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Performance of Soft Handoff in PCS Environment

by

Rajeev K. Bector

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirement
for the degree of **Master of Engineering**

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
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Submitted by

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in partial fulfillment of the requirements
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December 16, 1998

Abstract

As more and more people are starting to use Cellular and PCS services the traffic density required to be handled by these systems is increasing very rapidly. These systems cope with this increasing user density by dividing the coverage area into smaller cells known as microcells. The side effect of using microcells is the increased number of and quite frequent crossings of cell boundaries by the mobile users. This leads to higher handoff activity in both Hard handoff as well as Soft handoff.

Soft handoff is natural choice for CDMA system because of the universal frequency reuse in CDMA. There are three parameters, namely T_{ADD} , T_{DROP} and t_{DROP} , that control Soft handoff (SHO) algorithm. Proper settings of these parameters influence the performance of SHO algorithm thus that of the system itself. An averaging parameter, namely Length of Averaging Interval d_{avg} that is designed to average out the shadowing effects of channel, also greatly affects the performance of any handoff algorithm. Current thesis studies the optimization of these four parameters to find optimal operating ranges for them in the given environment. The study uses IS-95 based SHO algorithm that uses carrier-to-interference ratio of received pilots for comparison during the SHO process. From these results the parameter that affects the system performance the most has been identified. Later extending our study of the effect of this parameter we estimated quantitatively the amount of system capacity enhancement due to SHO. A 25-75% of capacity enhancement has been observed.

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To My Dear Parents

Performance of Soft Handoff in PCS Environment

Table of Contents

Abstract	iii
Acknowledgement	iv
Table of Contents	vii
List of Figures	x
List of Acronyms and Symbols	xv
Chapter 1 Introduction	17
1.1 Introduction	17
1.2 Motivation	20
1.3 Thesis Objectives	22
1.4 Thesis Organization	23
1.5 Thesis Contributions	25
Chapter 2 CDMA Concepts: Background and Literature Survey	27
2.1 Evolution of Cellular and Mobile Telephony	27
2.2 CDMA: An overview	29
2.3 PN-Sequences	36
2.3.1 Maximal-length Sequences (m-sequences)	40
2.3.2 Gold Codes	41
2.4 Soft Handoff (SHO) in CDMA	42
2.4.1 Pilot Sets	43
2.4.2 Soft Handoff (SHO) parameters	44
2.4.3 Handoff Messages	44
2.4.4 SHO Example	46
2.4.5 Performance of SHO	48
2.4.5.1 Link Quality Indicators	48
2.4.5.2 Resource Allocation Indicators	49

Chapter 3 Simulation Model	56
3.1 Spreading Sequence Generator Model	56
3.2 Transmitter Model.....	60
3.3 Channel Model	64
3.3.1 Propagation Loss Model	64
3.3.2 Long-term Fading Model	65
3.3.3 Small Scale Fading	68
3.3.4 Multipaths Model	70
3.4 Receiver Model	74
3.5 Soft Handoff Algorithm	80
3.6 Power Control Algorithms	82
3.6.1 Up Link Power Control Algorithm	83
3.6.1.1 Open Loop Power Control	84
3.6.1.2 Closed Loop Power Control	84
3.6.2 Down Link Power Control Algorithm	86
 Chapter 4 Parameters Optimization Results	 88
4.1 Input and Output Metrics.....	88
4.1.1 Input Parameters Metrics	88
4.1.2 Performance Indicators Metrics	91
4.2 Simulation Scenarios and Parameters	93
4.2.1 Scenario I	97
4.2.2 Scenario II.....	97
4.2.3 Simulation Parameters	98
4.2.4 Received C/I or Ratios Profiles	101
4.3 Effect of Soft Handoff Parameters on its Performance.....	109
4.3.1 Effect of Add Threshold, T_{ADD}	109
4.3.2 Effect of Drop Threshold, relative T_{DROP}	122
4.3.3 Effect of Drop Timer, t_{DROP}	133
4.4 Effect of Averaging Interval, d_{avg} , on SHO Performance.....	144
4.5 Identifying Parameter affecting Performance the most	158

Chapter 5 Impact of SHO on Capacity	159
5.1 Soft handoff Performance in Scenario II.....	160
5.2 Estimating the Impact of SHO on CDMA Capacity.....	172
5.2.1 Average SHO Performance Across the Cell.....	173
5.2.2 Impact of SHO on Network Performance.....	183
 Chapter 6 Conclusion	 195
6.1 Conclusion.....	195
6.2 Suggested Future Work.....	201
 Appendix	 203
References	207

List of Figures

Figure 2-1:	Fast frequency hopping spread spectrum system	31
Figure 2-2:	Time hopping spread spectrum system	31
Figure 2-3:	Spreading and despreading of a CDMA DS signal (Block Diagram). . . .	31
Figure 2-4:	Spreading and despreading of a CDMA DS signal (Signals and Bandwidth at different stages)	32
Figure 2-5:	Example of a linear feedback shift register	39
Figure 2-6:	Correlation properties of m-sequences (chip duration $T_c = 4$ samples/chip and period $NT_c = 124$ samples).	39
Figure 2-7:	A simple 2-cell Soft Handoff scenario	47
Figure 3-1:	Model used to generate family of Gold codes with period $N=31$	58
Figure 3-2:	Autocorrelation of m-sequence with chip duration $T_c = 4$ samples/chip and period $NT_c = 124$ samples and its crosscorrelation with another m- sequence	59
Figure 3-3:	Autocorrelation of a code from a family of Gold codes with chip duration T_c $= 4$ samples/chip and period $NT_c = 124$ samples and its 3-valued crosscorrelation with another code of same family.	59
Figure 3-4:	Transmitter model	63
Figure 3-5:	Theoretical and actual autocorrelation of the Log-normal fading using Gudmundson's spatial correlation model	67
Figure 3-6:	Model of the multipath channel along with pathloss, log-normal shadowing and short term (Rayleigh\Ricean) fading	73
Figure 3-7:	Model of the Rake receiver used in the simulations	76
Figure 3-8:	Up link despreading of signals at BSs l, m and n received from kth MS and equal gain combining of decision variables at MSC received from BSs l, m and n in 3-BS soft handoff	78
Figure 3-9:	Down link despreading and combining of signals at kth MS received from BSs l, m and n in 3-BS soft handoff	78

Figure 4-1:	CDMA network of 10 Cells with BS-to-BS distance of 1600 meters and MS moving in a straight line from BS1 towards BS2..	94
Figure 4-2:	Top view of the CDMA Network shown in previous figure.	94
Figure 4-3:	Profiles of C/Is of the Pilots of Candidate BSs received at the mobile as it moves from BS1 to BS2	102
Figure 4-4:	Profiles of C/Is of the Pilots of Candidate BSs received at Mobile during travelling interval of interest, i.e., interval [400, 1200].	102
Figure 4-5:	Probability of inclusion of BSs in the Active Set for $T_{ADD} = -15\text{dB}$, $T_{DROP} = 0\text{dB}$ & $t_{DROP} = 0$ samps.	106
Figure 4-6:	Effect of T_{ADD} on Probability of inclusion of BS1 in the AS (Prob1)..	117
Figure 4-7:	Effect of T_{ADD} on Probability of inclusion of BS2 in the AS (Prob2)..	117
Figure 4-8:	Effect of T_{ADD} on Probability of inclusion of 3rd BS in the Active Set (Prob3)..	118
Figure 4-9:	Effect of T_{ADD} on Fraction of distance MS in SHO (F_{SHO}), in 2-Cell SHO (F_{2SHO}) and in 3-Cell SHO (F_{3SHO})	118
Figure 4-10:	Effect of T_{ADD} on Average Size of Active Set (ASA)	119
Figure 4-11:	Effect of T_{ADD} on Mean Number of Active Set Updates (NAUs)	119
Figure 4-12:	Effect of T_{ADD} on Required Down Link Transmit Power per Active Channel (TxPDL)	120
Figure 4-13:	Effect of T_{ADD} on Required Up Link Transmit Power (TxPUL)	120
Figure 4-14:	Trade-off between average Down Link Transmit power (TxPDL) and Number of AS Updates (NAUs)	121
Figure 4-15:	Trade-off between average Up Link Transmit power (TxPUL) and Number of AS Updates (NAUs)	121
Figure 4-16:	Effect of T_{DROP} on Probability of inclusion of BS1 in the AS (Prob1)	128
Figure 4-17:	Effect of T_{DROP} on Probability of inclusion of BS2 in the AS (Prob2)	128
Figure 4-18:	Effect of T_{DROP} on Probability of inclusion of 3rd BS in the Active Set (Prob3).	129

Figure 4-19: Effect of T_{DROP} on Fraction of distance MS in SHO (F_{SHO}), in 2-Cell SHO (F_{2SHO}) and in 3-Cell SHO (F_{3SHO})	129
Figure 4-20: Effect of T_{DROP} on Average Size of Active Set (ASA)	130
Figure 4-21: Effect of T_{DROP} on Mean Number of Active Set Updates (NAUs)	130
Figure 4-22: Effect of T_{DROP} on Required Down Link Transmit Power per Active Channel (TxPDL)	131
Figure 4-23: Effect of T_{DROP} on Required Up Link Transmit Power (TxPUL)	131
Figure 4-24: Trade-off curve between Average Size of the Active Set (ASA) and Number of Active Set Updates (NAUs)	132
Figure 4-25: Effect of t_{DROP} on Probability of inclusion of BS1 in the AS (Prob1)..	139
Figure 4-26: Effect of t_{DROP} on Probability of inclusion of BS2 in the AS (Prob2)..	139
Figure 4-27: Effect of t_{DROP} on Probability of inclusion of 3rd BS in the AS (Prob3)	140
Figure 4-28: Effect of t_{DROP} on Fraction of distance MS in SHO (F_{SHO}), in 2-Cell SHO Distance (F_{2SHO}) and in 3-Cell SHO Distance (F_{3SHO})	140
Figure 4-29: Effect of t_{DROP} on Average Size of Active Set (ASA).	141
Figure 4-30: Effect of t_{DROP} on Mean Number of Active Set Updates (NAUs). . . .	141
Figure 4-31: Effect of t_{DROP} on Required Down Link Transmit Power per Active Channel (TxPDL)	142
Figure 4-32: Effect of t_{DROP} on Required Up Link Transmit Power (TxPUL). . . .	142
Figure 4-33: Trade-off between the Average Size of the Active Set (ASA) and Number of Active Set Updates (NAUs)	143
Figure 4-34: Effect of d_{avg} on received average C/I ratios for BS1.	145
Figure 4-35: Closer look at the received average C/I ratios for BS1 around T_{DROP} . .	145
Figure 4-36: Effect of d_{avg} on received average C/I ratios for BS2.	146
Figure 4-37: Closer look at received average C/I ratios for BS2 around T_{ADD}	146
Figure 4-38: Effect of d_{avg} on received average C/I ratios for BS3/BS4.	147
Figure 4-39: Closer look at received average C/I ratios for BS3/BS4 around T_{ADD} .	147

Figure 4-40:	Closer look at received average C/I ratios for BS3/BS4 around T_{DROP} .	148
Figure 4-41:	Effect of d_{avg} on Probability of inclusion of BS1 in the AS (Prob1) . . .	153
Figure 4-42:	Effect of d_{avg} on Probability of inclusion of BS2 in the AS (Prob2) . . .	153
Figure 4-43:	Effect of d_{avg} on Probability of inclusion of 3rd BS in the AS (Prob3) .	154
Figure 4-44:	Effect of d_{avg} on Fraction of distance MS is in SHO (F_{SHO}), in 2-Cell SHO Distance (F_{2SHO}) and in 3-Cell SHO Distance (F_{3SHO})	154
Figure 4-45:	Effect of d_{avg} on Average Size of Active Set (ASA)	155
Figure 4-46:	Effect of d_{avg} on Mean Number of Active Set Updates (NAUs)	155
Figure 4-47:	Effect of d_{avg} on Required Down Link Transmit Power per Active Channel (TxPDL)	156
Figure 4-48:	Effect of d_{avg} on Required Up Link Transmit Power (TxPUL)	156
Figure 4-49:	Trade-off between Mean Num Updates (NAUs) and Mean Down Link Transmit power (TxPDL)	157
Figure 4-50:	Trade-off between Mean Num Updates (NAUs) and Mean Up Link Transmit power (TxPUL)	157
Figure 5-1:	Zoomed top view of the CDMA Network showing the mobile paths in Scenarios II	161
Figure 5-2:	Effect of T_{ADD} on Fraction of distance MS in Soft Handoff (F_{SHO}) for all ten travel routes of Scenario II	168
Figure 5-3:	Effect of T_{ADD} on Average size of Active Set (ASA) for all ten travel routes of Scenario II.	168
Figure 5-4:	Effect of T_{ADD} on Mean Number of Active Set Updates (NAUs) for all ten travel routes of Scenario II	169
Figure 5-5:	Change in the Average Received power at mobile with increase in Y-Coordinate (from 0 to 462 meters) relative to that received at Y-Coordinate = 0	169
Figure 5-6:	Effect of T_{ADD} on Mean Up Link Tx-power (TxPUL) (including the effect of Up link Open Loop Power Control) for all ten travel routes of Scenario	

	II	170
Figure 5-7:	Effect of T_{ADD} on Mean Up Link Tx-power (TxPUL) (excluding the effect of Up link Open Loop Power Control) for all ten travel routes of Scenario II	170
Figure 5-8:	Effect of T_{ADD} on Mean Down Link Tx-power (TxPDL) for all ten travel routes of Scenario II	171
Figure 5-9:	Required Average Up Link Tx-power (TxPUL) averaged over all ten travel routes	178
Figure 5-10:	Average Size of AS (ASA) averaged over all ten travel routes	178
Figure 5-11:	Mean Fraction of distance MS in Soft Handoff (F_{SHO}) averaged over all ten travel routes	179
Figure 5-12:	Mean Signalling Load per User (NAUs) averaged over all ten travel routes	179
Figure 5-13:	Average gain G (dB) in required Up Link Tx-powers for each T_{ADD} level relative to that for T_{ADD} level of -7dB	180
Figure 5-14:	Zoomed top view of the Network showing the region IA and IB	181
Figure 5-15:	Top view of the CDMA Network with Soft Handoff region shown as shaded area	182
Figure 5-16:	Average Gain in Performance due to SHO at each T_{ADD} level relative that for T_{ADD} level of -7dB	192
Figure 5-17:	Average number of supported Users at each T_{ADD} level	192
Figure 5-18:	Percent increase in capacity at each T_{ADD} level relative that for T_{ADD} level of -7dB	193
Figure 5-19:	Percent increase in Capacity Vs. Percent increase in the required Number of Channel Elements or Cell-site Modems	193
Figure 5-20:	Percent increase in Capacity Vs. Percent Increase in Network Signalling Load	194

List of Acronyms and Symbols

d_{avg}	Length of Averaging Interval
E_c/I_T	Carrier-to-interference Ratio
F_{SHO}	Fraction of Total Travel Distance (or Time) the MS is in Soft Handoff
F_{2SHO}	Fraction of Total Travel Distance (or Time) the MS is in 2-Cell SHO
F_{3SHO}	Fraction of Total Travel Distance (or Time) the MS is in 3-Cell SHO
T_{ADD}	Add Threshold
T_{DROP}	Drop Threshold
t_{DROP}	Drop Timer
M_{SHO}	Number of users in Soft Handoff Region
M_{Tot}	Total number of supported users
N_{SHO}	Fraction of users in Soft Handoff Region
AMPS	Advanced Mobile Phone System
ANCEs	Average number of required Channel Elements
AS	Active Set
ASA	Average Size of the Active Set
BPSK	Binary Phase Shift Keying
BER	Bit Error Rate
BS	Base Station
CDMA	Code Division Multiple Access
DCS	Digital Cellular Service
DS	Direct Sequence
DSP	Digital Signal Processing
FDMA	Frequency Division Multiple Access
FH	Frequency Hopping

GSM	Global System for Mobile Communications
HHO	Hard Handoff
IS-54, 95, 136	Electronic Industry Interim Standard-54, 95, 136
ISI	Inter Symbol Interference
JTACS	Japanese Total Access Cellular System
JTC	Joint Technical Committee
MS	Mobile Station
MSC	Mobile Switching Center
MSK	Minimum Shift Keying
NAUs	Number of Active Set Updates
NMT	Nordic Mobile Telephone system
NTT	Nippon Telephone and Telegraph company
PCS	Personal Communications Services
PDC	Personal Digital Cellular
PN	Pseudo-random Noise
PSTN	Public Switched Telephone Network
QPSK	Quadrature Phase Shift Keying
RSS	Received Signal Strength
SHO	Soft Handoff
SS	Spread Spectrum
TACS	Total Access Cellular System
TDMA	Time Division Multiple Access
TH	Time Hopping
TNAUs	Total average NAUs
TxPDL	Average Down Link Transmit Power
TxPUL	Average Up Link Transmit Power
UPN	Universal Personal Networks

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1

Introduction

1.1 Introduction

The concept of cellular mobile radio telephony was first introduced by AT&T Bell Laboratories [31] in late 1960s and early 1970s. Since the implementation of cellular systems in late 1970s and early 1980s the demand for cellular communications has grown enormously all over the world. The reason being the convenience of having a tetherless connection anywhere, at any place and at anytime. In the past decade not only there had been an unprecedented growth in the number of people using cellular services but also there had been a rapid increase in demand for a number of new services like voice, data, etc. to be provided by the cellular services. In North America (NA) in 1983 a 40MHz wide spectrum was allocated in the 800MHz band which was later expanded to 50MHz because of rapid rise in demand for mobile services. But the rapid growth in demand for cellular services rendered this 50MHz spectrum insufficient. Thus in early 1995 another 120 MHz wide spectrum in the 1900MHz band, known as PCS spectrum, was opened up in NA. The intention was not only to be able to provide new services that would complement the

cellular services but also to compete with them. Similarly in Europe apart from 800/900MHz cellular band a new spectrum between 1710-1880MHz, called DCS spectrum, was opened in the early 1990s for services called Universal Personal Network (UPN). PCS system, first proposed by Cox [32] and later discussed by other eminent authors [33]-[36], is visioned as a system that will provide us with *information at any time, at any place and in any form*. Thus PCS systems also known as third generation systems are expected to play an important role in future communications, since they should provide a universal access to a wide range of basic and supplementary services provided by fixed networks as well as mobile networks.

A cellular or a Personal Communications Services (PCS) system provides a wireless connection to any user in the radio range of the system. Large number of users over a large geographic area are accommodated by dividing this geographic area into small coverage areas known as cells. Each cell has a fixed transceiver called base station (BS), located at its center or edge, that communicates with a mobile station (MS) or user in its coverage region. The coverage of each cell is limited to a small geographic area by limiting the power of the transmitter of its BS. This enables another BS located some distance away to use same radio channels. Since the main idea of cellular and PCS systems is to serve mobile users at unspecified locations in the system service area. Thus a mobile user communicates with a BS using either a hand held portable transceiver unit or a transceiver unit installed in a vehicle. In any case because of the mobility of users it often happens that a user crosses into the coverage area of another cell while a call is in progress. Thus for

such a system it is very important to support services when a subscriber moves from the coverage area of one BS to that of another BS. A complex switching technique, called handoff, is required to let a call proceed without any interruption while a mobile moves from the coverage area of one BS to that of another BS. Thus handoff is an integral part of any mobile communications system.

