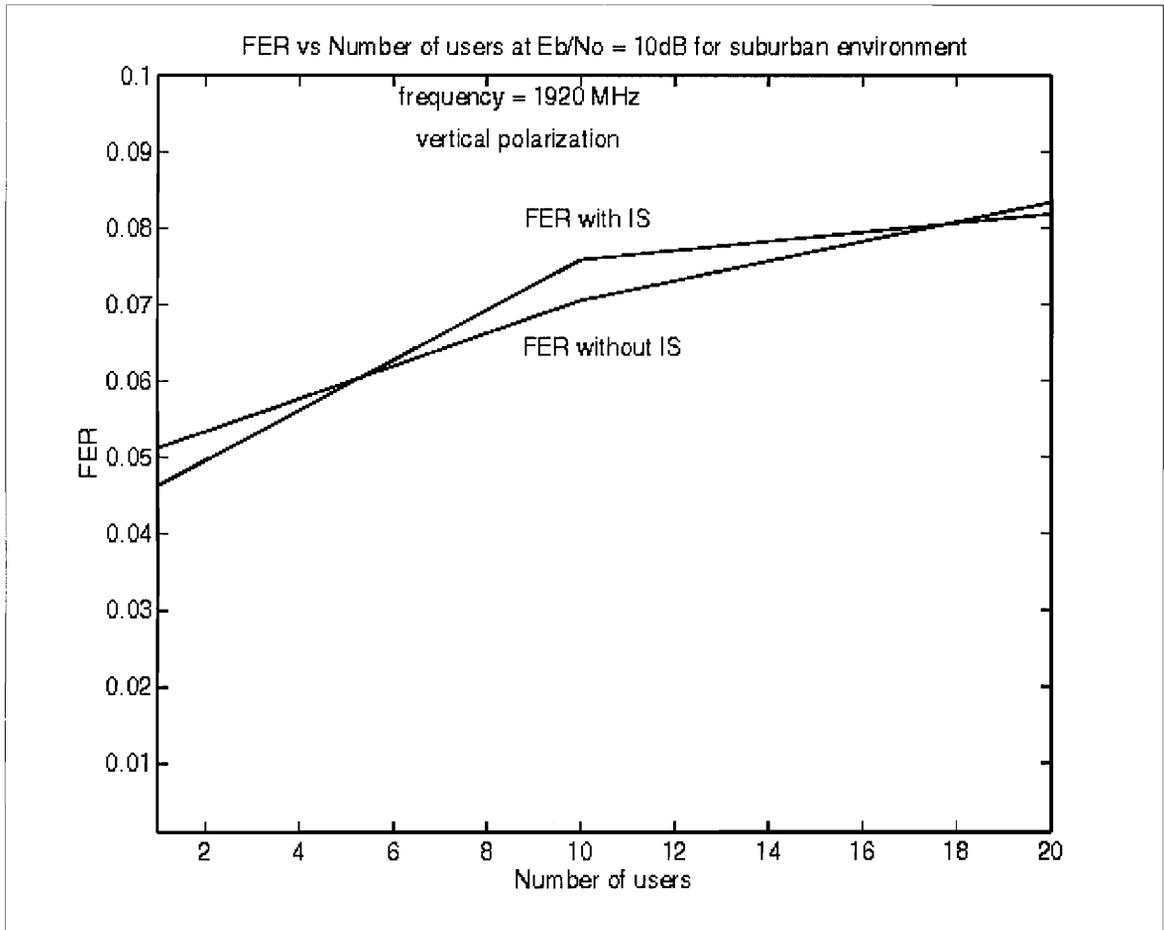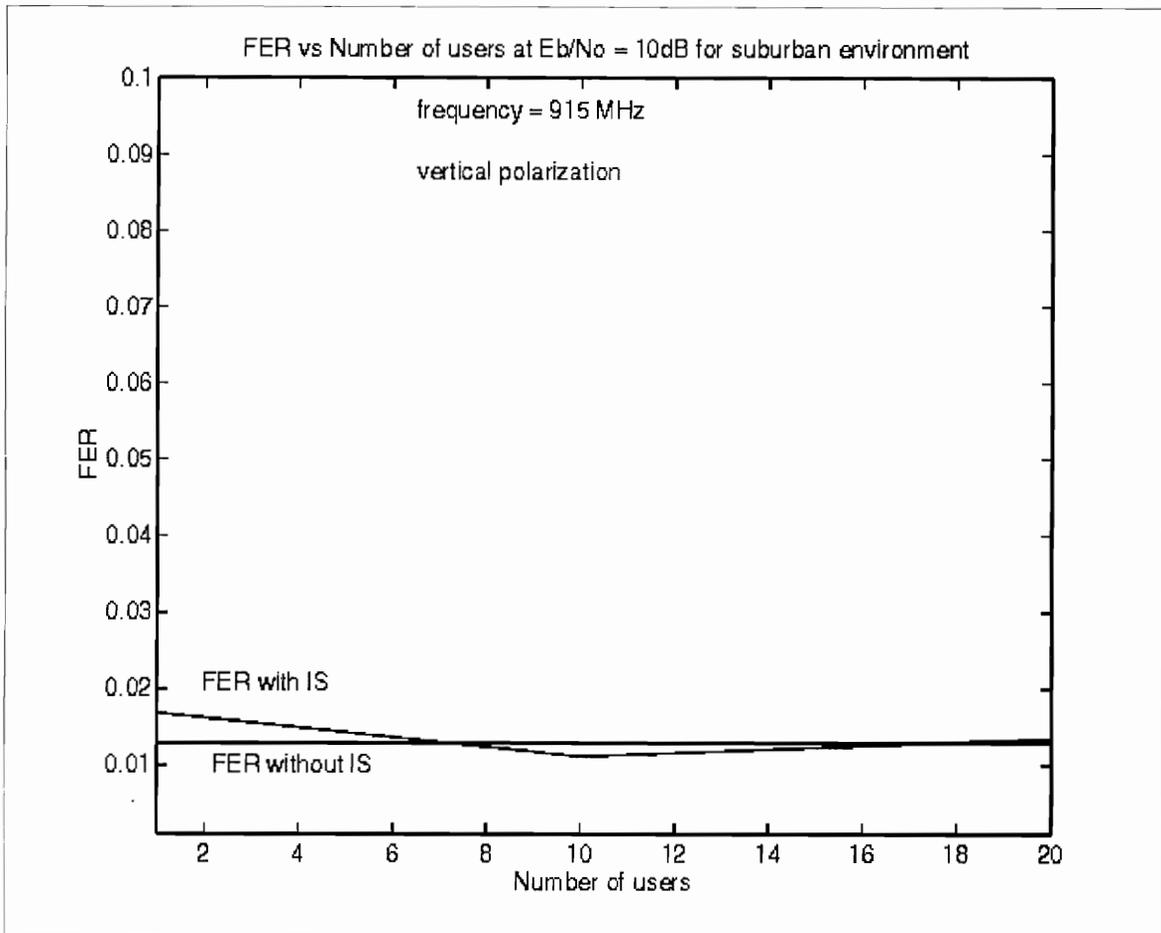Fig 5.10 - FER vs.number of users at Eb/No = 10dB for forward
channel in a heavy urban environment at
1920 MHz with vertical polarization