First-generation of cellular systems like Advanced Mobile Phone System (AMPS) used relatively less sophisticated handoffs but the second generation digital cellular systems, like Global System for Mobile Communications (GSM) in Europe and IS-54 in NA, use more superior handoffs by means of sophisticated Digital Signal Processing (DSP) techniques and algorithms. GSM and IS-54 use Time Division Multiple Access (TDMA) type of air interface and the handoff technique used by these systems is known as the Hard handoff (HHO). This is a consequence of “break before make” handoff between two BSs, and as the name suggests communication link between the mobile and current BS is broken at the same time while establishing link with another BS. Thus while the call is being handed over from one BS to another BS the communication link is not available momentarily which is noticeable to the user as a “click sound” and is quite annoying. Apart from that hard handoff is also known to have the problem of “Ping-Pong” effect that occurs near the cell boundaries where a constant handing back and forth of a mobile takes place between two BSs. This happens due to the inherent and unavoidable fading fluctuations in the Received Signal Strengths (RSSs) of BSs at the MS receiver.

In recent years another second generation North American cellular system known as IS-95

has emerged. It is based upon Code Division Multiple Access (CDMA) as its air interface and uses a different handoff technique known as Soft handoff (SHO). Soft handoff is facilitated by the universal frequency reuse characteristic of CDMA since it doesn't require a MS in handoff to switch frequencies. In IS-95 based CDMA cellular system a MS constantly monitors the signal strength from nearby BSs. As the MS approaches the cell boundary a link is established with another BS in a neighboring cell. The call is now carried by two or more BSs. Link with old BS is broken only once the link with another nearby BS with stronger signal is firmly established as a result the handoff process becomes seamless. Thus the handoff process by soft handoff technique not only appears seamless to the user but also is free from the "Ping-Pong" effect problem as experienced in HHO. This is a consequence of "make before break" handoff between the BSs. At the MS the signals received from each BSs are combined for a reliable communication link. Soft handoff technique is the subject of investigation of the current thesis.

1.2 Motivation

In IS-95 CDMA system, MS is designed to support the SHO process by measuring and reporting to the serving BS the strength of different received pilots. Pilot here is the carrier-to-interference or E_c/I_T ratio of the pilot channel associated with the forward CDMA traffic channel. Every MS maintains a pool of active BSs called Active Set (AS). The AS is updated based upon the result of comparison of the received pilot strengths to thresholds T_{ADD} and T_{DROP} in combination with drop timer t_{DROP} . The threshold T_{ADD}

controls adding a pilot to the AS and threshold T_{DROP} controls dropping a pilot from the AS. The third parameter t_{DROP} is a drop timer and is used to prevent a MS from dropping a pilot prematurely.

All types of handoffs including Soft handoff are expensive processes since they consume substantial processing power not only at MSs but at BSs and Mobile Switching Center (MSC) as well. Apart from that, in SHO, additional resources in terms of more than one traffic channels for single call are being used during the SHO process. On the other hand, because of the involvement of multiple BSs in communication with one MS that is in SHO, the channel diversity is used to enhance the quality of signal at the boundaries between two or more BSs. Therefore a trade-off has to be made between diversity advantage and resource utilization. Apart from that the process of adding and dropping of a BS from the Active Set (AS) of a MS, known as AS Update process, is not a single shot process. A number of signalling messages between the MS and the BS have to be exchanged for a substantial period of time before the BS is firmly assigned to (or dropped from) the AS. This complete process of signalling messages between MS and BS accounts for one AS Update event. Thus the larger the number of AS updates (NAUs) the larger will be the traffic on the control channels which implies more processing overhead on the network.

Moreover in digital cellular systems and more importantly in PCS systems, which are mostly deployed in urban or metro areas, the most effective way of combating the increased demand for service is by decreasing the cell area, called microcells, which leads

to high number of frequent crossings of boundaries of one or more cells by a MS while a call is in progress. Note that microcells are characterized by smaller cells, 0.4-2 km diameter and powers as low as 20 mW. As cell dimensions get smaller the mobiles cross cell boundaries and get involved in SHO more frequently. Consequently not only NAUs per call increase but the time mobile occupies more than one channel to carry single call also increases. From a network operator's point of view it is highly desirable to reduce the handoff time as much as possible. But on the other hand to ensure the link quality of a connection near boundary and to maintain the continuity of a call across the boundary between the cells an overhead in terms of handoff is unavoidable. Thus in a CDMA system the network operator is not only interested in keeping low the number of BSs talking simultaneously to a MS (i.e., smaller average size of AS) and the time for which multiple BSs talk to a MS during the soft handoff but also interested in keeping low the number of times an AS is updated (i.e., lower NAUs).

1.3 Thesis Objectives

The settings of SHO parameters are expected to influence the overall system performance quite significantly. In this thesis we study the effect of SHO on the system performance. To address this problem three objective have been set for the thesis. First objective deals with the optimization of the three SHO parameters, T_{ADD} , T_{DROP} , and t_{DROP} , and an averaging parameter, d_{avg} . Parameter d_{avg} is designed to average out the long-term fading and also affects the performance of the system substantially. The first objective is

to study in detail the process of optimization of the above parameters and to find the optimum operating ranges for them in the given PCS environment. The second objective is to identify the parameter that affects the performance the most. The third objective is to estimate the amount of capacity improvement that can be achieved due to Soft handoff in an IS-95 based CDMA system.

1.4 Thesis Organization

Including the current chapter the thesis has been organized into six chapters as follows.

Chapter 2 discusses briefly the evolution of Cellular and PCS wireless systems. An overview of CDMA and discussion on PN-sequences have been provided. Later the chapter discusses the Soft Handoff process, its advantages and disadvantages, the soft handoff parameters and the performance indicators for measuring the performance of a system. The chapter concludes with brief discussion on related work done by other authors.

Chapter 3 describes in detail the implementation of the simulation model. The chapter first describes the shift register model to generate the family of Gold codes. It also describes the structures of the transmitter and receiver including Rake receiver. In terms of channel model the chapter discusses different phenomena, like Frequency selective fading, short-term fading, long term fading and pathloss, that cause different types of channel impairments to a spread spectrum signal. Later mathematical models used to model these channel phenomena have been described. Finally the algorithms for Soft handoff and

power control have been discussed.

Chapter 4 presents the results of the optimization part of the problem. Effect of the three soft handoff parameters, T_{ADD} , T_{DROP} , and t_{DROP} , and an averaging parameter, d_{avg} , on the performance of the CDMA system has been studied on both Up and Down links in Scenario I as discussed in the same chapter. The performance indicators have been defined and monitored during simulations to measure the performance of the system. Later by making trade-offs between appropriate performance indicators the optimum operating ranges for above four parameters have been found in a given environment. From these results we also found out that of the four the parameter T_{ADD} is the one that affects the performance of the system the most.

Recognizing the fact that CDMA capacity is limited by Up link only and that parameter T_{ADD} is the one that affects the CDMA performance the most, in chapter 5 we extended our study of the effect of parameter T_{ADD} over Scenario II. Scenario II covers all possible situations over a cell including Scenario I. Later by deriving a capacity equation for CDMA that reflects the effect of soft handoff and using this equation along with results of Scenario II it has been shown that soft handoff in fact enhances the capacity of CDMA system by almost two times.

Chapter 6 summarizes the results from chapters 4 and 5, and draws conclusions from the research findings. It also suggests topics for future work.

1.5 Thesis Contributions

There are two major contributions of thesis. First one being providing a better understanding of the mechanism of Soft handoff and the effects of the three Soft handoff parameters on the performance of system. By means of simulations it not only shows how different parameters improve the available diversity thus reduce the average required Transmit powers on both Up and Down links, but it also bring to our attention the cost we have to pay in terms of increased network signalling load to achieve this improvement. Later by means of trade-off curves between different performance indicators the thesis emphasizes the importance of optimization of the Soft handoff parameters in order to achieve optimum performance of the system. Apart from the three Soft handoff parameters the thesis also studied in detail the effect of averaging parameter. Steps for the optimization of the overall performance of the system have been suggested.

The second contribution of the thesis is to provide a better understanding of the effect of Soft handoff on the capacity of CDMA system. By deriving a capacity equation for CDMA that takes into account the tendency of Soft handoff of lowering the required Transmit powers the thesis depicts the capacity enhancement effect of the Soft handoff. Later by means of trade-off curves the thesis highlights the unavoidable costs, namely fixed cost in terms of required number of more channel elements and variable cost in terms of load on signalling infrastructure, that are required to be incurred in order to take advantage of the capacity enhancement effect of Soft handoff.

All the above mentioned issues are very important for a network operator where as some

of them are important for a systems designer and network optimization engineer. Though the tendency of a network operator is to operate its network at maximum possible capacity to maximize its returns but he/she might also like to operate at lower operating costs in terms of lower network signalling load. The thesis provides him/her a better understanding of where and how to draw line to get the most optimum performance of the system. A network optimization engineer also shares the same concern and in addition wants to know the Soft handoff parameter to which the system performance is most sensitive. This thesis accomplishes this objective. From system designers point of view not only he/she must be able to know how much capacity enhancement is there but also how many additional channel elements or channel modems per cell he/she needs to provide in the design of a Base Station to account for the capacity enhancement advantage of the Soft handoff. The thesis has also covered that aspect appropriately.

2

CDMA Concepts: Background and Literature Survey

The current chapter discusses briefly the evolution of cellular and mobile telephony followed by an overview of CDMA technology. A discussion on properties and generation of PN-sequences has been included. Finally the chapter concludes with a discussion on Soft Handoff, its parameters, different performance indicators and related work done by other researchers.

2.1 Evolution of Cellular and Mobile Telephony

Cellular systems obtain high spectral efficiency by reusing frequency pairs within the system which is accomplished through the use of a grid of low-power transceivers physically deployed throughout the system in groups of channels called cells. A channel is defined as a frequency band or a time-slot or a code word depending if the multiple access scheme being used to share the propagation medium is FDMA or TDMA or CDMA.

In the beginning stages of wireless communications services, in late 1970s and early

1980s, the first generation analog cellular systems like Advanced Mobile Phone System (AMPS) in NA; NMT in Scandinavian countries; TACS in UK, Italy, Australia, etc.; Radiocom in France; C-450 in Germany and Portugal; and NTT-800/JTACS in Japan; were deployed to cater to the needs of relatively smaller group of cellular subscribers [34], [35]. The first generation analog systems employed FDMA to share the common transmission medium. With the increasing popularity of cellular services in last decade it became increasingly difficult to accommodate this increasing demand with then existing analog systems. Thus in the early 1990s, to satisfy the increasing demand of wireless services, the first generation systems were followed by more robust second generation cellular systems that are based upon digital transmission techniques.

Digital cellular systems, by means of relatively inexpensive DSP integrated circuit technology, not only provide increased capacity in the same bandwidth but also the superior voice quality, more privacy and wide range of data services. Four TDMA based digital cellular standards came up all over the world. In NA IS-54 was designed to coexist with AMPS. Its frequency upshifted version called IS-136 with additional capabilities has also been standardized. A single very comprehensive standard called Global System for Mobile communication (GSM) has been developed to replace different existing analog systems in Europe. GSM and its frequency upshifted version Digital Cellular Service-1800 (DCS-1800) has become quite popular in Europe, Asia, Australia and some Latin American countries. Japanese developed their own standard called Personal Digital Cellular (PDC). All these TDMA based systems are narrowband systems and improve

capacity relative to their first generation counter parts by allowing several time multiplexed users on one frequency channel. However these narrowband systems do not perform that well on a time dispersive or frequency-selective channel thus suffer from ISI. Thus TDMA based systems require complex adaptive equalization techniques to mitigate the effect of ISI [37].

Recently in United States (US), new CDMA based digital cellular systems IS-95 for use in the 800MHz band and IS-95+ for use in the 1900 MHz band have been developed. These wideband direct sequence (DS) spread spectrum (SS) CDMA systems can resolve and combine to their advantage the mulipaths that cause ISI in TDMA and FDMA based systems [17], [21]. This CDMA does by using multiple correlating receivers called Rake receivers that have been discussed in section 3.4 where we discuss the structure of receiver for our simulation model. After the widespread success of cellular CDMA in US the Joint Technical Committee (JTC) is considering CDMA as strong contender for air interface for standard for PCS systems. An overview of CDMA follows in the next section.

2.2 CDMA: An overview

On the basis of the type of spreading technique used spread spectrum systems can be classified into three type: Frequency-hopping (FH) spread spectrum (SS), Time-hopping (TH) SS and Direct Sequence (DS) SS. In a FH-SS system the allocated spectrum, known as total hopping bandwidth, is divided into M frequency channels of bandwidth wide enough to include most of the power in a narrowband modulation burst. The hopping takes

place over these M carrier frequencies contained in the hopset. In FH-SS the signal frequency is constant for a specified time duration referred to as a time chip, τ_c . It is frequently convenient to categorize FH-SS systems as either “fast-hop” or “slow-hop”. A fast-hop system, shown in figure 2-1, is usually considered to be one in which the frequency hopping takes place at a rate greater than the message bit rate. In a slow-hop system the hop rate is less than the message bit rate. In a TH-SS system the transmission time is divided into intervals known as frames and each frame is divided into M time slots. During each frame one and only one time slot is modulated with a message as shown in figure 2-2. All of the message bits accumulated in the previous frame are transmitted in a burst during the selected time slot.

The system where the bandwidth spreading is done by direct modulation of a data-modulated carrier by a wideband spreading signal or code is known as Direct-Sequence (DS) Spread Spectrum (SS) system. The DS-SS is an averaging type system where the reduction of interference takes place because interference can be averaged over a large time interval. The FH-SS and TH-SS systems are avoidance systems where the reduction in interference occurs because the signal is made to avoid the interference a large fraction of the time. Moreover FH-SS and TH-SS systems are relatively complex to implement thus almost all of the existing CDMA systems are DS-SS based. Thus we will discuss DS-SS system in little more detail. In its simplest form a DS-SS system has been shown in figure 2-3 where the data information signal $b(t)$ is multiplied by a wideband signal $c(t)$ which is the output signal of the sequence generator. The properties and theory of different

Figure 2-1: Fast frequency hopping spread spectrum system

Figure 2-2: Time hopping spread spectrum system

Assuming $c(t)c(t) = 1$ for all bits which is true for any bipolar waveform encoded as 1, -1

Figure 2-3: Spreading and despreading of a CDMA DS signal (Block Diagram)

Figure 2-4: Spreading and despreading of a CDMA DS signal (Signals and Bandwidth at different stages)

types of spreading signals have been discussed in section 2.3.

The signal, $b(t) c(t) = y(t)$, that is eventually transmitted occupies bandwidth far in excess of the minimum bandwidth to transmit the data information. We observe, in figure 2-4, that the combined signal waveform shown has more high frequency changes than the changes in the data information since $(1/T_c) \gg (1/T_b)$ where T_b and T_c are the bit intervals of information stream and DS stream respectively. T_c is also known as chip time. The original signal is recovered back by multiplying the received signal, $b(t) c(t) = y(t)$, by the exact replica of spreading signal $c(t)$. If the signal propagation delays the output $b(t) c(t)$ by some propagation time, the second occurrence of $c(t)$ must be delayed by same amount to synchronize it with original $c(t)$. The amount of system performance improvement that is achieved by using spread spectrum techniques over the system that doesn't use spread-spectrum technique is known as the processing gain of the spread spectrum system and is usually measured as the ratio between the spread-spectrum bandwidth, $f_{ss} = 1/T_c$, and the bandwidth, $f_b = 1/T_b$ of information bearing signal.

In the last paragraph we discussed the DS-SS system in its simplest form but in real systems for the robustness of the system the process is little more complex. Depending upon the type of Spread Spectrum modulation scheme employed DS-SS systems are further classified as Binary Phase Shift Keying (BPSK) DS-SS, Quadrature Phase Shift Keying (QPSK) DS-SS and Minimum Shift Keying (MSK) DS-SS systems. BPSK DS-SS is most simple of all in terms of required hardware. A constant envelope data-modulated carrier having power P , frequency ω_c and data phase modulation $\theta_d(t)$ can be

mathematically represented as

$$x_d(t) = \sqrt{2P} \cos(\omega_c t + \theta_d(t)) \quad (2.1)$$

In BPSK modulation the phase of the carrier changes instantaneously by 180 degrees. Thus BPSK Spread Spectrum signal can be obtained by multiplying the data waveform $x_d(t)$ by a spreading waveform function $c(t)$ that can have values of ± 1 only. Thus BPSK spreaded transmit signal $x_t(t)$ is mathematically represented as

$$x_t(t) = \sqrt{2P} c(t) \cos(\omega_c t + \theta_d(t)) \quad (2.2)$$

This transmitted signal is received at the receiver after some transmission delay of T_d together with some interference and Gaussian noise. The demodulation of signal is accomplished by remodulating or correlating the received signal with replica of spreading waveform that is generated at the receiver and is delayed by an estimate of transmission delay time $\hat{T}_d$. This process of correlation of the received signal with delayed version of spreading waveform is known as despreading. The signal component at the output of the receiver is represented as

$$x_d(t) = \sqrt{2P} c(t - T_d) c(t - \hat{T}_d) \cos((\omega_c t + \theta_d(t - T_d)) + \phi) \quad (2.3)$$

where T_d is the actual transmission delay and $\hat{T}_d$ is the estimated transmission delay at the receiver, and ϕ is the random phase. If perfect synchronization between the spreading waveform at the receiver and that at the transmitter is achieved, i.e., if $\hat{T}_d = T_d$, the product $c(t - T_d) \cdot c(t - \hat{T}_d) = 1$ thus the signal component of the received signal at the output of the

receiver is equal to $x_d(t)$ except for random phase ϕ and can be demodulated using a conventional phase demodulator.

A DS-SS CDMA multiple access system uses the spread-spectrum modulation and demodulation techniques to facilitate the access of a common communication channel by multiple users. Each user in a cell is assigned a unique orthogonal code that is used to spread its data signal. The spreading signal chosen must have the property of facilitating the demodulation of the transmitted signal by the intended receiver and making the demodulation by the unintended user as difficult as possible. This is made possible by the orthogonality of assigned codes that make different users not to interfere with each other. Apart from providing a multiple access technique, DS-SS CDMA system has several other advantages outlined below:

I) CDMA provides resistance to interference and jamming. This is due to the fact that at the receiver when a desired user is being despread by correlating the received signal with the exact replica of its assigned code only the information signal of desired users gets despread. Signals of all other users including jamming signals (if any) remain spreaded over the spread bandwidth thus decreasing their effect in the information bandwidth. The processing gain (PG) of the system also affects the amount of interference experienced from other users. The larger the PG the smaller the interference from other users.

II) CDMA masks the transmitted signal in the background noise thus lowering the probability of being intercepted by an adversary. Spreading process reduces the amplitude

of the signal by the factor equal to the PG thus making the transmitted signal more noise like which makes the signal highly unlikely to be intercepted.

III) CDMA provides resistance to signal self interference due to multipath reception or frequency-selective fading. This is due to the property of the spreading codes. Ideally a spreading code is an infinitely long random sequence of binary digits with no correlation to its own shifted version. Thus two replicas of a signal with arrival time more than one chip-time apart have no correlation between them. Thus CDMA can resolve the multipaths to its advantage. This is one of the inherent advantage of CDMA based systems over TDMA based systems.

2.3 PN-Sequences

From the discussion in section 2.2 it is quite clear that the spreading codes that are used in DS-SS CDMA multiple access systems must have some special properties. In this section we shall discuss different types of spreading codes, their properties and models to generate them. A spreading waveform is usually generated using a shift register the contents of which during each interval are some linear or nonlinear combination of its contents in the preceding time interval. The output of binary shift-register generator is known as spreading code which takes on binary values 0 or 1 only. The spreading waveform $c(t)$ that takes on values of ± 1 only is obtained from the spreading code and is actually applied to the input of spreading or despreading modulator. Ideally a spreading code would be an infinite sequence of equally likely binary digits. This requires an infinite storage both at

transmitter and receiver which is not practicable. Thus all the systems employ periodic sequences with noise like properties known as pseudorandom sequences (or PN codes or sequences). The maximal-length codes and Gold codes along with other codes come under the category of PN codes.

We can represent a periodic sequence of binary digits ..., b_{-2} , b_{-1} , b_0 , b_1 , b_2 ,... from alphabet $\{0, 1\}$ by a polynomial $b(D) = \dots, b_{-2}D^{-2} + b_{-1}D^{-1} + b_0 + b_1D + b_2D^2 + \dots$ where the delay operator D^j means that the binary symbol, that multiplies with it, occurs in the j -th time interval [28]. Since the code is periodic with a period of N , thus $b_n = b_{n+N}$ for any n . The spreading waveform $c(t)$ can be derived from this spreading code as below

$$c(t) = \sum_{n=-\infty}^{\infty} a_n p(t - nT_c) \quad (2.4)$$

where $a_n = (-1)^{b_n}$ and $p(t)$ is the pulse that begins at 0 and ends at T_c . The waveform $c(t)$ is also periodic with a period $T = NT_c$. The periodic autocorrelation function of $c(t)$ is given by

$$R_c(k, \tau_\epsilon) = \left(1 - \frac{\tau_\epsilon}{T_c}\right) \theta_b(k) + \frac{\tau_\epsilon}{T_c} \theta_b(k+1) \quad (2.5)$$

where k can assume any integer value and $0 \leq \tau_\epsilon < T_c$. The discrete periodic autocorrelation function $\theta_b(k)$ in the above equation is obtained by substituting $a_n^* = a_n$ in the formula for discrete periodic cross-correlation function of two codes $b(D)$ and $b'(D)$ given by

$$\theta_{bb}(k) = \frac{1}{N} \sum_{n=0}^{N-1} a_n a_{n+k}^* \quad (2.6)$$

where $a_n = (-1)^{b_n}$. In the following section we will see that a family of PN-codes called m-sequences have two valued discrete periodic autocorrelation function $\theta_b(k)$ which makes them favorite for use in Spread Spectrum applications. Multistage shift registers are used to generate PN codes because shift registers with feedback and feedforward connections are capable of performing polynomial multiplication and division over $\text{GF}(2)$ ¹. Figure 2-5 is an example of a linear feedback shift register generator and shows an r -stage shift register generator.

Three important observations can be made from above figure 2-5. First, g_0 is always 1. Second, since all g 's cannot be zero thus given a nonzero initial condition the all-zeros state of the generator is never reached. Third, since an r -stage shift register has at most $2^r - 1$ nonzero states, the output must be periodic with a period of at most $2^r - 1$ and in most cases it is significantly less than $2^r - 1$. There are two families of PN codes, namely maximal-length sequences or m-sequences and Gold codes that have the maximum possible period $N = 2^r - 1$. Brief discussion on m-sequences and Gold codes as follows.

1. $\text{GF}(M)$ is a notation for Galois Field with a field of M elements. Galois field is a term used [28] for a finite field in the world of finite-field arithmetic which is used in the design and analysis of generators of code sequences.

Figure 2-5: Example of a linear feedback shift register

Figure 2-6: Correlation properties of m-sequences (chip duration $T_c = 4$ samples/chip and period $NT_c = 124$ samples)

2.3.1 Maximal-length Sequences (m-sequences)

Shift register sequences that have the maximum possible period for an r -stage shift register are known as the maximal-length sequences or m-sequences. Some of the properties of m-sequences that are particularly of interest for Spread Spectrum applications are:

I) The periodic autocorrelation function $\theta_b(k)$ is two-valued function given by

$$\theta_b(k) = \begin{cases} 1 & k = lN \\ -\frac{1}{N} & k \neq lN \end{cases} \quad (2.7)$$

where l is an integer and N is the sequence period. Substituting this in equation (2.5) we get the autocorrelation function $R_c(\tau)$ of spreading waveform $c(t)$ derived from m-sequence of period N . Expression for autocorrelation function $R_c(\tau)$ for a m-sequence with chip duration T_c as follows

$$R_c(\tau) = \begin{cases} 1 - \frac{\tau}{T_c} \left(1 + \frac{1}{N}\right) & 0 \leq \tau \leq T_c \\ -\frac{1}{N} & T_c < \tau < (N-1)T_c \\ \frac{\tau}{T_c} \left(1 + \frac{1}{N}\right) - \frac{1}{N} & (N-1)T_c \leq \tau < NT_c \text{ or } 0 < \tau \leq T_c \end{cases} \quad (2.8)$$

Figure 2-6 shows the autocorrelation and crosscorrelation properties of m-sequences.

II) If modulo-2 sum of an m-sequence is performed with any other phase shift of the same sequence we get another phase of the same sequence.

III) Sliding a window of width r along sequence for N shifts will give each r -tuple except

all-zero r-tuple only once.

2.3.2 Gold Codes

Gold codes were invented in 1967 keeping in mind the multiple-access aspect of spread-spectrum. Gold codes have very well behaved cross-correlation properties as given by equation (2.9). Gold codes are obtained by a modulo-2 addition of specific relative phases of special pairs of m-sequences, called preferred pairs, that must satisfy three conditions as discussed in [29]. Let $b(D)$ and $b'(D)$ be the preferred pair with a period $N = 2^n - 1$ then the family of Gold codes is defined by the set $\{b(D), b'(D), b(D)+b'(D), b(D)+Db'(D), b(D)+D^2b'(D), \dots, b(D)+D^{N-2}b'(D), b(D)+D^{N-1}b'(D)\}$. Thus a family of Gold codes obtained from a preferred pair of period N consists of $N+2$ codes with two of them being the m-sequences of preferred pair itself. A table of such preferred pairs of m-sequences to generate Gold codes for different periods have been given in [29]. The cross-correlation properties of preferred pairs of m-sequences thus Gold codes are three valued as given by the following equation

$$\text{Cross-correlation} = \begin{cases} \left(-\frac{1}{N}\right)^{r(n)} \\ -\frac{1}{N} \\ \frac{1}{N}[r(n) - 2] \end{cases} \quad \text{where } r(n) = \begin{cases} 1 + 2^{0.5(n+1)} & \text{for } n \text{ odd} \\ 1 + 2^{0.5(n+2)} & \text{for } n \text{ even} \end{cases} \quad (2.9)$$

and n being the degree of generator polynomial

The model that was used to generate family of Gold codes for simulations have been discussed in section 3.1 of chapter 3.

2.4 Soft Handoff (SHO) in CDMA

Cellular systems obtain high spectral efficiency by reusing frequency pairs within the system which is accomplished through the use of a grid of low-power transceivers physically deployed throughout the system in groups of channels called cells. A channel is defined as a time-slot or a frequency band or a code depending if TDMA or FDMA or CDMA multiple access scheme is being used to share the propagation medium. Since covered area of each cell is relatively small, it is often necessary to handoff a call in progress from one cell to another. Traditionally, a hand-off designated the process that automatically transfers the call control from one BS to another BS. But now a days hand-off is considered as a more general process whose functions are:

- I) To maintain an acceptable speech quality during the call.
- II) To maintain the call while the mobile crosses cellular borders.
- III) To maintain the concept of the planned cellular network avoiding congestions.

The basic physical fact that happens in the hand-off in TDMA or FDMA based systems is the change of Radio Frequency (RF) channel. This type of handoff process is known as hard handoff. CDMA based systems on the other hand use a different handoff technique known as Soft handoff (SHO). Since CDMA channels are distinguished by means of distinct codes assigned to different MSs thus a MS is not required to switch frequencies during the SHO process. During SHO a MS near a cell boundary establishes links with other eligible neighboring BSs in addition to having a link with its currently serving BS.

This means during SHO a call is carried by more than one BS and link with old BS is broken only once the link with other strongest BS is firmly established. This makes the SHO process seamless. In the process of SHO a MS maintains different sets of BSs as discussed below.

2.4.1 Pilot Sets

Pilot is referred to the E_c/I_T of Pilot Channel associated with the Forward CDMA Traffic Channel. Once a call is established, the MS is constantly searching for possible cell sites that might be good candidate for soft handoff. Most of the search time is limited to looking for BSs that are specified in the neighbor list found on the Paging Channel. Pilots of different BSs received at a MS are classified into the following categories depending upon their relative strengths received at the MS.

- I) *Active Set (AS)*: The pilots associated with the Forward Traffic Channels assigned to the MS.
- II) *Candidate Set (CS)*: The pilots that are not currently in the AS but have been received by the MS with sufficient strength to indicate that the associated Forward Traffic Channels could be successfully demodulated.
- III) *Neighbor Set (NS)*: The pilots that are not currently in the AS or the CS but are likely candidates for handoff.
- IV) *Remaining Set (RS)*: The set of all possible pilots in the current system on the current CDMA frequency assignment, excluding the pilots in the NS, the CS and the AS.

2.4.2 Soft Handoff (SHO) parameters

There are three parameters, namely T_{ADD} , T_{DROP} and t_{DROP} that control the SHO algorithm [16].

- I) The parameter T_{ADD} is a pilot detection threshold. It controls adding of a pilot to the AS. If a pilot's E_c/I_T in the NS or RS is above the T_{ADD} , it will be moved to the AS or CS.
- II) The parameter T_{DROP} is the pilot drop threshold. If a pilot's E_c/I_T , that is in AS or CS, is below the T_{DROP} for more than a time period specified by t_{DROP} , the pilot is moved to the NS.
- III) The parameter t_{DROP} is a drop timer. It is specified in seconds and is used to prevent a mobile from dropping a pilot prematurely in a fading environment. The MS will maintain a handoff drop timer for each pilot in the AS and CS. The MS shall start the timer whenever the strength of the corresponding pilot becomes less than the preset threshold of T_{DROP} . The MS will reset and disable the timer if the strength of the corresponding pilot exceeds the threshold T_{DROP} .

2.4.3 Handoff Messages

Soft handoff occurs when a MS moves from the coverage area of one CDMA BS to that of another. The BS that has direct control of call processing is known as primary BS and can initiate forward control messages. The BS that does not have a direct control of call processing is known as secondary BS. There is only one primary BS whereas there may be one or two secondary BSs assigned to a CDMA call. A number of messages are

exchanged between MS and primary BS, and between primary BS and secondary BS during the process of SHO.

Soft Handoff is typically initiated by the MS. The MS will send an autonomous *Pilot Strength Message* whenever any of the following events occur:

- I) The strength of a Neighbor Set or Remaining Set pilot is found to be above the T_{ADD} threshold.
- II) The strength of a Candidate Set pilot exceeds the strength of an Active Set pilot.
- III) The strength of an Active Set pilot has been below the T_{DROP} threshold longer than the time t_{DROP} .

Following messages are exchanged between the primary BS and secondary or target BS and MS after SHO has been initiated. The target BS may belong to same or different MSC.

- I) *Mobile Soft handoff Request Message* is sent by the primary BS to target BS indicating that a MS soft handoff is permissible. Long code mask of MS is included in the message.
- II) Secondary BS begins transmitting traffic on Forward Traffic Channel and acquires Reverse Traffic Channel. It sends *Handoff Acknowledge Message* to primary BS indicating that it has acquired the MS. It also includes its assigned Walsh code as part of the message.
- III) Primary BS sends a *Handoff Direction Message* to MS and includes the received Walsh code as part of its message.

IV) MS updates its pilot sets, starts listening to target BS and sends a *Handoff Completion Message* to primary BS. Thus in SHO MS listens to the two or three BSs on different Walsh codes simultaneously while each of the BSs listens to the same transmission from the MS.

2.4.4 SHO Example

Figure 2-7 shows an example of a soft handoff scenario where the secondary BS first gets added to AS and later dropped as its pilot strength drops below the preset threshold. The sequence of events are shown from MS's perspective.

- (1) Pilot strength of BS2 exceeds T_{ADD} . MS sends a Pilot Strength Measurement Message to BS1 and transfers pilot to the Candidate Set (CS).
- (2) Handoff Direction Message is sent from both BS1 and BS2 to the MS.
- (3) MS transfers pilot to the AS and sends a Handoff Completion Message.
- (4) Pilot strength of BS2 drops below T_{DROP} . MS starts the drop timer t_{DROP} .
- (5) Handoff drop timer expires. MS sends a Pilot Strength Measurement Message to BS1.
- (6) BS1 sends a Handoff Direction Message to MS.
- (7) MS moves pilot from the AS to the NS and sends a Handoff Completion Message to primary BS.

Figure 2-7: A simple 2-cell Soft Handoff scenario

2.4.5 Performance of SHO

During the SHO process the MS communicates with one or more target BSs without interrupting the link with serving or primary BS. In other words, a MS in SHO is connected with multiple BSs. For Forward link, the MS receiver coherently combines the signals from the BSs that are communicating with it. For Reverse link, depending upon the implementation, the MSC either selects the best or combines the reverse link signals received at the BSs that are in SHO with MS. This process provides diversity of forward and reverse traffic channels at the boundary between BSs. But this diversity advantage is not without any cost. In fact we are using more than one channel to carry single call whereas ideally we would like to use one channel per call. Moreover from section 2.4.3 we saw that a great number of control messages are being exchanged over the signalling channels and the network while a SHO is in progress. These messages generate a substantial amount of signalling traffic which is an unavoidable overhead on the system. Thus a trade-off has to be made between diversity advantage of SHO and the overhead costs in terms of increased signalling load and use of more than one channel per call. The performance of a network system can be assessed by two types of indicators as described below:

2.4.5.1 Link Quality Indicators

Link quality indicators indicate how reliable the network link quality is and can be measured in terms of following indicators.

- I) Average Down link E_c/I_T for a given system load. It is a measure of the quality of Down link for a given load.
- II) Average Up link E_c/I_T for a given system load. This is also a measure of the quality of Up link for a given load.
- III) Required Down link Average Transmit Power, $TxPDL$: $TxPDL$ is the required average Down link Transmit power per channel to achieve a desired preset BER or FER on Down link.
- IV) Required Up link Average Transmit Power, $TxPUL$: $TxPUL$ is the required average Up link Transmit power to achieve a desired preset BER or FER on Up link.

2.4.5.2 Resource Allocation Indicators

Resource allocation indicators indicate how efficient the system is in terms of resources utilization. Following are some of the resource allocation indicators that can be used depending upon which resource or resources of the network are of interest to us. The indicators that we'll be using in our simulations have been discussed in little more detail than other indicators.

- I) Traffic Carried T_R : T_R measures the expected number of channels occupied in each cell. Traffic is usually expressed in terms of Erlangs.
- II) Probability of Blocking a new Call, P_B : P_B measures the blocking probability of a newly originated call.

III) Probability of Blocking a Call in Handoff, P_{CB} : P_{CB} measures the probability that all the channels are occupied in the new cell at the time when current cell tries to handoff a call to the new cell.

IV) Average Size of Active Set, ASA: ASA measures the expected number of BSs in the AS of a MS in a system that uses soft handoff algorithm to handover the MS among 2 or more cells. In a system that uses Hard Handoff (HHO) algorithm $ASA = 1$ since mobile is communicating with only one BS at a time. Whereas $ASA \geq 1$ for the system that uses soft handoff with a maximum possible value of 2 for 2-Cell SHO and 3 for 3-Cell SHO system. ASA is a dual indicator because it not only is a measure of the amount of number of channels used to carry a single call but also provides us with a rough estimate of the amount of spatial diversity available on Up and Down Links. This available diversity due to soft handoff gets reflected as better link quality in terms of lower TxPDLs & TxPULs or higher Average Down link E_c/I_T & Average Up link E_c/I_T . Thus ASA of 2 can be looked at as a diversity of order 2 and ASA of 3 implies diversity of order 3. But it should be kept in mind that ASA gives us a very rough estimate of diversity because the strengths of all the BSs in the AS won't be equal all the times during their membership of the AS. Thus ASA of 2 and 3 means diversities of order slightly less than 2 and 3 respectively. In terms of system resource usage the ASA of 2 means one channel each from 2 candidate BSs and the ASA of 3 means one channel each from 3 candidate BSs have been used to carry a single call. Similarly $1 < ASA < 2$ implies that the 2nd channel from one of the candidate BSs is blocked only for some fraction of total travel time to carry a single call.

In the same fashion $2 < ASA < 3$ means that the 3rd channels from the candidate BSs is used only for some fraction of total travel time.

V) Mean Number of Active Set Updates, *NAUs*: *NAUs* is a measure of the expected number of times the membership of an AS changes over the travel time we are observing. As we already saw in sections 2.4.3 and 2.4.4 that each AS update involves an appreciable amount of signalling being exchanged between MS & BSs over control channels and between BSs & MSC over the signalling network. Thus the value of *NAUs* is in fact a measure of the signalling load on the network. The lower the value of *NAUs* the smaller will be the signalling load on the network.

VI) Fraction of Total Travel Distance (or Time) the MS is in Soft Handoff (F_{SHO}), that the MS is in 2-Cell SHO (F_{2SHO}) and that the MS is in 3-Cell SHO (F_{3SHO}): F_{SHO} measures the fraction of total travel time a mobile is in SHO. Thus it also gives us an estimate of amount of time for which mobile uses more than one channel to carry a single call. Later in chapter 5 we'll use it to estimate the soft handoff region in terms of fraction of cell area and to estimate the fraction of a cell's mobile population that is in soft handoff at any instant in time. F_{2SHO} and F_{3SHO} are measures of the fraction of time mobile was involved in 2-cell and 3-cell soft handoff respectively. In fact $F_{SHO} = F_{2SHO} + F_{3SHO}$.

VII) Trunking Resource Efficiency, *TRE*: *TRE* is a measure of expected system channel utilization efficiency. *TRE* is defined as $TRE = 1/(ASA)$. Thus *TRE* is always 1 for HHO system whereas it varies between 0 to 1 for SHO. The higher the *TRE* the better is the

Trunking Resource Efficiency.