5.2.4 FER Simulation In An Urban Environment :

The channel impulse response data was taken at 4022 Chestnut St. in Philadelphia, PA.
The data showed an enormously large value of rms delay spread. This was conjectured to
be due to other interfering transmitters.

The simulation results obtained with this data were contradictory to expected values. The BER values ranged from 10 % to 20 % and the FER values were extremely high (close to 50 %). These values of BER or FER are unacceptable for the performance of any practical cellular system. Though the exact cause of the data being corrupted cannot be known, it can be conjectured that the data was corrupted due to other interfering transmitting sources.

The simulations were not carried out for the urban case and hence are not displayed.

5.2.5 FER Simulation In A Suburban Environment With Circular Polarization:

Table 5.4 below compares the FER values of the original system in a suburban environment with those obtained after the implementation of Importance Sampling. The results have been obtained for Eb/No = 10dB value for systems with 1 or 20 users. For 10 users, the results have been obtained for Eb/No values of 5dB, 10dB and 15dB. Both 1920 MHz and 915 MHz frequencies have been tried in the simulation runs. Circular polarization of the antenna has been used.

TABLE 5.4 - FER Results In A Suburban Environment With Circular Polarization

Frequency	Number of users	Eb/No in dB	FER without IS	FER with IS
1920 MHz	1	10	0.064103	0.071480
	10	5	0.096154	0.103164
		10	0.083333	0.071482
		15	0.096154	0.081030
	20	10	0.083333	0.087654
915 MHz	1	10	0.006410	0.006901
	10	5	0.006410	0.006103
		10	0.006410	0.003688
		15	0.001282	0.001342
	20	10	0.006410	0.005835

Figure 5.11 below shows the variation of FER values with Eb/No for a cellular system in a suburban environment with 10 users and a carrier frequency of 1920 MHz. Figure 5.12 shows the results for a carrier frequency of 915 MHz. It is clear that the FER values decrease with an increase in the Eb/No value. The results have been obtained using circular polarization and the forward channel has been simulated.