Network resources being limited must be utilized very efficiently. Thus in CDMA system a network operator is not only interested in keeping low the number of BSs talking simultaneously to a MS (i.e., smaller average size of AS) and the time for which multiple BSs talk to a MS but also the number of times an AS is updated (i.e., lower NAUs). The SHO parameters, discussed in section 2.4.2, control the handoff activities. Their settings greatly affect the system performance. If add threshold T_{ADD} is set at a lower value a MS will see more pilots above the threshold. This results in a large handoff region and more handoff activity as the MS may have to swap the pilots. More handoff activity results into higher signalling traffic. If T_{ADD} is too high a MS may not enter into the soft handoff region until it is close to boundary. Thus because of not much diversity the link quality decreases. Since drop threshold T_{DROP} and drop timer t_{DROP} control dropping a pilot from the AS. Thus a higher T_{DROP} and/or lower t_{DROP} cause a pilot being dropped sooner that results into more handoff activities and smaller handoff regions. This results into higher signalling traffic as well as lower link quality. Whereas a lower T_{DROP} and/or higher t_{DROP} results into more pilots being maintained in the AS. This can cause a MS to be in 3-BS handoff for excessive period of time.

The values of SHO parameters influences greatly the efficiency of SHO algorithm and that of the overall performance of the system. In a system where we have unlimited network resources at our disposal and transmit power is the only constraint we would like

to have T_{ADD} as low as possible, T_{DROP} and t_{DROP} as large as possible so that we could maximize the available diversity to keep the transmit powers to minimum. However we know that we have limited network resources and must be utilized very efficiently. Thus there is a need to study the optimization problem of soft handoff parameters so that by setting them optimally the optimum performance of the system can be obtained. This means optimum link quality with optimal number of AS updates and more than one channel per call tied for only for optimal period of time. Since in SHO the MS maintains link with more than one BS to carry single call, thus two more concerns need to be addressed. First concern again is important from a network operator's point of view and the concern is if the system is loosing or gaining capacity due SHO. The second concern is important from both network operator and systems designer point of view. The concern is that if the system is gaining capacity then how many more channel elements (modems) the BS should be provided with so as to not only to support more channels per call being used due to SHO but also to enable the system to support more users due to increase in capacity (if any) due to SHO. In this thesis all these concerns have been addressed.

In the past researchers by means of simple analytical models have tried to compare the performance of HHO and SHO [20], [38], [15]. By making assumptions about average user distributions in [20] and [38] the estimates of the difference in fade margins between HHO and SHO have been computed. Viterbi et al. [20] taking into consideration macroscopic diversity enjoyed by SHO have shown the fade margin for SHO is 6dB lower than that for HHO. This analysis ignored some small macroscopic diversity that HHO also

has. Whereas Chopra et al. in [38] by considering this diversity in HHO found this difference in fade margins to be only 3dB. Their model assumed that a handoff can occur within half a second after last handoff which is not always true in real systems because of network delay in handoff execution. A more refined model by Rege et al. [15] that took into consideration the network delay in their model showed a fade margin difference of 4dB. These aforementioned works showed that SHO in fact is a better handoff method than HHO. Since minimum transmitted power is directly related to the fade margin thus smaller fade margin means smaller transmitted power at MS. Smaller transmitted power at the MS means smaller interference. The interference levels are affected by the choice of SHO parameters. The intent of this thesis is to study the parameters optimization and the trade-offs between different performance indicators, and try to quantify the improvement in capacity of CDMA due to SHO. Some work has been done on the parameter optimization problem. Because of the complexity of analysis involved most of the work had been in the form of simulation studies with the exception of Zhang [3]. Zhang following a simple model, with only two BS and no interferers, analytically studied the effect of parameter drop timer only on the system performance. This kind of analysis for a system with more than two BSs and few interferers becomes too complicated. In [23] Seite used simulations to study the effect of varying the difference between add and drop thresholds on the link quality and showed that the performance worsens as this difference exceeds 7dB. This study did not report the add and drop thresholds used and their individual effects on the performance of the system. Now Whang et al. in [25] used add

and drop thresholds to be at the same level and specified them relative to the signal level from the strongest BS. Whereas IS-95 standard [16] specifies the add and drop thresholds in terms of C/I ratio E_c/I_T . In [24] Su and Chen studied the effect of varying the ratio of the area of handoff region to that of cell. As this ratio was lowered they reported lower probability of blocking a new call as well as lower probability that all channels are occupied. Lower TRE and τ_R have been reported for increase in the same ratio.

In our simulation model unlike [3] we are studying 3-BS handoff with interferers also present in the network. Our study of parameters optimization is different from [23] and [25] in the sense that we studied the effect of the SHO parameters individually, and the thresholds levels used are in terms of the ratio E_c/I_T and not just the Received Signal Strengths (RSSs). Study of the effect of averaging length parameter d_{avg} on performance has also been included. Averaging length parameter d_{avg} helps in averaging out the effect of shadowing. An appropriate length of averaging interval d_{avg} also needs to be selected in order to get optimal performance of the system. The reason being that choosing d_{avg} too small won't average out effectively the shadowing effects from the signals received from different BSs at the MS. Thus, the residual shadowing effect might cause unnecessary fluctuations in E_c/I_T ratios thus resulting into excessive handoff activity or AS updates. On the other hand, having d_{avg} too large might bring in the effect of pathloss into the average value of E_c/I_T thus inducing wrong decisions about AS membership. Finally using the results of the optimization study of SHO parameters we estimated the enhancement in the capacity of the system due to SHO.

3

Simulation Model

This chapter discusses in detail different blocks of the simulation model that were used in the study of the performance of Soft Handoff based CDMA system. The simulation model has been implemented in terms of the following functional blocks:

- I) Spreading Sequence Generator Model
- II) Transmitter Model
- III) Channel Model
- IV) Receiver Model
- V) Soft Handoff Algorithm
- VI) Power Control Algorithms

3.1 Spreading Sequence Generator Model

From the discussion in sections 2.2 and 2.3 it is quite clear that for the efficient operation of a Spread Spectrum system, the spreading waveform $c(t)$ must have properties so that the phase of the received spreading code $c(t - T_d)$ can easily be determined initially and later

tracked by the receiver. This is made possible by selecting the spreading waveform $c(t)$ to be maximal-length sequences (m-sequences) that have a two-valued autocorrelation and very good crosscorrelation characteristics as indicated by property I of m-sequences as discussed in section 2.3.1. Thus m-sequences are quite suitable for Spread Spectrum applications like CDMA. But since there are not many distinct m-sequences available so that each Base Station (BS) could be assigned one for its identification thus they as such are not suitable for multiple access applications of SS systems. In real DS-SS multiple access communications systems, by using properties II and III of m-sequences as discussed in section 2.3.1, different phase shifts of a m-sequence of sufficiently large period are used to distinguish among different BSs in the system. For instance in IS-95 based CDMA system a PN-sequence of period $N = 2^{15} - 1 = 32767$ chips with 512 possible time offsets is used to identify 512 BSs. For this type of scheme to work the minimum difference between the phases or time offsets assigned to two adjacent BSs should be such that it exceeds the largest possible propagation delay in the network. Because of memory limitations on computers in our simulations it was not possible to use m-sequence of such a length. It was found that use of spreading sequences of maximum length of the order of $31 (2^5 - 1)$ chips only was feasible. But with such a small length it was not possible to have enough number of different phases of this m-sequence so that each of the 10 BSs could be assigned a distinct phase in order to identify them without any ambiguity. Moreover there are not many m-sequences of period 31 available so that each of the 10

Figure 3-1: Model used to generate family of Gold codes with period $N=31$

Figure 3-2: Autocorrelation of m-sequence with chip duration $T_c = 4$ samples/chip and period $NT_c = 124$ samples and its crosscorrelation with another m-sequence

Figure 3-3: Autocorrelation of a code from a family of Gold codes with chip duration $T_c = 4$ samples/chip and period $NT_c = 124$ samples and its 3-valued crosscorrelation with another code of same family

BSs could be assigned a distinct spreading code. Thus the best possible solution was to use Gold Codes for the identification of different BSs as well as different mobile users in the system. Gold codes are obtained by modulo-2 addition of specific relative phases of preferred pairs of m-sequences. Figure 3-1 shows the model used to generate Gold codes of period $N=2^n-1=31$ with primitive generator polynomials, of degree $n=5$, for a preferred pair taken from [29]. The three valued cross-correlation of preferred pairs of m-sequences and the Gold codes generated from them is shown in figure 3-3. On Downlink each BS and on Uplink each MS was assigned a distinct code sequence from this set of Gold codes. Comparing the cross-correlation properties between two m-sequences, shown in figure 3-2, to those between two codes of the same family of Gold codes, shown in figure 3-3, we see that they are almost the same. This implies that use of Gold codes instead of m-sequences to isolate one BS or MS from another won't affect the results of our simulations.

3.2 Transmitter Model

In a multiuser system where more than one user transmit simultaneously. The constant-envelope data-modulated transmit signal of k -th user is given by

$$x_k(t) = \sqrt{2P_s} b_k(t) c_k(t) \cos(\omega_c t + \theta_k(t)) \quad (3.1)$$

where $b_k(t)$ is the data signal which is deterministic on pilot channels but random on traffic channels, $c_k(t)$ is the Gold code sequence of period N allocated to k -th user, P_s is the power at which signal is being transmitted, ω_c is the carrier frequency and $\theta_k(t)$ is the carrier

phase of the k -th user. Data waveform $b_k(t)$ can be represented as

$$b_k(t) = \sum_{i=1}^{\infty} b_{ki} \psi_b(t - iT_b) \quad \text{where pulse } \psi_b(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T_b \\ 0 & \text{elsewhere} \end{cases} \quad (3.2)$$

where T_b is the bit period and $b_{ki} = (-1)^{a_i}$ and a_i is zero for pilot channel but $a_i \in \{0, 1\}$ with equal probability for traffic channel. Similarly spreading waveform $c_k(t)$ with period of N can be represented as

$$c_k(t) = \sum_{i=1}^N c_{ki} \psi_c(t - iT_c) \quad \text{where pulse } \psi_c(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T_c \\ 0 & \text{elsewhere} \end{cases} \quad (3.3)$$

where T_c is the chip period and $c_{ki} = (-1)^{\alpha_i}$ and $\alpha_i \in \{0, 1\}$ with equal probability. Since the period of spreading code $c_k(t)$ is N thus this DS-SS communication system is said to have a processing gain of N .

Since the choice of modulation scheme wouldn't affect the way Soft Handoff works thus in our simulations we used BPSK for both data modulation as well as spreading modulation. For the sake of convenience all processing has been done at baseband level. Thus the baseband equivalent equation is given by

$$x_k(t) = \sqrt{P_S} \sum_{i=1}^{\infty} \sum_{j=1}^N b_{ki} c_{kj} \psi(t - iNT_c - jT_c) \quad \text{where pulse } \psi(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T_c \\ 0 & \text{elsewhere} \end{cases} \quad (3.4)$$

Since power control is also being considered as part of simulation model thus it is appropriate to discuss how it is incorporated in the transmitter model though discussion

for Up link and Down link power control algorithms has been dealt with in section 3.6. Now the maximum transmit power P_R of a MS on Up link is designed to reach the BS when MS is at the cell vertices $r = R$. If the MS is closer to BS or is well within the cell the required transmit power P_S will be less than the maximum designed power P_R . The ratio $\zeta(r) = P_S/P_R$ gives the factor by which power control algorithm attenuates the power so that interference to other users may be kept minimum. Without loss of generality same is also true for BS's transmit power on Down link. Incorporating effect of power control in equation (3.4) the transmit signal of k -th user intended for j -th BS or the j -th BS's signal intended for k -th user, given that it is r_k distance away from the j -th BS, can be expressed as below and shown in figure 3-4

$$x_{k,j}(t|r=r_k) = \sqrt{P_R \zeta(r_k)} \sum_{i=1}^{\infty} \sum_{n=1}^N b_{ki} c_{kn} \psi(t - iNT_c - nT_c) \quad \text{where pulse } \psi(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T_c \\ 0 & \text{elsewhere} \end{cases} \quad (3.5)$$

Figure 3-4: Transmitter model

3.3 Channel Model

In wireless environment the signal transmitted by a transmitter or transceiver would propagate over certain terrain before being received by a receiver or transceiver at the other end at certain distance. The effect of terrain configuration manifests itself in terms of long-term fading characteristic which follows a log-normal variation. Long-term fading model has been discussed in detail in section 3.3.2. In mobile wireless environment other three effects a transmitted signal has to go through are as follows. First is the excessive path loss because of the strong reflected path combining destructively with direct path, thus normally 4th power law is applied. Some models with a breakpoint have been proposed by researcher. A model with breakpoint has been used and described in section 3.3.1. Second effect is that man made objects surrounding the receiver generate a multipath fading on the received signal. Rayleigh and Rician models have been suggested to model this kind of fading and have been discussed in section 3.3.3. Third phenomenon observed is time delay spread that exists due to the time dispersiveness of the medium. Because of this a receiver at the other end not only receives the symbol itself but also many delayed copies of it. This causes ISI or Frequency-Selective Fading in the received signal. Some models like Equal-variance, Exponential-variance, etc. have been suggested to simulate delay spread effects and have been discussed in section 3.3.4.

3.3.1 Propagation Loss Model

Hartley [6] has suggested a propagation model for a signal propagating in urban environment. His model consists of two slopes with a breakpoint and can be expressed as:

$$g(r) = \frac{C}{r^\alpha (1 + r/g)^\beta} \quad (3.6)$$

where C is a constant that depends upon the heights of transmitter and receiver antennas and the carrier frequency [30], r is the distance from the transmitter, α is the basic attenuation rate and β is the additional attenuation-rate coefficient for distances greater than the breakpoint g . Normally g is said to lie between 100-300m, and measurements in [6] and [7] show that α and β are around 2 [10]. This model with $g = 150m$, and α and β with value 2 each have been used.

3.3.2 Long-term Fading Model

Mean received power also known as local mean is a random variable because of shadow variations caused by large terrain features like buildings and hills in macrocells, and buildings and other objects like vehicles etc. in microcells. Empirical studies have shown that the mean power received at a wireless receiver some distance away from the transmitter follows log-normal distribution. Effect of shadowing is modeled as an independent Gaussian random variable with zero mean and standard deviation σ varying between 4-12dB. The simulations assume a standard deviation of 6dB which models quite well the shadowing in urban situation. Studies, by different researchers [8] and [18], have also shown that shadowing process has some spatial correlation over some distance. Gudmundson in [8] proposed a simple model where shadowing is modeled as Gaussian White Noise process that has been filtered through a first-order low pass filter. Mathematically the model can be represented as below

$$P_{n+1}(dB) = \xi P_n(dB) + (1 - \xi)z_n \quad (3.7)$$

where $P_n(dB)$ is the mean squared envelop level in dB received at location n . The spatial correlation parameter ξ controls the spatial decorrelation of shadowing and is further given by $\xi = \epsilon_D^{((vT)/D)}$ where ϵ_D is the correlation between two points distance D apart (approximately 0.3 at 10m in Urban environment). v and T are speed (m/s) and sampling time (secs) respectively. Variable z_n in equation (3.7) is a zero-mean Gaussian random variable with an autocorrelation of $R_{zz}(k) = \hat{\sigma}^2 \delta(k)$ where $\hat{\sigma}$ is related to the standard deviation of shadowing σ_L as $\sigma_L^2 = \frac{1-\xi}{1+\xi} \hat{\sigma}^2$. The spatial correlation of process $P_n(dB)$ is an exponential spatial correlation function given by

$$R_P(k) = \sigma_L^2 \xi^{|k|} \quad (3.8)$$

Figure 3-5: Theoretical and actual autocorrelation of the Log-normal fading using Gudmundson's spatial correlation model

In simulations the sampling time τ was fixed at 0.6 secs which corresponds to a distance of 10 meters at speed v of 60 Km/h. Figure 3-5 shows the theoretical and actual spatial autocorrelation of Log-normal fading using Gudmundson's model with 6dB standard deviation. Log-normal fading for Up and Down links for each MS-BS pair of signal path has been considered to be identical whereas shadowing between two different combinations of BS-MS pairs have been assumed to be independent of each other.

3.3.3 Small Scale Fading

Apart from long-term fading every signal received at a wireless receiver is also faded by short term fading. Because of the natural and man-made objects that are in the immediate neighborhood of receiver the received signals are subjected to phenomena of reflection, scattering and diffraction. Consequently multiple-plane waves arrive at a receiver from many different directions and with different delays. The multiple-plane waves combine vectorially to produce a composite received signal. This phenomena is termed as multipath propagation and causes short term fading. The carrier frequencies used in mobile radio applications are so high that even small changes in the differential delays due to receiver mobility cause large changes in the phases of arriving plane waves. The phase differences cause constructive and destructive addition of arriving waves thus causing large variations in phase and amplitude of the composite signal. Because of receiver's movement these spatial variations in the envelop get translated into time variations and the phenomena is known as envelop fading and is known to be Rayleigh distributed in macrocellular environment where no LOS path exists. Thus received complex envelop $z(t)$

in macrocellular environment has a Rayleigh distribution at any time t , with pdf given by,

$$p_z(x) = \frac{x}{\sigma^2} \exp\left\{-\frac{x^2}{2\sigma^2}\right\} \quad (3.9)$$

where average power is given by, $E[z^2] = 2\sigma^2$.

In microcellular (PCS or Urban) environment since the heights of receiving antennas are closer to the ground thus in PCS environment there is a great possibility of existence of LOS path between the transmitter and receiver. Thus in microcellular environment received complex envelop $z(t)$ is assumed to be Ricean distributed. The pdf of Ricean distribution is expressed as,

$$p_z(x) = \frac{x}{\sigma^2} \exp\left\{-\frac{x^2 + s^2}{2\sigma^2}\right\} I_0\left[\frac{xs}{\sigma^2}\right] \quad (3.10)$$

where s^2 and $2\sigma^2$ are the powers of the specular and scattered components. The Rice factor, κ , is given by the ratio $\kappa = \frac{s^2}{2\sigma^2}$ and when $\kappa = 0$ the channel exhibits Rayleigh fading.

Traditionally all received signals, desired as well interfering signals have been considered to be subjected to Rayleigh fading only. In microcellular systems, an undesired signal from a distant user may be modeled by Rayleigh distribution, but the desired signal may not be modeled well by Rayleigh fading, since a LOS path may exist within a microcell [9]. In [10] a Ricean/Rayleigh fading model has been suggested where desired signal,

because of the existence of LOS path (dominant signal), is subjected to Ricean fading whereas distant signals (from neighboring/distant microcells) are subjected to Rayleigh fading. We follow a similar approach. For transmitter-receiver distances greater than 800 meters the signal received at a receiver is considered to be Rayleigh faded. Jake's fading simulator [19] was used to generate Rayleigh faded envelopes. However for transmitter-receiver distances less than or equal to 800 meters the signal received at a receiver is considered to be Ricean faded. In such case Ricean fading with Rice Factor, κ , varying linearly between 12 to 0 dB has been used. κ is set to 12 dB at a distance less than or equal to 100 meters and 0 dB for distances equal to boundary, i.e., 800 meters in this case. In this case first Rayleigh fading distribution was obtained from Jake's simulator which was later converted into Ricean distribution for desired signal by adjusting its Rice factor κ to a value between 0 to 12dB depending upon receiver's distance from the desired transmitter. For carrier frequency of 1.9 GHz and speed of 60 Kmph the maximum doppler frequency is about 106 Hz which implies that the coherence time of short term faded channel is 4 msec [30]. Now with a transmission symbol rate of 9.6 K symbols/sec the symbol period is 0.104 msec. Thus, since the coherence time of the channel is greater than symbol period the channel is said to be exhibiting slow fading characteristics.

3.3.4 Multipaths Model

As we already know that due to the time dispersiveness of the wireless medium the transmitted signal experiences the time delay spread phenomena. Because of this phenomena a receiver at the other end of communication path receives the symbol along

with one or more delayed copies of itself. This causes ISI or Frequency-Selective Fading in the received signal [11] - [13]. Various authors [11], [17], [26] and [27] have suggested various models, e.g., Equal-variance, Exponential-variance, etc., to model the effects of delay spread. Exponential-variance model have been used to model the Frequency-Selectivity characteristic of the channel. In this model variance of received paths is given by an exponentially decaying expression e^{-L_m} where L_m in number of chips is the delay in the arrival time of the m -th path relative to the first received path. This model gives us an exponentially decaying power delay profile with a decay rate of approximately 4.5dB per chip. A 3-path model with a maximum delay-spread of $6T_c$ has been used to simulate the effect of multipaths which at a chip rate of 1.25MHz accounts for a delay spread of 4.8 microsec which covers the worst case delay spread scenario in an urban environment. The 3 paths are uniformly distributed over 6 chips with the assumption that first path always occurs at no delay or delay of zero chip. The channel power profile is normalized such that the sum of the variance of the three independent multipaths is unity. The complex low pass impulse response of the multipath channel can be expressed as

$$h_M(t; \tau) = \sum_{l=1}^L A_l(t) \delta\{\tau - \tau_l(t)\} \exp\{j\phi_l(t)\} \quad (3.11)$$

where A_l , ϕ_l and τ_l are magnitude, phase and propagation time delay associated with the l -th path.

Now as the spread-spectrum signal at the output of the transmitter of k -th user given by

equation (3.5) is transmitted asynchronously through the channel. This signal propagates along various multipaths so that at the receiver a constructive or destructive superposition of the attenuated and time-delayed replicas of $x_k(t)$ is produced. Signal over each multipath is affected by an independent short term fading. Thus the overall channel impulse response, given that the transmitter-receiver distance of r_k , can be modeled as tapped delay line structure as below

$$h((t;\tau)|r = r_k) = \sqrt{g(r_k)}m(t) \sum_{l=1}^L \alpha_l(t)A_l(t)\delta\{\tau - \tau_l(t)\}\exp\{j\phi_l(t)\} \quad (3.12)$$

where $\alpha_l(t)$ is the short term independently faded (Rayleigh/Ricean) envelop for the l -th path obtained from the model as discussed in section 3.3.3, $m(t)$ is the log-normal fading factor obtained after converting into ratio the value obtained (in dB) from the model represented by equation (3.7) with a desired spacial correlation, and $g(r_k)$ is the pathloss for k -th user with a transmitter-receiver distance of r_k . Because of the relative motion between the transmitters and receivers the channel path parameters A_l , ϕ_l and τ_l are time variant. However, we assumed that they remain constant over 12 data bits duration which is quite a reasonable assumption. The transmission time for 12 bits of data at 9.6 Kbps is 1.25 msec and that is about *one third* of that of the coherence time of the channel. The model of this multipath channel, and the signal of k -th user received at j -th BS or signal of j -th BS received at k -th user given that k -th user is located at distance r_k from the j -th BS is shown in figure 3-6 as follows.

τ_1 and τ_2 are uniformly distributed over intervals $[T_c, 5T_c]$ and $[\tau_1 + 1, 6T_c]$

Figure 3-6: Model of the multipath channel along with pathloss, log-normal shadowing and short term (Rayleigh/Ricean) fading

3.4 Receiver Model

Figure 3-6 shows how the channel distorts the signal of desired MS on Up link, i.e., the k -th user, or desired BS on down link, i.e., the j -th BS. Similarly signals of other users and BSs are distorted by the channel and are also received at the receiver of a MS or a BS. In a multiple access system received signal at j -th BS is the sum of the channel distorted signals of all the users in the cell and can be represented as below

$$q_j(t) = \sum_{k=1}^{N_M} q_{k,j}(t) + n(t) \quad (3.13)$$

Similarly received signal at k -th MS is sum of the channel distorted signals of all the neighboring BSs in the cell and can be represented as below

$$q_k(t) = \sum_{j=1}^{N_B} q_{k,j}(t) + n(t) \quad (3.14)$$

where N_M and N_B are the number of MSs and BSs respectively. Term $n(t)$ in both the above equations is the lowpass equivalent of the receiver noise which is a zero-mean AWGN with a two-sided power spectral density of $N_0/2$. Since AWGN has infinite frequency range thus infinite noise variance, thus to bandlimit the white noise at the receiver the received signal $q_j(t)$ at BS receiver and $q_k(t)$ at MS receiver are passed through a filter at the input of their receivers.

Since the channel is frequency-selective in nature the signal received at the receiver consists of multiple copies of transmitted signal, each experiencing a different delay and

amplitude attenuation depending upon the instantaneous power delay profile of the multipath channel. In narrowband systems like FDMA and TDMA these multiple received copies of transmitted signal cause ISI and equalization techniques are required to undo the ISI effect. Whereas the same multiple received copies in a wideband system like CDMA provides the system with multipath diversity. Since CDMA signal has sufficiently wide bandwidth its receiver can resolve and combine these multiple copies of the signal to its advantage. CDMA does this by using multiple correlating receivers called Rake receivers. A delayed-reference-type Rake receiver has been simulated to accomplish the multipath resolution and combining of received signals. This has been accomplished using a digital delay line at the output of the local spreading code generator to provide delayed samples of the despreading code. It has been assumed that the amplitudes and time delays of each path are already known to the receiver. Therefore, the signal arriving at each of the Rake arms is despreaded by an appropriately delayed version of the despreading code of the receiver. Thus if there are L resolvable multipaths the Rake receiver has L parallel correlator detector branches with L -th branch locking exactly to the L -th path. Each path is demodulated independently and detector outputs of all paths combined to form the decision variable, $\hat{z}_k$. Usually there are 3 paths that are strong enough to add usefully to improve the received signal. Beyond 3 paths not only signal becomes too weak to be useful but the processing becomes expensive too. Thus usually maximum of 3-finger Rake receiver is used with each finger synchronized perfectly to one of the 3 paths. The model of 3-path delayed-reference-type Rake receiver, as shown in figure 3-7, has been used.

Figure 3-7: Model of the Rake receiver used in the simulations

For Up link, as shown in figure 3-7, the input to Rake receiver will be $q_j(t)$ which is the sum of signals received at the j -th BS from all users including desired user k . The received signal is correlated with the appropriately delayed replica of Gold code, $c_k(t - \hat{\tau}_d)$, assigned to desired user k , where $\hat{\tau}_d$ is the estimate of the propagation delay in the first received multipath. The outputs z'_1 , z'_2 and z'_3 of the correlators are integrated over symbol period, T_b , and sampled at the end of every T_b interval as given by equation (3.16) and shown in figure 3-7. Later the sampled outputs z_1 , z_2 and z_3 of the correlators are weighted with α'_1 , α'_2 and α'_3 respectively to obtain the decision variable, $\hat{Z}_{k,j}$ at j -th BS as given by equation (3.15).

$$\hat{Z}_{k,j} = \sum_{n=1}^3 \alpha'_n z_n \quad \text{where weighting coefficient} \quad \alpha'_n = \frac{z_n^2}{\sum_{n=1}^3 z_n^2} \quad (3.15)$$

The total received despread signal $\hat{Z}_{k,j}$ consists of the sum of two parts. First part being autocorrelated signal of desired user k and the other part being the sum of the crosscorrelated signals of other users.

$$z_n = \int_0^{T_b} z'_n(t) dt \bigg|_{t=T_b} \quad (3.16)$$

Figure 3-8: Up link desreading of signals at BSs l , m and n received from k th MS and equal gain combining of decision variables at MSC received from BSs l , m and n in 3-BS soft handoff

Figure 3-9: Down link desreading and combining of signals at k th MS received from BSs l , m and n in 3-BS soft handoff

On Up link each BS has one such Rake Receiver each for every individual channel to process the signal received from every possible individual MS it can support. And since our system allows for a soft handoff involving up to 3 BSs thus we can have up to 3 BSs talking simultaneously to a MS. Thus on Up link the BSs that are in soft handoff with same MS send their decision variables, $\hat{z}_{k,j}$ s, to the MSC which performs equal gain combining on them and takes the detection decision as shown in figure 3-8.

In figure 3-8 $q_l(t)$, $q_m(t)$ and $q_n(t)$ are the sums of signals of all the users including desired user k being received at the receivers of BSs l , m and n respectively. τ_{d_l} , τ_{d_m} and τ_{d_n} are the propagation delays experienced by the signal of desired MS k to BSs l , m and n respectively and the local replicas of code assigned to MS k must be delayed by these delays in addition to multipath delays. $\hat{z}_{k,l}$, $\hat{z}_{k,m}$ and $\hat{z}_{k,n}$ are the decision variables that are sent by BSs l , m and n to MSC to be able to combine them with equal gains to get the final decision variable $\hat{z}_k$ and to take detection decision. The detected symbol is routed to its proper destination and the decision is also conveyed back to BSs l , m and n for the purpose of Up link power control which has been discussed in section 3.6.1.

On Down link though similar process of combining the signals from different sources or BSs is performed but it has to be done at MS itself. Again since our system allows for a soft handoff involving up to 3 BSs. Thus at the MS we need 3 Rake receivers, of the type shown in figure 3-7, one each to process the signal received from each of the 3 BSs in the AS as shown in figure 3-9. In figure 3-9 $q_k(t)$ is the sum of signals of all the BSs, including

desired BSs l , m and n , being received at the receiving antenna of MS k . This received signal is split into 3 parts and one part each is sent to three different 3-branch Rake receivers resident in MS and tuned to appropriately delayed local replicas of the spreading codes assigned to BSs l , m and n . τ_{d_l} , τ_{d_m} and τ_{d_n} are the propagation delays experienced by the signals of BSs l , m and n respectively in reaching the antenna of MS k and the local replicas of codes assigned to BSs l , m and n must be delayed by these delays in addition to multipath delays. $\hat{Z}_{k,l}$, $\hat{Z}_{k,m}$ and $\hat{Z}_{k,n}$ are the decision variables that are obtained at the outputs of the 3 Rake receivers. MS combines them with equal gains to get the final decision variable $\hat{Z}_k$ and takes detection decision on the basis of decision variable $\hat{Z}_k$.

Thus in this way CDMA not only exploits the inherent *micro-diversity* to its advantage by combining the multipaths using Rake receiver but also exploits the *macro-diversity* that is made available to it by soft-handoff. Figures 3-8 and 3-9 show the combining mechanism that have been used on Up and Down links respectively.

3.5 Soft Handoff Algorithm

IS-95 SHO algorithm was used as standard for the simulation of SHO. It must be noted that though an attempt was made to implement the Soft Handoff (SHO) algorithm as closely as possible to the one described in IS-95 standard yet it is not the exact implementation of that described in IS-95. Brief description of the implementation of SHO algorithm is as follows.

There are three parameters namely add threshold T_{ADD} , drop threshold T_{DROP} , and drop

timer t_{DROP} that control the SHO algorithm. In IS-95 CDMA system, MS is designed to support the SHO process by measuring and reporting to the serving BS the strength of different received pilot signals. The SHO procedure involves the maintenance of an Active Set (AS) of BSs based on their received pilot strengths or E_c/I_T ratios relative to the thresholds or parameters of soft handoff algorithms. The first parameter T_{ADD} is the upper threshold that controls adding a pilot to the AS. For a BS to become eligible for the membership of AS its pilot strength must be above T_{ADD} . A BS will be added to the AS if its pilot strength is above T_{ADD} or if it is stronger than the weakest member of the AS in case the AS is already full. The second parameter T_{DROP} is the lower threshold that controls dropping a pilot from the AS. A BS that is member of the AS is dropped from the membership of the AS if its pilot drops below T_{DROP} and remains below T_{DROP} for a preset period of time. The third parameter t_{DROP} is a drop timer and is used to prevent a MS from dropping a pilot prematurely in a fading environment. It implies that in order for a BS, that is member of AS, to be dropped from the AS the pilot strength of that member must be remain below threshold T_{DROP} for a time period at least equal to t_{DROP} . If E_c/I_T of any BS that is not a member of the AS exceeds the T_{ADD} , the BS will be added to the AS and the set of active base stations for k -th MS is given by $B_k = \{i | T_k^{(i)} \geq T_{ADD}\}$ where $T_k^{(i)}$, is the E_c/I_T of the received pilot signal from i -th BS at k -th MS. User k is said to be in SHO when set B_k contains more than one BS. Similarly if the E_c/I_T of a BS, that is currently the member of the AS, drops below threshold T_{DROP} the MS initializes a drop

timer with value t_{DROP} and starts it. The MS resets and disables the timer if the E_c/I_T of pilot goes above threshold T_{DROP} before the timer expires and the BS remains in the AS. The BS is removed from the AS if the timer expires.

Every time a BS is added to or dropped from the AS a large number of signalling messages are exchanged between MS and the concerned BS, and between BS and MSC. Thus every time AS is updated, i.e., a BS added or dropped, a substantial amount of signalling load is generated over the control channels and the network. We can make an estimate of change in this signalling load by keeping track of the change in the Number of AS Updates (NAUs) per user or in some time interval. The larger the NAUs the larger is the signalling load. In our simulations we will monitor NAUs as performance indicator for the network signalling load.

3.6 Power Control Algorithms

Portables or mobiles in wireless environment must rely on limited battery energy to conduct communications over a wireless channel. Thus, power control techniques for these devices are very desirable to enable them to transmit at minimum possible powers. Moreover one of the fundamental enabling technologies of CDMA is power control. Since the limiting factor for CDMA system capacity is the total interference, controlling the power of each mobile is central to achieve maximum capacity. The fundamental purpose of power control is to maintain acceptable voice quality for a large number of users. Other equally important objectives of power control are:

- I) Maximum system capacity consistent with the voice quality objective.

II) Minimum power consumption for both the battery powered MS and BS transmitters.

Because the error rate is a direct measure of voice quality, the system is controlled by measured error rates rather than E_b/N_T . Thus in order to assure satisfactory quality, it is not sufficient to maintain a specific E_b/N_T , but is also important to respond to frame or bit errors as they occur. In order to provide a satisfactory voice quality for each individual mobile user, power control algorithms are specified to maintain an “average FER or BER” around the “desired FER or BER”. Since a call with an acceptable voice quality can be received at a BER of 0.001. Thus in our simulations the desired BER required to be achieved was set in the range of 0.001-0.002. To meet these objectives power control in CDMA minimizes the BS transmitted power via the forward link power control and minimizes the MS transmitted power via the reverse link power control. It must be noted that though an attempt was made to implement the power control algorithms as closely as possible to the algorithms described in IS-95 standard yet they are not the exact implementation of those described in IS-95. Brief description of the implementation of Up link and Down link power control algorithms is as follows.

3.6.1 Up Link Power Control Algorithm

In IS-95 CDMA system MSs are power controlled to the minimum transmit power that provides acceptable quality for the given conditions. As a result, each MS's signal arrives at approximately equal levels. In this way, the interference from one unit to another is held to a minimum. Two forms of power control are used for the reverse link:

- I) the autonomous MS power control known as *Open loop power control*, and
- II) power control directed by the BS and known as *Closed loop power control*. It is designed to adjust the MS transmit power to achieve a desired BER or FER. It has two components, the *inner loop* and the *outer loop* respectively. The outer loop is responsible for adjusting a BS's target E_b/N_T for a given mobile, while the inner loop is responsible for keeping the mobile as close to its target E_b/N_T as possible.

3.6.1.1 Open Loop Power Control

Open loop power control is required to compensate for the large dynamic range of signals experienced due to pathloss and shadowing in the coverage area. Open loop power control is based on the similarity of the loss of strength in signals on the forward and reverse links. The MS measures the total signal power received from all BSs at the MS's location. This total received power is used by the MS to adjust its transmitter power. The MS's autonomous power control will change its transmitter power following a step change in the total received power, ΔP_R . The MS's mean output power transitions to the final value to oppose the change ΔP_R . Thus the stronger the combined received signals, the lower the MS's transmitter power. A reduction in the total received signal level at the receive antenna will result in an increase in signal power from the transmitter.

3.6.1.2 Closed Loop Power Control

The open loop control is useful in establishing the link when originating a call and reacting to large path loss fluctuations from shadowing. However, the open loop

adjustments could cause over compensation. The closed loop power control is required to quickly and accurately control the MS signal strength received at the BS. The closed loop power control is faster and will compensate for errors in the open loop control. The algorithm, as specified by IS-95 standard [16], was used and is described as follows:

- I) At the time of setting up of a call the MS is initialized with a E_b/N_T setpoint to $pnom$. The $pnom$ that defines the nominal level of E_b/N_T at the beginning of the call was set at a level of 9dB.
- II) BS measures the average E_b on the first 1.25 msec worth of data from a 20 msec long received frame, computes an estimated E_b/N_T and compares this to the target E_b/N_T setpoint. This 1.25 msec worth of data is known as a power control group and there are 16 of them in every 20 msec long frame.
- III) If the estimated E_b/N_T is less than the setpoint the BS commands the MS to increase its power by 1 dB for the next power group, otherwise the BS commands MS to decrease its power by 1 dB. This process is called the *inner loop*. The BS commands MS to increase or decrease its power by using punctured forward link symbols in each forward control group. This process is repeated for every 1.25 msec intervals or 800 bps data rate. A '0' or '1' is sent depending if MS is required to increase or decrease its transmit power. The power control bits correspond to two coded data modulation symbols and are transmitted by randomly replacing the two coded data symbols from the control group. In our simulations we use only one control bit as no coding is being done on transmit channels. In IS-95 standard if a MS is in soft handoff selection combining at MSC is used on Up link

to improve the Up link quality and the MS receives commands to increase or decrease its transmit power from all the BSs that are in soft handoff with it. The MS decreases its power even if one of its active BSs asks it to reduce its power and increases its power only if all of them ask it to do so. But in our simulations since we are using equal gain combining on both Up and Down links thus on Up link MSC combines the decision variables from each of the BSs in soft handoff and makes decision as shown in figure 3-8. Apart from routing the detected signal to proper destination MSC also conveys the result back to the concerned BSs. Based upon these results each BS sends its command to MS to increase or decrease its transmit power. Since all the concerned BSs receive the same result from MSC thus the value of the power control bit sent by each BS to the MS is identical.