FER vs Eb/No for suburban environment using circular polarization

frequency = 1920 MHz

number of users = 10

FER without IS

FER with IS

Eb/No

Fig 5.11 - FER vs. Eb/No for 10 users for forward channel in a
suburban environment at 1920 MHz with
circular polarization

$x \, 10^{-2}$ FER vs Eb/No for suburban environment using circular polarization

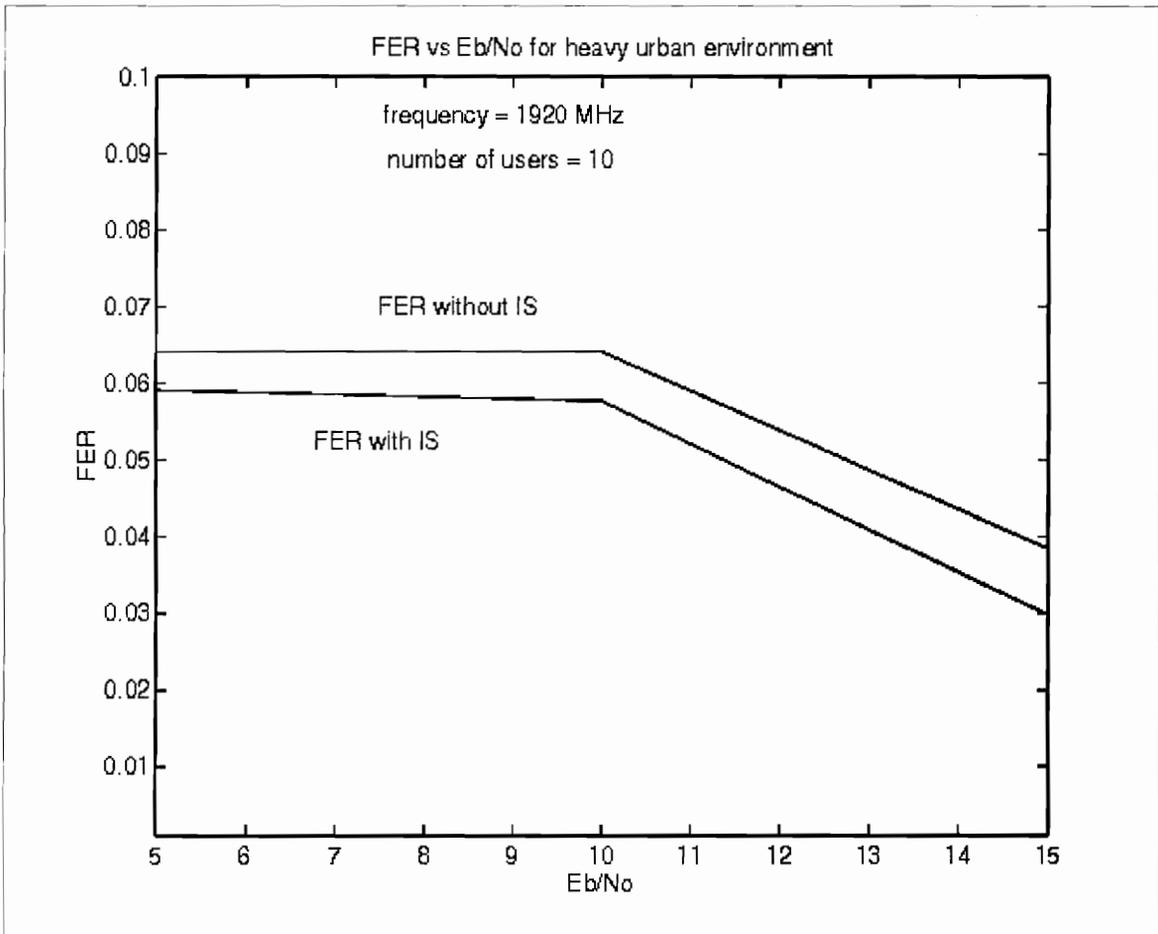frequency = 915 MHz

number of users = 10

FER without IS

FER with IS.