IV) At the end of each 20 msec frame the BS adjusts the setpoint E_b/N_T based on whether the last frame had FER or BER above or below the desired point. If the observed BER is greater than the desired BER the BS increases the set point by 1dB otherwise the BS decreases the set point by 0.1dB. The target E_b/N_T is changed on a frame basis. This process is called the *outer loop*. The new setpoint is then used by the inner loop for the next frame. The setpoint remains fixed during the frame but may change from frame to frame.

3.6.2 Down Link Power Control Algorithm

The performance of the MS is limited by the level of interference received not only from other users in the same cell but also from the users from neighboring cells. Down link

power control (DPC) attempts to reduce the BS power to the minimum required for each user served by that BS, and therefore reduces interference to all other users in the same cell and neighboring cells. Down link power control adjusts transmit power at the BS for each traffic channel independently. MSs with favorable propagation and interference conditions may require lower power on the average, but mobiles with less favorable propagation and interference conditions may require more power on the average. The DPC algorithm attempts to set each traffic channel transmit power to the minimum required to maintain the desired frame error rate or bit error rate on the signal received at each MS. The algorithm as specified by IS-95 standard [16] is as follows:

- I) Initialize traffic channel to nominal power.
- II) MS detects downlink frame errors and sends a report to BS.
- III) BS adjusts traffic channel power to maintain preset FER or BER objective. BS increases traffic channel power by 10dB when reported error rate is greater than the desired rate and decreases power by 1dB when reported error rate is smaller than the desired rate.
- IV) If power after increase is greater than maximum, set power to maximum allowed. If power after decrease is less than minimum, set power to minimum allowed. BS does this step to restrict the power dynamic range so the transmitter power never exceeds a maximum that would cause excessive interference, or falls below the minimum required for adequate voice quality.

4

Parameters Optimization Results

In this chapter, the results of the simulation study of the optimization of parameters are being presented. First the parameters to be optimized and the performance indicators used for performance evaluation have been discussed. Later simulation scenarios and simulation parameters are discussed first followed by the results.

4.1 Input and Output Metrics

Before the simulation scenarios and the results obtained from simulations are discussed, let us first define the performance indicators metrics and input parameters metrics. Input parameters metrics consists of the system parameters that we want to optimize. Performance indicators metrics consists of the performance indicators that we measure to compare the performance of system for different sets of input parameters. We want to study the impact of different input parameters on the performance of the system.

4.1.1 Input Parameters Metrics

Our input parameters metrics consists of Soft Handoff parameters, namely T_{ADD} , T_{DROP} and t_{DROP} , and Averaging parameter, i.e., Averaging Interval Length d_{avg} .

- I) Add Threshold, T_{ADD} : Parameter T_{ADD} controls adding a pilot to the AS is expressed in dB. The received pilot strength of a BS in terms of E_c/I_T ratio has to be above this threshold to attain the membership of the AS.
- II) Relative Drop Threshold, *relative* T_{DROP} : Relative T_{DROP} is the lower threshold of soft handoff algorithm expressed in dB. The *relative* T_{DROP} which is relative to the threshold T_{ADD} and is analogous to the *Hysteresis level* used in Hard Handoff. The IS-95 standard uses *absolute* T_{DROP} threshold which is an absolute value to specify the lower threshold. Both *relative* and *absolute* T_{DROP} represent the same threshold level. For instance if we have a T_{ADD} level of -13dB and *relative* T_{DROP} of 2dB then the threshold level we are referring to is *Absolute* $T_{DROP} = (T_{ADD} - \text{Relative } T_{DROP}) = (-13\text{dB} - 2\text{dB}) = -15\text{dB}$. If the received Pilot strength of a BS in terms of E_c/I_T ratio drops below this threshold level, represented by *relative* T_{DROP} or *absolute* T_{DROP} , for a predetermined period of time the BS is dropped from the membership of the AS.
- III) Drop Timer, t_{DROP} : Parameter t_{DROP} is the timer expressed in terms of number of samples or seconds. In order for a member BS to be dropped from the AS its received pilot strength in terms of E_c/I_T ratio must be below the T_{DROP} threshold for a time period at least equal to t_{DROP} . In IS-95 standard t_{DROP} is specified in terms of the time unit seconds but just for the sake of convenience in our simulations we will express t_{DROP} in terms of number of samples. Thus for a MS that is moving at a constant speed of 60 Km/h if a sample is obtained every 10 meters then this inter-sample distance of 10 meters is

equivalent to 600 msec or 0.6 sec in terms of time. This implies that $t_{DROP}(\text{in secs}) = t_{DROP}(\text{in samples}) \times 0.6$. For instance t_{DROP} values of 2, 5 and 20 samples correspond to 1.2, 3 and 12 sec.

IV) Averaging Interval Length, d_{avg} : Parameter d_{avg} is designed to average out the effects of Long-term fading or Shadowing which is one of the main cause of fluctuations in received average E_c/I_T ratio. Parameter d_{avg} is normally expressed in terms of meters. Thus for a MS moving at a speed of 60 Km/h if a sample is obtained every 10 meters then d_{avg} of 10 meters is equivalent to one such sample. Similarly d_{avg} of 20, 30 and 80 meters is equivalent to 2, 3 and 8 such samples respectively. Thus the vector length for the purpose of averaging for d_{avg} values of 20, 30 and 80 meters will be 2, 3 and 8 respectively.

The performance of a network system is very sensitive to soft handoff parameters and d_{avg} parameter. For instance in the case of parameter T_{ADD} we'll see that variations as low as 1 to 2 dBs can make a lot of difference in the performance of the system. Similarly in the case of d_{avg} we need to be very careful in selecting an appropriate length of averaging interval d_{avg} . The reason being that choosing d_{avg} too small won't average out effectively the shadowing effects from the C/I or E_c/I_T ratios of different BSs received at MS. Thus, remaining shadowing effect causes unnecessary fluctuations in C/I ratios that make MS to update its AS quite frequently thus driving the network signalling load up. On the other hand, having d_{avg} too large might bring in the effect of pathloss into the average

value of C/I or E_c/I_T ratios thus inducing wrong decisions about AS membership. For a service provider or network operator all the above mentioned parameters are very important because they not only affect the quality of the link in terms of required transmit powers on both Up and Down links but also the resources requirement and network signalling load in terms NAUs. It is not necessary that changing certain input parameter might improve both link quality as well as network signalling load. A network operator has to make a trade-off between the diversity advantage provided by the soft handoff and the network overhead in a given operational environment. Thus a network operator has to find optimum operating ranges in terms of these parameters so that an optimum link quality can be achieved without overloading the signalling network. In this chapter we will address this particular problem of optimization of these parameters and suggest the optimum operating ranges for them for given operational environment.

4.1.2 Performance Indicators Metrics

The performance indicators metrics consists of the indicators to measure and compare the performance of system for different values of four parameters we discussed in the previous section. The performance of a network system can be assessed by two types of indicators, namely, Link Quality Indicators and Resource Allocation Indicators. Both of them have been discussed in great detail in sections 2.4.5.1 and 2.4.5.2 of chapter 2. In the past various researchers depending upon the problem under study have used one or more of these performance indicators. For instance Seite in [23] used average Up link and Down link E_c/I_T to study the effect of soft handoff parameters on link quality. However in our

simulations we used average Down link and Up link Transmit powers (TxPDL and TxPUL) required to achieve a Bit Error Rate (BER) of 0.001 to 0.002 as link quality indicators. There are two reasons for this choice. First being that for an interference limited system like CDMA the powers transmitted by all the MSs and BSs in the system determine the average received E_b/N_T which in turn determines the capacity of the system. The lower the transmit powers the lower will be interference caused to the other users thus better link quality. That implies more capacity in terms of increased number of users that can be supported by each cell. The second reason is that Up link and Down link power control being the essential part of CDMA system it would be more meaningful to look at the changes in both Up link and Down link transmit powers. Later in chapter 5 relative gains in average TxPUL will help us in estimating the relative changes in the capacity of CDMA network with the changes in soft handoff parameters. Now Su and Chen in [24] used P_B and P_{CB} to study the performance of CDMA network in terms of resource allocation efficiency. Whereas Zhang and Holzman in [3] used ASA and NAUs to study the effect of soft handoff parameter Drop Timer, t_{DROP} , on the system resources. In our simulations we monitored the resource allocation indicator NAUs to keep track of the network signalling load associated with soft handoff. Whereas resource allocation indicators ASA and F_{SHO} were monitored to estimate the amount of system resources used for a single call. Later in chapter 5, F_{SHO} will be used to estimate the average number of users in soft handoff as a fraction of total number of supported users. Likewise NAUs and ASA will be used to estimate the average total signalling load and average total

number of channel modems required at cell site to support all the users in the cell. F_{2SHO} and F_{3SHO} were monitored to see how the composition of ASA is changing with changes in different input metrics parameters. F_{2SHO} and F_{3SHO} don't really convey any important additional information other than that provided by F_{SHO} and ASA.

4.2 Simulation Scenarios and Parameters

Figure 4-1 shows a network of 10 Hexagonal cells interconnected together through a mobile switching center (MSC). MSC also connects this network with PSTN or rest of the world. In real networks the coverage areas are not only irregular because of the shadowing effects due to buildings, trees, mountains and other terrain features but also the coverage areas of two or more cells overlap. For the purpose of modeling a common practice is to represent a network with hexagonal cells of equal sizes placed next to each other. The same approach has been followed here to represent our network of cells. The figure shows the BS transceivers located at the centers of their respective cells with a MS, i.e. a car, traversing through these areas.

Figure 4-1: CDMA network of 10 Cells with BS-to-BS distance of 1600 meters and MS moving in a straight line from BS1 towards BS2.

Figure 4-2: Top view of the CDMA Network shown in previous figure

Each hexagonal cell with sides 800m long has a radius of 924 meters which implies a distance of 1600 meters between any two adjacent Base Stations (BSs) situated at the center of their respective cells. In our simulations we diverge from IS-95 soft handoff algorithm in the sense that we have restricted our Neighbor Set to the 10 BSs in the network and the Candidate set contains one or more BSs out of set consisting of BS1, BS2, BS3 and BS4 that are not currently in the AS. Moreover we don't maintain Remaining Set of pilots in our system. Figure 4-1 shows the down link signals being received at the mobile. The Transmit (Tx) signals from SHO Candidate BSs are in solid lines where as those from Non-candidate BSs are in dashed lines. Signals of Non Candidate BSs that are received at the mobile are in fact the interfering signals for the mobile. Out of the 4 SHO Candidate BSs the ones that are not in the AS of mobile at any time are also seen as interferers by the mobile. On Up link the desired signal received at each of the active BSs is interfered by 3 users with signal powers equal to that of desired signal, 3 users with powers one-half of that of desired user and 3 users with powers one-fourth of that of desired user. In the beginning of the travel, i.e., at $X=400\text{m}$, this provides us with E_b/N_T of 9dB approximately. Later when interference signals to the desired signal received at each BS are generated the total power of interference is kept fixed at this value. For the sake of clarity Up link signals have not been shown in figure 4-1. The IS-95 Soft Handoff algorithm permits any number of BSs to be members of AS at the same time. It is up to the service operator to fix the maximum number of BSs the AS set can have at any

time. In [25] Wang and Wang have shown that there is a very small probability of 4 BSs being involved in soft handoff for nominal handoff thresholds settings whereas 3-cell handoff network provides better performance compared to 2-cell handoff network. Thus our study is based upon 3-cell handoff network. That means we allow at the most 3 BSs in the AS at any point in time which implies that our MS must be able to demodulate simultaneously the signals received from at least 3 BSs. This implies that in our simulations the resource allocation indicator ASA can have a maximum value of 3.

Figure 4-2 is the top view of the service area being considered where the locations of BSs are shown as points on X-Y coordinate system with BS1 located at (0, 0) co-ordinates. Path of MS's travel is shown by a line joining the centers of BS1 and BS2, and the direction of travel is shown by the arrow. It is quite clear that for this travel route the best candidate BSs for SHO are BS1, BS2, BS3 and BS4. The darkened part of the travel route is the part that joins the half way points of the two neighbors and stretches across the border between the two neighbors. This is the region that corresponds to co-ordinates (400, 0) to (1200, 0)¹ and is of interest to us as far as performance of soft handoff is concerned. We will study the performance of Soft Handoff in the following two scenarios.

1. The reason we want to exclude intervals [0, 400) and (1200, 1600] from the travel path is as follows. In interval [0, 400) the Received Signal Strengths (RSSs) of BSs BS2, BS3 & BS4 compared to RSS of BS1 and in interval (1200, 1600] the RSSs of BSs BS1, BS3 & BS4 compared to RSS of BS2 are too weak to contribute substantially to diversity. Thus limiting simulation interval to [400, 1200] allows us to focus on the performance of the system in the region around the boundary where MS receives weak RSSs not only from currently serving BS but also from neighbors. Limiting simulation interval to [400, 1200] also saves us from performing unnecessary computations in the non-SHO region which would not have given us any meaningful results. This helps us in reducing the simulation time quite substantially.

4.2.1 Scenario I

In Scenario I the mobile moves from X-coordinate 400 to X-coordinate 1200 with Y-coordinate kept fixed at 0 ($Y=0$) which corresponds to an interval $[400, 1200]$ along X-axis on our co-ordinate system. The performance indicators values we obtain are average values obtained over the interval $[400, 1200]$. In sections 4.3 and 4.4 we will study the effects of Soft Handoff Parameters (T_{ADD} , T_{DROP} and t_{DROP}) and Length of Averaging Interval (d_{avg}) on the performance of soft handoff in Scenario I. As already mentioned the performance indicator metrics to measure and compare the performance of soft handoff consist of Average Size of the Active Set (ASA), average Number of AS Updates (NAUs) and Fraction of Total Travel Distance (or Time) the MS was in Soft Handoff (F_{SHO}) as resource allocation indicators where as average required Tx-powers on Up link (TxPUL) and Down link (TxPDL) to achieve desired Bit Error Rate (BER) in the range of 10^{-3} to 2×10^{-3} as link quality indicators.

4.2.2 Scenario II

In sections 4.3 and 4.4 by studying the effect of 3 SHO parameters and Averaging Interval parameter in Scenario I we will be able to identify the parameter that influences the performance of the system the most. Then in section 5.1 we will extend the study of the effect of that particular parameter on soft handoff performance to another scenario which we will call as Scenario II. Scenario II has MS travelling on routes parallel to Scenario I (i.e., the starting and stopping points have the same X-coordinates as those of Scenario I)

but with Y-coordinate set to a different fixed value for each route. The Y-coordinate values are increased from 0 to 462 in equal convenient steps of 51m to 52m approximately. This gives us Y-coordinate values of 0, 52, 104, 156, 207, 258, 309, 360, 411 and 462 with one each fixed for one of the ten travel routes of Scenario II. In Scenario II the route with Y-coordinate equal to 0 ($Y=0$) is in fact exactly identical to Scenario I. The route with Y-coordinate equal to 462 ($Y=462$) is the route where MS passes through the point that is the common corner of the 3 neighboring cells, namely, BS1, BS2 & BS3. The average received signal strengths from the 3 BSs in the vicinity of their common corner point are equal and weakest possible in their respective coverage areas. Thus by means of Scenario II we will be able to study the performance of soft handoff in almost all possible received signal strength scenarios. Later because of symmetry associated with hexagonal cells we can use these results for the whole cell and as a matter of fact for the whole network of hexagonal cells. Again like Scenario I in Scenario II also the performance metrics consists of ASA, NAUs, F_{SHO} , TxPDL and TxPUL.

4.2.3 Simulation Parameters

All the simulation parameters that are being discussed in the following couple of paragraphs are the same for both Scenario I and Scenario II. The only difference between the two Scenarios is that in Scenario I only one travel route with Y-coordinate equal to 0 is being considered whereas in Scenario II ten travel routes with Y-coordinates 0, 52, 104, 156, 207, 258, 309, 360, 411 and 462 are being considered. On all the travel routes the MS is moving at a constant speed of 60 Km/h from a point 400 meters inside BS1's coverage

area (X-coordinate = 400) to a point 400 meters inside BS2's coverage area (X-coordinate = 1200). This corresponds to MS's travel over interval [400, 1200] in the direction of X-axis¹. The system is operating in PCS band with a carrier frequency of 1.9 GHz. The pathloss model, as discussed in section 3.3.1, has been used with a break point at 150 meters and with basic and additional exponents of 2 each. On the top of pathloss there is 6dB log-normal shadowing with a spatial correlation of 0.3 between two points 10 meters apart. Gudmundson's spatial correlation model, as discussed in section 3.3.2, has been adopted from [8]. CDMA being a wideband system the simulation model also considers the distortion caused due to Frequency Selective short term fading. Frequency Selective fading has been assumed to be due to 3 resolvable delayed paths of the same signal in an environment which has a maximum delay spread of $6T_c$. The powers across the multipath components is distributed as per exponential-variance model as discussed in section 3.3.4. At the MS as well as at the BSs 3-arm Rake receivers have been used to demodulate the signals of interest. On Down Link the signals from different BSs received at MS have been assumed to be uncorrelated amongst themselves. This assumption is quite true in Urban environment especially in our case where even the signal from same BS has very small spatial correlation. The same reasoning holds for Up Link where the signals from MS received at different BSs have been assumed to be uncorrelated amongst themselves.

The transmission bit rate on both links is 9.6 Kbps. During MS's travel after every 10

1. For convenience in this discussion we will be ignoring the Y-coordinate because the discussion is generic and is applicable to all ten routes of Scenario II including Scenario I. The interval between X-coordinates 400m and 1200m will be referred to as interval [400, 1200].

meters or 600 msec interval we first take 400 msec long composite sample of Pilots of all the BSs received at MS. This 400 msec averaging interval is greater than the 40% long interval required to average out the short term fading for 1.9GHz carrier. Apart from that another averaging process with an averaging interval, d_{avg} , of 20 meters length has been used to average out long term shadowing partially. Later in section 4.4 we will see that selection of d_{avg} is also very critical to the performance of the system. After averaging over interval d_{avg} the received average C/Is or E_c/I_T of the Pilots of the 4 candidate BSs are computed and passed on to IS-95 Soft Handoff algorithm which has been discussed in section 3.5. The Soft Handoff algorithm uses the received average E_c/I_T to update the membership of AS for preset values of SHO parameters. It has been assumed that because of perfect orthogonality of Walsh codes the Pilots and Traffic channels won't interfere with each other. Thus once the membership of the AS is known the composite sample of traffic signals received from all the BSs is demodulated separately using the spreading waveforms of the member BSs. These received demodulated signals of member BSs are combined coherently and then BER for Down Link is computed. Later Down Link Power Control algorithm, as discussed in section 3.6.2, is performed to adjust the Down Link Traffic Channel Power so that an average Down Link BER of 0.001-0.002 is maintained. At each sampling instant in distance average Transmit Power (TxP) per channel from the member BSs of the AS is computed. At the end of MS's travel we get a vector of average TxPs per channel for each sampling instant. From this vector we compute an average of

the average TxPs per channel by averaging over all the sampling instants spread evenly over the desired travel interval [400, 1200] to get average Down Link TxP (TxPDL). On Up link first Open Loop power control, as discussed in section 3.6.1.1, is performed on MS's Transmit power. Then 400 ms long samples of MS's signal received at each of the member BSs are taken and BER is computed after combining them coherently. Later Closed Loop Power Control algorithm, as discussed in section 3.6.1.2, is performed to achieve BER in the desired preset range of 0.001-0.002. Finally like Down Link the average Up Link TxP (TxPUL) is computed over desired traveling interval of [400, 1200]. Similarly Average Size of Active Set (ASA), Mean Number of AS Updates (NAUs), and Fraction of Travel Distance (or Time) the MS in Soft Handoff (F_{SHO}), that the MS in 2-Cell SHO (F_{2SHO}) and that the MS in 3-Cell SHO (F_{3SHO}) are also computed over the interval [400, 1200]. Also computed are Probability of inclusion of BS1 in AS (Prob1), Probability of inclusion of BS2 in AS (Prob2) and Probability of inclusion of 3rd BS in AS (Prob3) at every sampling instant in distance.