Fig 5.12 - FER vs. Eb/No for 10 users for forward channel in a suburban
environment at 915 MHz with
circular polarization

In the figures below (Figure 5.13 and Figure 5.14), the relation between FER and the
number of users in the system has been shown for same system. Figure 5.13 shows the
results for a frequency of 1920 MHz whereas Figure 5.14 shows similar results for a
frequency of 915 MHz. The results show clearly that the FER values increase with an
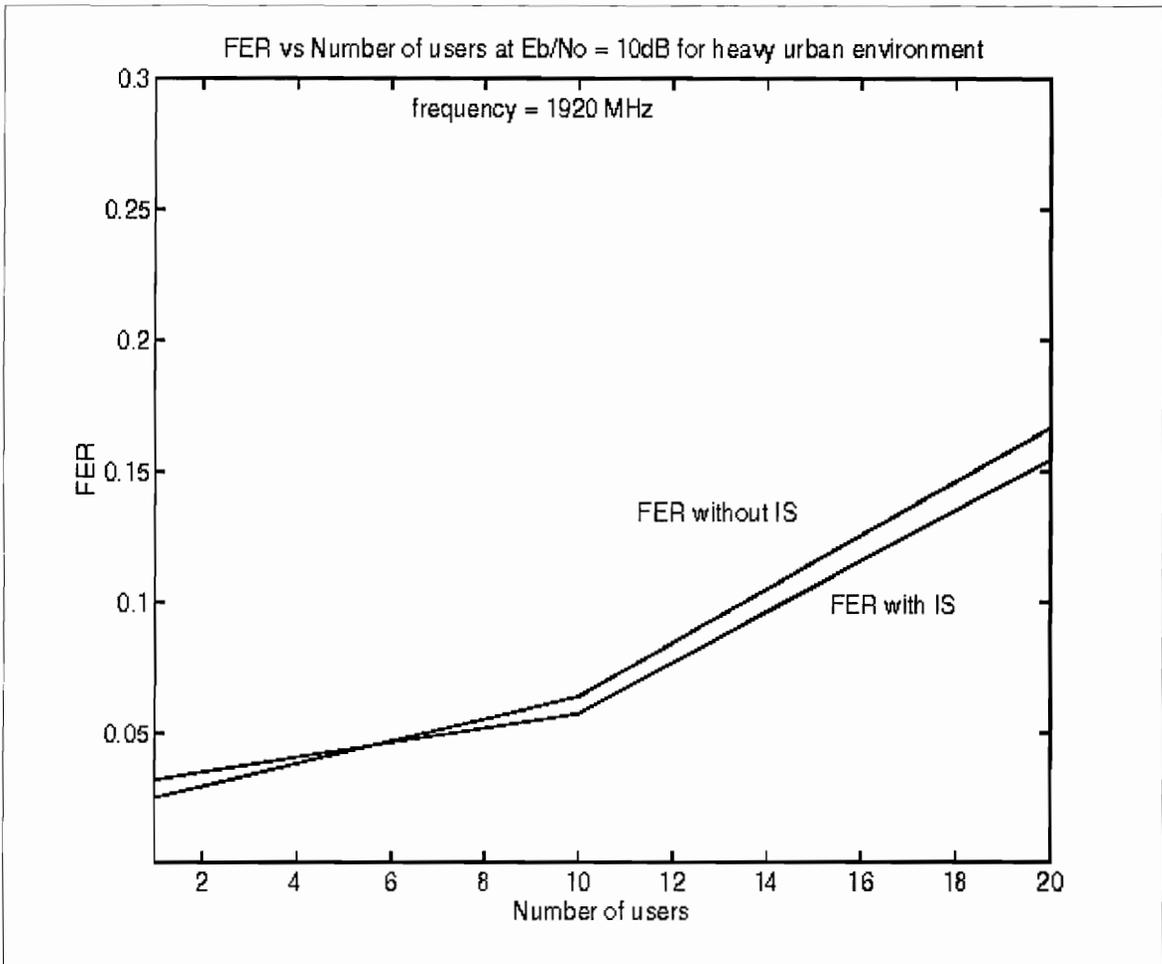increase in the number of users in the system. Circular polarization has been used for the
antenna system.

Fig 5.13 - FER vs.number of users at Eb/No = 10dB for forward
channel in a suburban environment at 1920 MHz
with circular polarization

x 10⁻²   FER vs Number of users at Eb/No = 10dB for suburban environment

FER vs. graph

Fig 5.14 - FER vs.number of users at Eb/No = 10dB for forward
channel in a suburban environment at 915 MHz
with circular polarization

5.3 Summary Of Results

In this chapter, the results of applying Importance Sampling techniques to the IS-95
CDMA system have been presented. The results show that the successful implementation
of IS techniques was able to duplicate the full simulation of complex CDMA systems in a
fraction of the time. The original results were based upon measured data taken in different

geographic locations. The SSSF for each of the results has also been provided to compare the accuracy for different savings ratios.

From the curves plotted in the chapter 5, it is seen that the FER reduces with the increase in the value of Eb/No. It increases with the number of users in the system. Also, in most of the cases, the value of FER is lesser at the lower frequency. The FER values are lower in the case of circular polarization as compared to the values with vertical polarization. All the above observations follow the expected trends in communication systems.

However, the simulations haven't been carried out for reverse channel and for circular polarization of antenna.

It was observed that the FER depends on the given measured data. It generally increased with the level of urbanization as can be expected due to increasing number of interferes in a more urban area. As expected, the FER increased with the number of people using the system.

5.4 Simulation Time Speed Up Factor

The aim of Importance Sampling is to reduce the amount of time required for the simulation. Though the results above prove that Importance Sampling techniques can be applied to simulate the system, yet the amount of simulation time saved is a more important factor. The reduction in time is achieved by reducing the number of bits sent. For each case, a particular shift value yields a different value of FER/BER. The values obtained are compared to the original values to study the amount of sacrifice in the efficiency to estimate the performance. This is traded off against the amount of time saved in the process. Importance Sampling has become a valuable tool to reduce simulation time in Monte Carlo systems.

In the simulation of the IS-95 CDMA system, an improvement factor of 10 was used. The IS technique applied sent $1/10^{th}$ of the original number of data bits to achieve this. The reduction factor in the simulation time was greater than 10 due to fewer complexities

involved in simulating fewer bits. The original IS-95 CDMA system took approx. 26 hrs. to simulate. The time required after implementing IS was approx. 1 hr 15 mins. The tables below shows the actual values of simulation time and the difference between the FER of system without IS and with IS applied to it. All the times noted have been rounded off to the nearest minute.

Table 5.5 below compares the simulation times observed for semi-rural data.

TABLE 5.5 Simulation Speed Up In System Using Semi-Rural Data

Frequency	Number of users	Eb/No in dB	Time With IS	Time w/o IS
1920 MHz	1	10	1 hr 18 mins	26 hrs 09 mins
	10	5	1 hr 15 mins	27 hrs 05 mins
		10	1 hr 13 mins	27 hrs 53 mins
		15	1 hr 16 mins	26 hrs 57 mins
	20	10	1 hr 29 mins	32 hrs 29 mins
915 MHz	1	10	1 hr 16 mins	27 hrs 31 mins
	10	5	1 hr 18 mins	28 hrs 46 mins
		10	1 hr 15 mins	27 hrs 18 mins
		15	1 hr 15 mins	26 hrs 19 mins
	20	10	1 hr 28 mins	31 hrs 49 mins

Table 5.6 below compares the simulation times observed for suburban data.

TABLE 5.6 Simulation Speed Up In System Using Suburban Data

Frequency	Number of users	Eb/No in dB	Time With IS	Time w/o IS
1920 MHz	1	10	1 hr 16 mins	26 hrs 42 mins
	10	5	1 hr 19 mins	30 hrs 21 mins
		10	1 hr 13 mins	29 hrs 49 mins
		15	1 hr 12 mins	29 hrs 41 mins
	20	10	1 hr 24 mins	35 hrs 06 mins
915 MHz	1	10	1 hr 17 mins	26 hrs 53 mins
	10	5	1 hr 13 mins	31 hrs 09 mins
		10	1 hr 13 mins	31 hrs 04 mins
		15	1 hr 16 mins	30 hrs 37 mins
	20	10	1 hr 24 mins	39 hrs 17 mins

Table 5.7 below compares the simulation times observed for Heavy Urban data.

TABLE 5.7 Simulation Speed Up In System Using Heavy Urban Data

Frequency	Number of users	Eb/No in dB	Time With IS	Time w/o IS
1920 MHz	1	10	1 hr 10 mins	28 hrs 03 mins
	10	5	1 hr 14 mins	29 hrs 48 mins
		10	1 hr 13 mins	29 hrs 32 mins
		15	1 hr 13 mins	28 hrs 29 mins
	20	10	1 hr 26 mins	32 hrs 39 mins

6 SUMMARY AND CONCLUSION

6.1 Summary

The aim of the thesis was to implement Importance Sampling technique for the 1.25 MHz CDMA IS-95 standard. This work may be considered as an extension or improvement to the previous bit error rate simulator (BERSIM) performance evaluation of the IS-95 system. The system was originally simulated by Yingjie Li [Li 93] and one of the points mentioned in the category of 'future work to be done' was to speed up the simulation process. The main cause of the enormous time that the system originally took was that in a spread spectrum system, the spreading of the bits over chips involves a computationally complex procedure and therefore simulation time is reduced by a factor equal to the processing gain of the system.