4.2.4 Received C/I or E_c/I_T Ratios Profiles

Before discussing the results in the sections that follow let us first look at the profile of received Pilot strengths in terms of Carrier-to-Interference (C/Is) or E_c/I_T ratios of Candidate BSs and the Probabilities of inclusion of candidate BSs in the Active Set (AS), namely Prob1, Prob2 and Prob3.

Figure 4-3: Profiles of C/Is of the Pilots of Candidate BSs received at the mobile as it moves from BS1 to BS2

Figure 4-4: Profiles of C/Is of the Pilots of Candidate BSs received at Mobile during travelling interval of interest, i.e., interval [400, 1200].

Figure 4-3 shows the profile of C/Is of the candidate pilots being received at the mobile while it travels at a constant speed of 60 Km/h from BS1 to BS2 along a straight line joining the centers of the two BSs. The averaging interval length d_{avg} of 20 meters has been used to average out the long term variations. Figure 4-3 also shows the state of the AS (i.e., Number of BSs in the AS) of the mobile at all the sampling points in distance by a 3-level solid curve near the bottom of the figure. The lowest level corresponds to the state of AS where it has only one member in the AS whereas middle and top levels correspond to the states of AS where it has 2 and 3 members respectively in the AS. Any transition from any one state (level) to another accounts for one AS update (NAUs). Since we have 20 state transitions thus we have 20 NAUs in this case. This value of NAUs is for Soft Handoff (SHO) parameters values of -15dB, 0dB, 0 samples and 20m for T_{ADD} , relative T_{DROP} , t_{DROP} and d_{avg} respectively. In the later sections we'll see that how an optimum choice of these parameters help us in reducing NAUs.

Notice that we don't have too many (in fact not even a single) transitions before 400 meters and after 1200 meters points which justifies restricting our simulation interval to [400, 1200]. To have a closer look at the C/I ratios profiles and the state of AS in the interval of interest let us zoom in onto the interval [400, 1200] of figure 4-3 to obtain figure 4-4. Figure 4-4 shows the fine details of variations in the received C/Is of candidate BSs and corresponding changes in the state of AS over one travel of the MS over the interval [400, 1200].

Both figures 4-3 and 4-4 also show threshold T_{ADD} just to give a feeling of the levels of the received C/I ratios of different BSs relative to T_{ADD} . It is quite clear from both figures 4-3 and 4-4 that C/I ratio for BS1 is quite high while MS is closer to BS1 and drops quite slowly till MS has moved as far away as 3/4th of the distance to boundary from BS1. If MS keeps on moving further away from the BS1 the rate of decay increases with C/I ratio of BS1 decaying faster than before. Once the MS has crossed over the boundary and is well within the coverage area of BS2 the rate of decay increases even more as a result of which the C/I ratio of BS1 starts decreasing even faster than before. The reason for this kind of behavior of BS1's C/I ratio is that in the beginning Received Signal Strength (RSS) of BS1 is very high compared to the total Received Interference which also includes signals from other potential soft handoff candidates BS2, BS3 and BS4. As MS moves away from BS1 towards the boundary its RSS (i.e., the received Carrier) starts decreasing whereas RSSs from BS2, BS3 and BS4 (i.e., the received Interference) start increasing thus the C/I ratio for BS1 starts decreasing. Later when MS is inside the coverage area of BS2 and is still moving away from BS1 (towards BS2) the RSS from BS1 diminishes at even faster rate because of power law where as RSS from BS2 becomes very strong thus making C/I ratio of BS1 decay even faster than before. In this region though RSSs from BS3 and BS4 are also decreasing but BS2's signal is growing very strong which offsets the loss in the RSSs of BS3 and BS4. In the similar fashion it can be explained that why received C/I ratio of BS2 increases as MS moves towards BS2 starting from a point closer to BS1. Again looking at figures 4-3 and 4-4 we observe that C/I ratios

of BS3 and BS4 are very small while MS is far away from the boundary. The C/I ratios start rising quickly in the beginning as MS moves towards the boundary and the rate of rise in C/I ratios decreasing as MS approaches the boundary. The C/I ratios of BS3 and BS4 achieve certain maximum around the boundary and start to decrease once MS crosses into BS2's boundary. The rate of decay in the C/I ratios is small in the beginning but keeps on increasing as MS keeps on moving away from the boundary. Once MS is quite far away from boundary the C/I ratios decay even faster. The reason for this kind of behavior of C/I ratios of BS3 and BS4 is that while MS is away from the boundary and closer to BS1 the RSSs of BS3 and BS4 are very small compared to RSS of strongest interferer BS1 thus making C/I ratios of BS3 and BS4 very small. As MS moves closer to boundary we see gradual increase in the C/I ratios of BS3 and BS4 as their RSSs increase where as the RSS of interferer BS1 has gone down quite appreciably and that of BS2 though rising but is still quite low. Around or at the boundary the RSSs of BS3 and BS4 are maximum thus we see maximum C/I ratios for BS3 and BS4 around boundary. As MS moves into BS2's boundary and towards BS2 the RSS of interferer BS2 increases appreciably whereas RSSs of BS3 and BS4 decrease quite fast thus we see a fast decline in their C/I ratios.

Figure 4-5 shows the Probabilities of inclusion of BS1, BS2 and 3rd BS (BS3 or BS4) in the AS for SHO parameters values of $T_{ADD} = -15$ dB, relative $T_{DROP} = 0$ dB (absolute $T_{DROP} = -15$ dB) and $t_{DROP} = 0$. In the later sections we'll observe that having absolute

Figure 4-5: Probability of inclusion of BSs in the Active Set for $T_{ADD} = -15\text{dB}$, $T_{DROP} = 0\text{dB}$ & $t_{DROP} = 0$ samps

T_{DROP} few dBs lower than T_{ADD} and/or having non-zero positive integer value for t_{DROP} will have the effect of shifting slightly to the right the falling right-hand sides of the Probability curves for BS1 and 3rd BS.

The reason being that with absolute T_{DROP} few dBs lower than T_{ADD} and/or having non-zero positive integer value for t_{DROP} the SHO algorithm has the tendency to retain BS1 and 3rd BS (BS3 or BS4) in the AS for periods longer than before. We observed in figure 4-3 that while MS is in BS1's boundary since the received C/I ratio for BS1 is quite high compared to the absolute T_{DROP} (which in this case is same as $T_{ADD} = -15$ dB) the probability of inclusion of BS1 in AS, i.e. Prob1, has a maximum value of 1 or the probability of excluding BS1 from the AS is zero.

After travelling some distance into the BS2's coverage area BS1's C/I ratio starts diminishing thus making probability Prob1 also drop quite quickly towards zero. In case of BS2 in the beginning while MS is quite far from BS2 (or well within BS1's coverage area) the C/I ratio of BS2 though rising yet not high enough to be included in AS. Thus probability of inclusion of BS2 in the AS, i.e., Prob2, remains zero in the beginning until BS2's C/I ratio is in the vicinity of threshold $T_{ADD} = -15$ dB and here the probability Prob2 starts rising quite quickly and achieves the maximum value of 1 even before the MS crosses over into BS2's boundary.

Similarly probability of inclusion of 3rd BS (BS3 or BS4) in AS, i.e., Prob3, is zero in the beginning because of their very low C/I ratios but starts rising near the region where their

C/I ratios hover around threshold T_{ADD} . Near the boundary the probability Prob3 achieves some maximum between values 0 to 1 depending upon the levels of T_{ADD} and T_{DROP} , and once MS has crossed over and travelled few 10s of meters into the coverage region of BS2 the Prob3 starts falling again towards zero. In the later sections we will observe that the points in distance where the probabilities Prob2 and Prob3 start rising and the maximum value that Prob3 achieves are largely affected by threshold T_{ADD} and d_{avg} , and only very slightly affected by threshold T_{DROP} and drop timer t_{DROP} . On the other hand the points in distance where the probabilities Prob1 and Prob3 start falling towards minimum are largely affected by thresholds T_{ADD} , T_{DROP} and drop timer t_{DROP} , and only very slightly affected by d_{avg} .

4.3 Effect of Soft Handoff Parameters on its Performance

In the following subsections the simulation results of the effect of three SHO parameters T_{ADD} , T_{DROP} and t_{DROP} on the performance of SHO in Scenario I are presented. The average values of the performance indicators ASA, NAUs, TxPDL, TxPUL, F_{SHO} , F_{2SHO} and F_{3SHO} have been obtained by averaging over the travelling interval [400, 1200]. Discussion on the effect of each parameter on SHO Performance is as follows.

4.3.1 Effect of Add Threshold, T_{ADD}

Threshold T_{ADD} is first of the three SHO parameters whose effect on the SHO performance we wanted to study. In simulation Scenario I, keeping *relative* T_{DROP} and t_{DROP} fixed at some appropriate values of 2dB and 5 Samples respectively, as T_{ADD} threshold is lowered from -8 to -20dB in steps of 1dB the following effects are observed.

We observed that BS2 & 3rd BS qualify to be added to AS earlier than before with the lowering of threshold T_{ADD} . On the other hand BS1 & 3rd BS qualify to be dropped from AS later than before because absolute Drop Threshold gets lowered with the lowering of T_{ADD} . This makes the falling right hand sides of Probabilities of inclusion of BS1 and 3rd BS in the AS, namely Prob1 and Prob3, shift rightward as shown in figures 4-6 & 4-8 (please note the right shift in the falling right sides of the curves of both figures). Similarly rising left hand sides of the probabilities of inclusion of BS2 and 3rd BS in the AS, namely Prob2 and Prob3, get shifted leftwards as shown in figures 4-7 & 4-8 (please note left shift in the rising left sides of the curves of both figures). This implies that BS1, BS2 and 3rd

BS (BS3 or BS4) tend to be in the AS for longer periods than before and MS is in SHO for periods longer than before as shown by the rising Fraction of total travel distance the MS is in SHO (F_{SHO}) curve in figure 4-9. We observe that for T_{ADD} threshold levels of -9dB and -8dB, the curves for Fraction of total travel distance during which MS is in SHO (F_{SHO}) and Fraction of total travel distance during which MS is in 2-Cell SHO (F_{2SHO}) coincide whereas the curve for Fraction of total travel distance during which MS is in 3-Cell SHO (F_{3SHO}) is almost zero. The reason being that for T_{ADD} levels of -9dB and above the C/I ratios of BS3 and/or BS4 fall far below the threshold making Prob3 almost zero. But as we start lowering T_{ADD} below -9dB it enables 3rd BS to be included in the AS for increasingly longer distances of travel (or periods of time) which we see in terms of increasing Prob3 and F_{3SHO} in figures 4-8 and 4-9 respectively. This in turn influences the ASA in terms of gradual increase in the slope of the curve as seen in figure 4-10. In figure 4-9 we further notice that with the lowering of T_{ADD} the F_{2SHO} curve rises in the beginning, reaches some maximum around the T_{ADD} level of -13dB and starts declining slowly thereafter. Whereas F_{3SHO} starts rising slowly in the beginning but rate of rise increases as T_{ADD} is lowered further. Again referring to figure 4-9 the curve F_{SHO} rises almost linearly for most of the time with the lowering of the level of T_{ADD} except below -19dB where the curve starts to curve down slightly thus indicating decrease in marginal increase in F_{SHO} .

The combined effect of curves F_{2SHO} and F_{3SHO} is seen in Figure 4-10 in terms of the

Average Size of Active Set (ASA) of the mobile. In Figure 4-10 we observe that with the lowering of T_{ADD} from -8dB to -10dB the ASA increases almost linearly. The reason being that during this range of T_{ADD} levels the probability Prob3 is almost zero thus 3rd BS's contribution to the membership of the AS (F_{3SHO}) is negligible and the only contribution to the membership of AS is by two main BSs in terms of F_{2SHO} . As T_{ADD} is lowered further below -10dB the probability Prob3 increases which makes F_{3SHO} rise quite sharply which in turn implies 3rd BS starts contributing to the membership of AS quite substantially. Now the F_{2SHO} rises between T_{ADD} levels of -10 to -13dB and starts declining slowly thereafter where as F_{3SHO} rises very sharply for T_{ADD} levels of -10dB and below. The reason being that 3rd BS is contributing more and more to the membership of AS as we keep on lowering T_{ADD} . The combined effect of F_{3SHO} and F_{2SHO} is gradual increase in the slope of ASA curve for T_{ADD} levels between -10 to -15dB. Lowering T_{ADD} level further below -15dB we see slight decrease in the slope of the ASA curve. The reason being that though lowering the T_{ADD} level increases the probability of 2nd and 3rd BSs being included in the AS at distances farther from the boundary but the declining signal strengths of these BSs at such far distances is decreasing their probability of being included in the AS. Thus these two opposing phenomena make the marginal increase in the ASA smaller and smaller with the lowering of T_{ADD} below -15dB levels.

Now increase in ASA means that we have more BSs communicating simultaneously with MS for longer periods which means we have larger spatial diversity available for longer

periods. This larger available diversity improves the quality of signal on both Down and Up Links in terms of lower BER. The lower BER in turn gets translated into lower required average Down Link Transmit Power (TxPDL) and average Up Link Transmit Power (TxPUL) by means of Down and Up Link Power Control algorithms respectively. Figures 4-12 and 4-13 show the reduction in the required TxPDL and TxPUL as threshold T_{ADD} is lowered. The marginal reduction in TxPDL and TxPUL is not always proportional to the corresponding marginal increase in the ASA. In Figures 4-12 and 4-13 we notice that if we lower T_{ADD} from -8 to -15dB the reduction in TxPDL and TxPUL is almost linear. Lowering T_{ADD} levels further below -15dB we notice a decrease in the marginal reduction of TxPDL and TxPUL even though ASA is still increasing at a substantial marginal rate as seen in Figure 4-10. The reason is that though with the lowering of T_{ADD} below -15dB the 3rd BS is in the membership of AS for increasingly longer portions of travel (as shown by sharply rising F_{3SHO} curve in figure 4-9) but the RSS of 3rd BS received at MS during these additional portions of travel is quite low compared to the RSS levels of BS1 and/or BS2. Because of relatively lower RSS of 3rd BS its contribution to the diversity advantage is not much during these additional portions of travel. This reduces the rate of marginal improvement in the BERs on Down Link which in turn reduces the marginal reduction in the TxPDL for T_{ADD} levels below -15dB as seen in figure 4-12. A similar effect is seen on Up Link. In this case RSS of MS received at 3rd BS during these additional portions of travel is quite low compared to that received at BS1 and/or BS2. Thus the contribution by the 3rd order of diversity is not

much and manifests itself in terms of reduced marginal reduction in TxPUL for T_{ADD} levels below -15dB as seen in figure 4-13. Till now in our discussion we saw that by lowering the level of T_{ADD} we gain in terms of lower Tx-powers on both Up and Down Links which in turn not only reduces interference to other mobile users of currently serving BS and of neighboring BSs but also extends the battery life of the MS.

But all this gain in terms of reduced Tx-powers TxPUL and TxPDL is not for free. We will see in the following discussion that we have to pay a price in terms of the network signalling load. Let us first see what happens to the network signalling load (NAUs) as level of T_{ADD} is changed. In figure 4-11, that depicts the effect of T_{ADD} on NAUs, we notice that lower the T_{ADD} level the higher the NAUs are. Now we know that BS1 and BS2, being quite strong compared to the threshold T_{ADD} for most part of the travel, will get dropped from/added to the AS very few times thus won't affect the NAUs that much. Whereas since BS3 and BS4 are not so strong compared to the threshold T_{ADD} their C/I ratios hover around the thresholds. Thus, they may get dropped from or added to the AS substantially more number of times than BS1 and BS2 do. Another reason why BS3 and BS4 largely affect the NAUs is as follows. We already know that with the lowering of T_{ADD} both BS3 and BS4 become eligible for inclusion into the AS for increasingly longer portions of travel (as indicated by the increase in the area under the Prob3 curves in figure 4-8). Since BS3 and BS4 are of almost same average signal strengths thus during the interval they both qualify to be included in the AS. Thus they keep on contesting between

themselves for the 3rd place in the AS and each time one replaces the other in the AS it accounts for one NAU. Since lowering T_{ADD} extends this contention interval hence we see an increase in the NAUs.

Now lowering T_{ADD} to a value too low not only increases the signalling load (in terms of higher NAUs) on the Network but also locks for longer periods multiple BSs (in terms of larger ASA) to carry the same single call and might not provide that much of gain in terms of lower Transmit Powers as indicated in figures 4-12 and 4-13. On the other hand raising T_{ADD} to a level too high though reduces the signalling load in terms of NAUs but lowers the available diversity (lower ASA) also. Lower available diversity makes the quality of link go down in terms of higher BERs which in turn gets translated into higher Transmit powers to achieve desired BER. Thus a trade-off has to be made between the network signalling load (NAUs) and Tx-powers. Figures 4-14 and 4-15 show the trade-off curve between NAUs and Down Link Transmit Power (TxPDL), and that between NAUs and Up Link Transmit Power (TxPUL) respectively. The optimum operating range lies at the knee of the trade-off curves shown in figures 4-14 and 4-15 and corresponds to the T_{ADD} threshold range of -12 to -17dB in the given operational environment.

Let us compare quantitatively the system performance at three operating points with one being at T_{ADD} level of -14dB that lies right in the middle of the optimum operating range, second being at T_{ADD} level of -8dB that lies above the optimum operating range and third being at T_{ADD} level of -18dB that lies below the optimum operating range. At -14dB

T_{ADD} threshold compared to -8dB we are operating at approximately 3.0dB lower average Down Link Transmit Power (TxPDL) and 2.9dB lower average Up Link Transmit Power (TxPUL). This implies that by being at T_{ADD} of -14dB we require only 50% of TxPDL and 51% of TxPUL needed at T_{ADD} level of -8dB. Thus there is a reduction of 50% and 49% in required average Transmit Powers on Down and Up links respectively with the lowering of threshold T_{ADD} from -8 to -14dB. This reduction in Tx-power on down link implies lower interference to mobiles in the neighboring cells. Whereas reduction in Tx-power on up link not only implies lower interference to other users in the currently serving cell but also to the users in neighboring cells. We will see in next chapter that this reduction in Up Link Transmit Power helps in increasing the capacity of the CDMA system. Moreover lower Transmit power on Up Link also implies increased life of the battery of mobiles between two rechargings. But we have to pay price in terms of increased network signalling load (NAUs) for this advantage of lower Transmit powers. There is an increase in NAUs by more than a factor of 2 (from 3 to 6.5) with the lowering of T_{ADD} level from -8dB to -14dB. On the otherhand raising threshold T_{ADD} from -18dB to -14dB increases the TxPDL and TxPUL by 20% only (0.8dB increase approx.) whereas reduction in NAUs is by more than a factor of 4 (from 27 to 6.5).