Interference Limited Systems

The CDMA system suffers from multiple access interference due to the large number of users. This interference is one of the primary causes of errors. However, while implementing of Importance Sampling techniques to the IS-95 system, the multiple access interference was not dealt with and the Gaussian Noise in the channel was modified to generate more errors. The maximum number of users simulated for was 20.

If the number of users in the system becomes too large, the multiple access interference becomes the chief cause of errors and the channel noise is not a major contributor to the generation of errors. Biasing the channel noise would not affect the BER much. In order to implement IS techniques in such a situation, the interference could be assumed to be normally distributed and IS techniques could be applied to the normal distribution.

This work has shown that Importance Sampling can be applied to complicated systems to speed up the simulation time. The simulations were verified by comparing results with full Monte Carlo simulation trials. The results were also verified for different parameter settings. The simulations were performed using the following parameters:

(i) Both the forward (base station to mobile) and the reverse channel (mobile to base station) were simulated.

(ii) A carrier frequency of 1920 MHz was used in the simulation.

(iii) The results were focused on Frame Error Rates.

(iv) The simulation was carried out for Eb/No ranging from 5 to 20 dB.

(v) The transmitted data was generated randomly.

(vi) The results were verified for different number of users.

(vii) A Rake receiver was implemented in the system.

(viii) Different schemes for Important Sampling were tried and the shift method was chosen based on the ease of implementation.

The CDMA IS-95 was studied in detail. The standard is described in chapter 2. Chapter 2 also shows the block diagrams and explains the functions of the various components in the CDMA system. The entire code which already existed for the system was studied in length to figure out where the IS technique could be implemented and integrated into the system. The detailed study of the system led to the important observation that the bits were not independent in the CDMA system. This led to the idea of determining Frame Error Rates (FER) instead of Bit Error Rates (BER).

The most important step was to actually implement the IS technique. A simple baseband communication system was developed to serve as a model and different IS techniques were implemented on it. The results were very encouraging. The code for the Sub-Optimum and Improved Importance Sampling Techniques is provided in chapter 8. The application of IS techniques to the simple model has been described in chapter 4. The simple system was then modified to a spread spectrum system and IS techniques were applied. The results were again encouraging. Chapter 4 deals with the mathematical

derivation of weights and the calculations involved in calculating the BER and FER of the system.

Finally, IS techniques were applied to the actual IS-95 CDMA system. The most appropriate results were obtained using Improved Importance Sampling and IIS was the chosen technique for all further simulation runs. The results of the simulation trials along with the numeric values and curves are provided in chapter 5.

Appendix B contains the code for IS techniques and the simple communication system modeled. It also contains the code for calculating the weights and generating Gaussian Noise and instructions for operating this code.

6.2 Future Work

The implemented IS technique has shown improvements by reducing simulation times by an order of magnitude. However, most of the references indicated that an improvement of the order of 3 to 8 should be expected. While implementing IS techniques in the CDMA system, this could not be achieved with a great degree of accuracy. Some studies mention that as the memory of the system gets larger, the sample size savings factor (SSSF) gets smaller. That could be one possible reason as the memory of the system was very large (512). However, according to authors like Chen, Smith and Shafi [Chen 90], for systems with very large memory, the effective memory can be considered as a smaller number (truncation) than the actual memory. The paper by Chen [Chen 90] indicates that the effective memory of a decoder with a (n,k,m) convolutional encoder can be given as

$$\text{Effective memory} = 2n\tau + n$$

where τ is the truncation length of the Viterbi decoder.

The above suggested method could be very useful in the CDMA system if it worked. The successful operation of the above mentioned idea could lead to greatly simplifying the code for IS techniques used.

Importance Sampling is one of the prominent techniques implemented to speed up the simulation of the system. Another possible solution is to use FFT techniques to convolve the channel in the frequency domain. This could possibly lead to a significant reduction in the large simulation time faced in the real time simulation process.

The choice of Improved Importance Sampling was based on the fact that other techniques suggested did not give accurate results. The detailed understanding of each method and it's successful application could lead to a better version of IS implementation and finally leading to a greater amount of SSSF.

The results of IS techniques have been verified for a single data rate of 9600 bps. The IS-95 standard requires the simulation to be performed under variable data rates of 9600, 4800, 2400 and 1200 bps. The implementation of the vocoder (currently being implemented) could add to the complexity of the system. It would however generate the desired variable data rate. The authenticity of IS techniques should be validated after implementing the vocoder also.Many people in the industry are now looking at the GSM (Group Special Mobile) standard. This may encourage it's implementation in the future. It would be an interesting challenge to implement IS techniques in the GSM standard.

Importance Sampling is a general approach to simulate all communication systems using the Monte-Carlo simulation procedure. It's working is not limited to the CDMA IS-95 system only.

The concept of IS should be understood by most people working in the field of simulating communication systems and it's application to all forms on simulation studies should be strongly encouraged.

BERSIM is patented and commercial versions are available at the Intellectual Properties Division of Virginia Polytechnic Institute & State University (VPI&SU).

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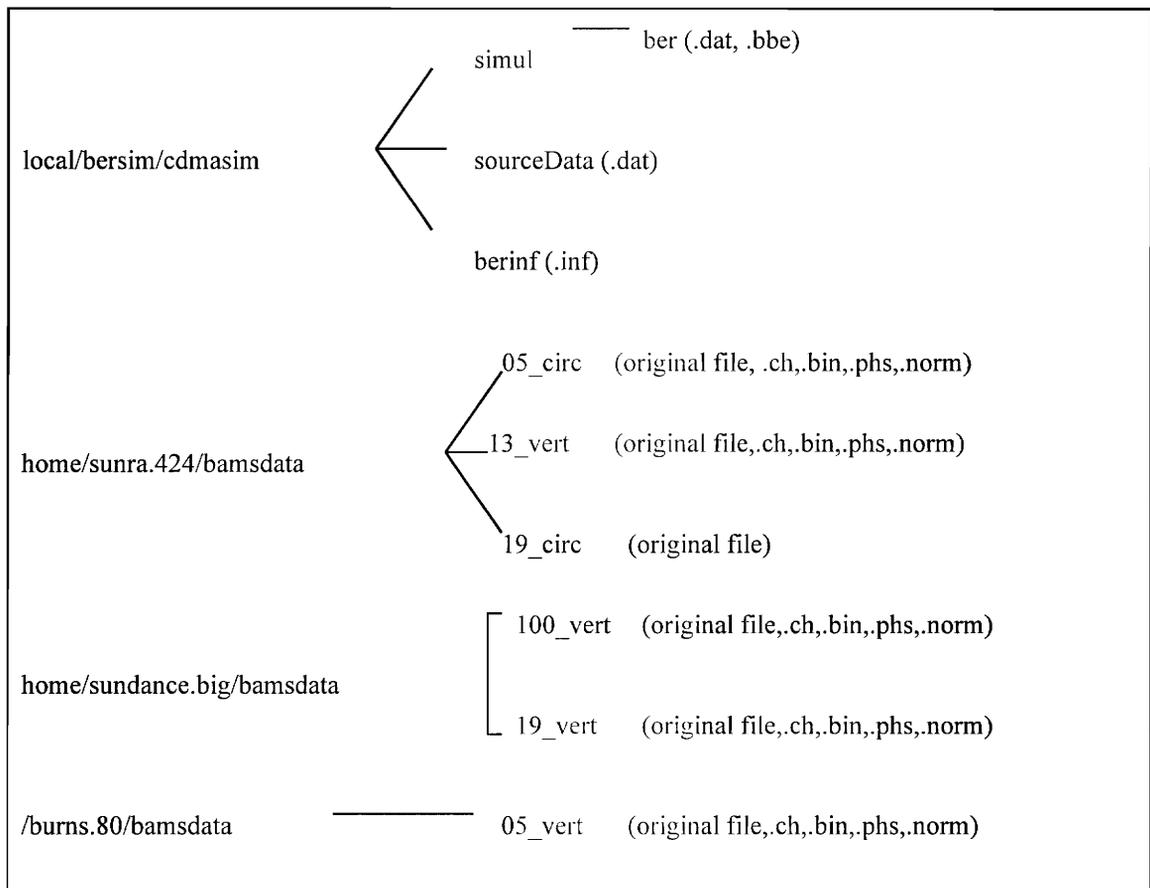
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APPENDIX

A.1 File Directories And Paths

Bersim uses the following files, which are located in directories as listed below:

```
                                              ber (.dat, .bbe)
                                   simul
local/bersim/cdmasim                          sourceData (.dat)

                                   berinf (.inf)


                                   05_circ    (original file, .ch,.bin,.phs,.norm)

home/sunra.424/bamsdata            13_vert    (original file,.ch,.bin,.phs,.norm)

                                   19_circ    (original file)


                                   100_vert   (original file,.ch,.bin,.phs,.norm)
home/sundance.big/bamsdata
                                   19_vert    (original file,.ch,.bin,.phs,.norm)


/burns.80/bamsdata                 05_vert    (original file,.ch,.bin,.phs,.norm)
```

Directories :

local/bersim/cdmasim - It contains executable file **bersim** and source code

simul/ber - It contains **.dat** and **.bbe** files. The **.dat** file has all the parameters used in the simulation. The **.bbe** file saves the bit error rate pattern and is a binary file.

sourceData - It contains the binary source data file **.dat** which is specified by the user for user defined data.

berinf - It contains the parameter **.inf** file used in the simulation.

The simul, sourceData and berinf directories need to be set under the **bersim** directory.

home/sunra.424/bamsdata - It contains the original **.sep** files, the **.ch** channel information file, the **.bin** binary power magnitude, the **.phs** phase and the **.norm** normalized power magnitude files for the data for following environmental conditions:

05_circ : Suburban Using Circular Polarization
13_vert : Semi-Rural Using Vertical Polarization
19_circ : Heavy Urban Using Circular Polarization

home/sundance.big/bamsdata - It contains the original **.sep** files, the **.ch** channel information file, the **.bin** binary power magnitude, the **.phs** phase and the **.norm** normalized power magnitude files for the data for following environmental conditions:

100_vert : Urban Using Vertical Polarization
19_vert : Heavy Urban Using Vertical Polarization

home/burns.80/bamsdata - It contains the original **.sep** files, the **.ch** channel information file, the **.bin** binary power magnitude, the **.phs** phase and the **.norm** normalized power magnitude files for the data for following environmental conditions:

05_vert : Suburban Using Vertical Polarization

Note that within these file names, "1" indicates that the data has been recorded at 1920 MHz and "2" indicates 915 MHz.

Different noise thresholds have been set for different environmental settings:

23 dB for 19_vert
14 dB for 100_vert
17 dB for 05_vert
23 dB for 13_vert
17 dB for 19_circ
17 dB for 05_circ

Parameter Entry:

The following parameters can be entered for simulation runs:

chanDire : forwardChan, reverseChan

numUsers: 1 to 63
channel : additive WGN, external
tRecovery : strongest, RAKE
Eb/No : any value in dB
carrier Freq : 915 MHz, 1920 MHz
chanFile : different environmental data files
dataSource : random, userDefined
bitErrorPat : TRUE, FALSE
outageFlag : TRUE, FALSE
outageBlkLen : 192
outageThresh : 2/192 (10/192 for heavy urban data)

Simulator Programs:

The simulator software is located in the following directory :

/home/u1/sanjay/thesis/bersim/cdmasim

The program contains the following files for the original system:

cdmaCommon.h, bersim.c, getPNseq.c, convolutionCode.c, cdmaSimulFu.c, tranceiver.c, cdmaExtern.c, simulation.c

The program for the implementation of Importance Sampling techniques to the system consists of files with extensions to the above names. The extensions are prefixes and postfixes and mean the following:

Environment - hu for heavy urban
              sr for semi-rural
              su for suburban
              u for urban

Number of users - 10 or 20 for corresponding number of users.
              No value assumes 1 user by default

Frequency - Prefix 9 is used for a frequency of 915 MHz
              The default value of the frequency is 1920 MHz

Eb/No - 5, 10 or 15 imply the corresponding Eb/No value in dB

A.2 Simulation Commands

To run the simulator, type

xybersimza

where **x** indicates the number of users for which the simulation has been done

$x = 10$ implies 10 users and $x = 20$ implies 20 users in the system
If x has no value, it implies only 1 user

y indicates the environmental conditions:

$y = sr$ implies semi-rural environment
$y = hu$ implies heavy urban environment
$y = u$ implies urban environment
$y = su$ implies suburban environment

z indicates the Eb/No value in dB

$z = 5$ implies 5dB
$z = 10$ implies 10dB
$z = 15$ implies 15dB

a indicates the amount of shift in the Importance Sampling code

$a = 01, 02, 03, \ldots\ldots\ldots\ldots\ldots, .15$ for corresponding shift values

For example 910hubersim504 implies the following:

Frequency used = 915 MHz
Number of users = 10
Eb/No = 5dB
Shift = 0.04

The results of Importance Sampling are stored in res files with similar extensions in the directory
                    home/sanjay/thesis/bersim/cdmasim

VITA

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