It is quite clear that the system performance is quite sensitive to parameter T_{ADD} . T_{ADD} affects the system performance to a great extent both in terms of link quality and signalling load. Operating at above the optimum operating range makes the system

inefficient in terms of required Transmit powers whereas operating below the optimum operating range makes the system inefficient in terms of network signalling load performance. Thus it is very important that we set the T_{ADD} threshold at an appropriate level in the optimum operating range which we found to be in the range -12 to -17dB for given operational environment. The optimum operating range might change slightly with the nature of terrain and might depend on the environment the system is operating in, i.e., if operating in Urban or Suburban area. The purpose of this thesis is not to define the exact optimum operating range for a CDMA system but to understand the effect of changing the T_{ADD} threshold on different performance indicators and also to understand the systematic process of optimizing the performance of a CDMA system by making different trade-offs which is very important from a service provider or network operator's point of view.

Figure 4-6: Effect of T_{ADD} on Probability of inclusion of BS1 in the AS (Prob1) Figure 4-7: Effect of T_{ADD} on Probability of inclusion of BS2 in the AS (Prob2)

Figure 4-8: Effect of T_{ADD} on Probability of inclusion of 3rd BS in the Active Set (Prob3)

Figure 4-9: Effect of T_{ADD} on Fraction of distance MS in SHO (F_{SHO}), in 2-Cell SHO (F_{2SHO}) and in 3-Cell SHO (F_{3SHO})

Figure 4-10: Effect of T_{ADD} on Average Size of Active Set (ASA)

Figure 4-11: Effect of T_{ADD} on Mean Number of Active Set Updates (NAUs)

Figure 4-12: Effect of T_{ADD} on Required Down Link Transmit Power per Active Channel (TxPDL)

Figure 4-13: Effect of T_{ADD} on Required Up Link Transmit Power (TxPUL)

Figure 4-14: Trade-off between average Down Link Transmit power (TxPDL) and Number of AS Updates (NAUs)

Figure 4-15: Trade-off between average Up Link Transmit power (TxPUL) and Number of AS Updates (NAUs)

4.3.2 Effect of Drop Threshold, relative T_{DROP}

Relative T_{DROP} is the second of the SHO parameters we are studying. Again in Scenario I, keeping T_{ADD} and t_{DROP} fixed at some appropriate values of -15dB and 5 samples respectively, as we increase the relative threshold T_{DROP} from 0 to 12dB (correspondingly lower the absolute T_{DROP} threshold from -15 dB to -27 dB) we observe the following effects on the performance of the system.

We already know that due to long term fading the received C/I ratios of candidate BSs fluctuate around their respective mean C/I ratios. Because of these fluctuations either a candidate BS is added to the AS in case its C/I ratio exceeds the threshold T_{ADD} or a member is dropped from the AS in case its C/I ratio stays below the absolute T_{DROP} for a prefixed interval of time or a member is replaced by a better non-member BS in case the AS is full. This adding, dropping and replacing of the BSs not only contribute to the signalling load in terms of NAUs but also affect the probabilities of inclusion of different BSs into the AS. Now increasing the relative T_{DROP} (or lowering the absolute T_{DROP}) allows more margin on the lower side of the fluctuating C/I ratios of member BSs to remain above absolute T_{DROP} and meet the criterion that keeps them as member of the AS (or prevents them from being dropped from the AS). Later in this section we will see that this not only improves the probabilities of inclusion of different BSs in the AS which in turn increase the available diversity (in terms of ASA) but it might also reduce the NAUs. In figures 4-17 & 4-18 we notice that the Probabilities of inclusion of BS2 & 3rd

BS in the AS, i.e., Prob2 and Prob3 respectively, increase very slightly with increase in the relative T_{DROP} in the first half of the travel (please note very slight left shifts in the rising left sides of the curves of both figures). The reason being that as the MS is moving towards boundary (away from BS1 and closer to BS2 and 3rd BS) the C/I ratios of BS2, BS3 and BS4 that are being received at MS improve consistently thus it is very unlikely that BS2 and 3rd BS will be dropped within a very short period after being added to AS for the first time. On the other hand we notice the Probabilities of inclusion of BS1 and 3rd BS in the AS, namely Prob1 and Prob3, increase substantially with increase in the relative T_{DROP} in second half of the travel as shown in figures 4-16 & 4-18 (please note right shifts in the falling right sides of the curves in both figures). The reason being that though the C/I ratios of BS1 and 3rd BS that are being received at the MS are decreasing as MS moves away from the boundary yet the SHO algorithm because of increasing relative T_{DROP} (or lowering absolute T_{DROP}) tries to retain BS1 & 3rd BS in the AS for longer periods than before. The larger the relative T_{DROP} the longer the SHO algorithm tries to retain BS1 and BS3 in the AS before dropping one or both of them from the AS. The combined effect of increase in these Probabilities of inclusion of different BSs is that the Fraction of the total travel distance the MS is in Soft Handoff (F_{SHO}) and that the MS is in 3-Cell Soft Handoff (F_{3SHO}) increase whereas the Fraction of the total travel distance the MS is in 2-Cell Soft Handoff (F_{2SHO}) decreases as shown in figure 4-19. The combined effect of changes in F_{3SHO} and F_{2SHO} is an increase in the Average Size of Active Set

(ASA) as shown in figure 4-20. We notice that with the increase in the relative T_{DROP} the ASA increases almost linearly in the beginning (upto a relative T_{DROP} value of 4dB approximately) but the slope of ASA curve starts decreasing with any further increase in relative T_{DROP} . Since increase in ASA means that we have larger spatial diversity for periods longer than before which in turn improves the quality of signal on both Down and Up Links. This improved quality of received signal gets translated into lower required TxPDL and TxPUL by means of Down and Up Link Power Control algorithms. The required TxPDL and TxPUL for different levels of relative T_{DROP} are shown in figures 4-22 and 4-23 respectively. But we notice that gains in terms of reduced TxPDL and TxPUL are not as much as we saw in the case of T_{ADD} in the previous section. In figures 4-22 and 4-23 we also notice that the marginal reduction in TxPDL and TxPUL is high in the beginning while relative T_{DROP} is increased from 0 to 4dB but the marginal reduction in transmit powers starts decreasing if relative T_{DROP} level is increased any further and becomes almost negligible for relative T_{DROP} levels of 7dB and above.

Let us see what happens to the network signalling load or NAUs as relative T_{DROP} is changed. Figure 4-21 shows the effect of changing the relative T_{DROP} on NAUs. It is quite clear from the figure that the larger the relative T_{DROP} the lower will be the NAUs and the reason for that is as follows. From our discussion in previous section we already know that BS3 and BS4 are the ones that affect the NAUs largely because of their C/I ratios hovering around the thresholds (please see figure 4-4). This makes SHO algorithm

to drop from or add to the AS few times, the contending BSs BS3 and BS4, before one of them has been either added to or dropped from the AS permanently or for a comparatively long period. Now increasing the relative T_{DROP} (or lowering the absolute T_{DROP}) allows more margin on the lower side of their fluctuating C/I ratios to remain above the absolute T_{DROP} threshold and meet the criterion that keeps them in the AS (or prevents them from being dropped from the AS). Thus as the value of relative T_{DROP} is increased the SHO algorithm has the tendency to retain the member BSs in the AS for relatively longer period than was the case with smaller relative T_{DROP} . This implies that there is reduction in the frequency of dropping of BSs from the AS as the relative T_{DROP} is increased (or absolute T_{DROP} is lowered). This reduces unnecessary NAUs which implies reduced signalling load on the Network.

Till now we have seen that by increasing the relative T_{DROP} we not only gain in terms of reduced NAUs but also slightly in terms of small reduction in transmit powers TxPDL and TxPUL. But looking at figures 4-21, 4-22 and 4-23 carefully we can see that increasing the relative T_{DROP} (or lowering absolute T_{DROP}) won't keep on reducing the NAUs, TxPDL and TxPUL for ever. We also notice in figure 4-20 that increasing relative T_{DROP} (or lowering absolute T_{DROP}) also increases the ASA which is an expense for the system in terms of more than one channel being used for longer periods to carry a single call. Thus we need to find an optimum operating range for relative T_{DROP} where the system operates at optimum signalling load in terms of NAUs and optimum resources in terms of

ASA. The optimum operating range can be determined from the knee of the trade-off curve between NAUs and ASA as shown in figure 4-24. The knee of this trade-off curve spans between 1 to 6dB approximately and gives us the optimum operating range in terms of parameter relative T_{DROP} .

Let us compare quantitatively the system performance at three operating points one being at relative T_{DROP} level of 3dB that lies near the midpoint of the optimum operating range, second being at relative T_{DROP} level of 0dB that lies below the optimum operating range and third being at relative T_{DROP} level of 10dB that lies above the optimum operating range. From figures 4-20, 4-21, 4-22 and 4-23 we see that increasing relative T_{DROP} from 0 to 3dB reduces NAUs quite substantially by more than a factor of 2 (from 16.38 to 7.36) at comparatively small cost of increase in ASA by 25% (from 1.61 to 2.01). Because of this increase in ASA (thus diversity) we have a small gain in terms of small reduction in required TxPDL (decrease of 0.225dB or 5.05% approx.) and TxPUL (decrease of 0.24dB or 5.4% approx.). On the other hand increasing the relative T_{DROP} from 3 to 10dB decreases NAUs by 23.5% (from 7.36 to 5.63) but at a cost of increase in ASA by 21.4% (from 2.01 to 2.44). Because of this small increase in ASA we have very small reduction in required TxPDL (decrease of 0.088dB or 2.0% approx.) and TxPUL (decrease of 0.082dB or 1.9% approx.).

Thus we notice that the parameter relative T_{DROP} affects the system performance to a large extent in terms of NAUs and ASA and to a very small extent in terms of transmit

powers TxPDL and TxPUL. Another point we noticed, while comparing system performance at three different operating points, is that the operating points in the lower side of the optimum operating range have more pronounced adverse effect on the system performance than that of the points in the higher side of the optimum operating range. This implies that network signalling load (NAUs) is very sensitive to lower values of parameter relative T_{DROP} and can be reduced by the selecting a adequately large relative T_{DROP} value. Thus to achieve the optimum system performance the system must be operated at some relative T_{DROP} level in the optimum operating range of 1 to 6dB in the given operational environment. The optimum operating range might be slightly different for different terrains and might depend if the system is operating in urban or suburban environment. From the above discussion of results we have seen that parameter relative T_{DROP} reduces the NAUs thus signalling load on the CDMA network. We have also seen that we might not gain substantially, compared to the gains we realized in case of parameter T_{ADD} , in terms of link quality or reduced required Tx-powers on both Up and Down links. Thus the best way to optimize the performance of the system is to first find an optimum operating point in terms of T_{ADD} from its trade-off curves (figure 4-14 or figure 4-15) which will give us a system operating at optimum link quality or optimum transmit power levels. Later the system performance in terms of resource allocation indicators NAUs and ASA can be optimized by obtaining an optimum operating point in terms of relative T_{DROP} from its trade-off curve (figure 4-24).

Figure 4-16: Effect of T_{DROP} on Probability of inclusion of BS1 in the AS (Prob1)

Figure 4-17: Effect of T_{DROP} on Probability of inclusion of BS2 in the AS (Prob2)

Figure 4-18: Effect of T_{DROP} on Probability of inclusion of 3rd BS in the Active Set (Prob3)

Figure 4-19: Effect of T_{DROP} on Fraction of distance MS in SHO (F_{SHO}), in 2-Cell SHO (F_{2SHO}) and in 3-Cell SHO (F_{3SHO})

Figure 4-20: Effect of T_{DROP} on Average Size of Active Set (ASA)

Figure 4-21: Effect of T_{DROP} on Mean Number of Active Set Updates (NAUs)

Figure 4-22: Effect of T_{DROP} on Required Down Link Transmit Power per Active Channel (TxPDL)

Figure 4-23: Effect of T_{DROP} on Required Up Link Transmit Power (TxPUL)

Figure 4-24: Trade-off curve between Average Size of the Active Set (ASA) and Number of Active Set Updates (NAUs)

4.3.3 Effect of Drop Timer, t_{DROP}

Parameter t_{DROP} is the third and the last of the SHO parameters we study. Again in Scenario I, keeping T_{ADD} and relative T_{DROP} fixed at -15dB and 2dB respectively, as we increase t_{DROP} from 0 to 40 samples we observe that it has the same effect on system performance as we saw in the previous section by increasing the relative T_{DROP} . We already know that the received C/I ratios of candidate BSs due to shadowing fluctuate around their respective mean C/I ratios. Because of these fluctuations either a candidate BS is added to the AS in case its C/I ratio exceeds the threshold T_{ADD} provided the AS is not full or a member is dropped from the AS in case its C/I ratio stays below the absolute T_{DROP} for an interval at least t_{DROP} samples long or a member is replaced by a better non-member BS in case the AS is full. This adding, dropping and replacing of the BSs not only contribute to the signalling load in terms of NAUs but also affect the probabilities of inclusion of different BSs into the AS. Now increasing t_{DROP} allows more time for low fluctuating C/I ratios of member BSs to recover and remain above absolute T_{DROP} and meet the criterion that keeps them as member of the AS (or prevents them from being dropped from the AS). Later in the section we will see that this not only improves the probabilities of inclusion of different BSs into the AS which in turn increase the diversity (in terms of higher ASA) but also might reduce the NAUs. In figures 4-26 & 4-27 we notice that the Probabilities of inclusion of BS2 & 3rd BS in the AS, i.e., Prob2 and Prob3 respectively, increase very slightly with increase in the t_{DROP} in the first half of the travel

(please note very slight left shifts in the rising left sides of the curves of both figures). The reason being that as the MS is moving towards boundary (away from BS1 and closer to BS2 and 3rd BS) the C/I ratios of BS2, BS3 and BS4 received at MS improve thus it is very unlikely that BS2 and 3rd BS (BS3 or BS4) will be dropped within a very short period after being added to AS for the first time. On the other hand we notice the Probabilities of inclusion of BS1 and 3rd BS in the AS, namely Prob1 and Prob3, increase substantially with the increase in the t_{DROP} in the second half of the travel as shown in figures 4-25 & 4-27 (please note right shifts in the falling right sides of the curves in both figures). The reason being that though the C/I ratios of BS1, BS3 and BS4 received at the MS are decaying as MS moves away from the boundary yet the SHO algorithm because of increasing t_{DROP} interval tries to retain BS1 and 3rd BS (BS3 or BS4) in the AS for longer periods than before. The larger the t_{DROP} the longer the SHO algorithm tries to retain BS1 and 3rd BS in the AS before dropping one or both of them from the AS. The combined effect of increase in these Probabilities of inclusion of different BSs is that the Fraction of the total travel distance in which MS is in Soft Handoff (F_{SHO}) and that in which MS is in 3-Cell Soft Handoff (F_{3SHO}) increase whereas the Fraction of the total travel distance in which MS is in 2-Cell Soft Handoff (F_{2SHO}) decreases as shown in figure 4-28. The combined effect of changes in F_{3SHO} and F_{2SHO} is an increase in the Average Size of Active Set (ASA) as shown in figure 4-29. We notice that with the increase in t_{DROP} period the ASA increases almost linearly in the beginning (upto a

t_{DROP} value of 20 approximately) but the marginal increase of ASA starts decreasing with any further increase in t_{DROP} . This increase in ASA implies higher diversity which in turn helps in lowering the required TxPDL and TxPUL by means of Down and Up Link Power Control algorithms. The required TxPDL and TxPUL for different Drop Timer values have been shown in figures 4-31 and 4-32. Again like the case in relative T_{DROP} the gains in terms of reduced TxPDL and TxPUL are quite small compared to those we saw in the case T_{ADD} in the section 4.3.1. In figures 4-31 and 4-32 we also notice that the marginal reduction in TxPDL and TxPUL is comparatively high in the beginning while t_{DROP} is increased from 0 to 11 samples but this marginal reduction in transmit powers starts decreasing if t_{DROP} is reduced any further and becomes almost negligible for t_{DROP} values of 25 and above.

Figure 4-30 shows the effect of t_{DROP} on NAUs. It is quite clear from the figure that the larger the t_{DROP} lower will be the NAUs and the reason for that is as follows. From our discussion in section 4.3.1 we already know that BS3 and BS4 are the ones that affect the NAUs largely because of their C/I ratios hovering around the thresholds (please see figure 4-4). This makes SHO algorithm to drop from or add to the AS the contending BSs, BS3 and BS4, few times before one of them has been either added to or dropped from the AS permanently or for a comparatively long period. This implies that increasing the timer value t_{DROP} allows more time to the low fluctuating C/I ratios to recover and remain above the threshold absolute T_{DROP} , and meet the criterion that keeps them being

included in the AS (or prevents them from being dropped from the AS). Thus as the value of timer t_{DROP} is increased the SHO algorithm has the tendency to retain the member BSs in the AS for relatively longer period than was the case with lower t_{DROP} . This implies that there is reduction in the frequency of dropping/adding of BSs from/to the AS as the t_{DROP} is increased. This reduces unnecessary NAUs which implies reduced signalling load on the Network.

As was the case with relative T_{DROP} we have seen that by increasing the t_{DROP} we not only gain in terms of reduced NAUs but also slightly in terms of very small reduction in transmit powers TxPDL and TxPUL. But looking at figures 4-30, 4-31 and 4-32 carefully we can see that increasing the t_{DROP} won't keep on reducing the NAUs, TxPDL and TxPUL for ever. We have also noticed in figure 4-29 that increasing t_{DROP} also increases the ASA which as we already know is an expense for the system in terms of more than one channel being used for longer periods to carry a single call. Thus we need to find an optimum operating range for the drop timer t_{DROP} where the system is operating at optimal signalling load in terms of NAUs and using optimal resources in terms of ASA. The optimum operating range is determined by the knee of the trade-off curve between NAUs and ASA as shown in figure 4-33. The knee of this trade-off curve spans between 2 to 20 samples approximately and gives us the optimum operating range for the parameter t_{DROP} .

Let us now compare quantitatively the system performance at three operating points one

being at t_{DROP} of 14 that lies near the midpoint of the optimum operating range, second being at t_{DROP} of 0 that lies below the optimum operating range and third being at t_{DROP} of 30 that lies above the optimum operating range. From figures 4-29, 4-30, 4-31 and 4-32 we see that increasing drop timer t_{DROP} from 0 to 14 reduces NAUs quite substantially by more than a factor of 2 (from 14.17 to 6.97) at comparatively small cost of increase in ASA by 21.2% (from 1.65 to 2.0). Because of this increase in ASA (thus diversity) we have a small gain in terms of small reduction in required TxPDL (decrease of 0.185dB or 4.35% approx.) and TxPUL (decrease of 0.191dB or 4.5% approx.). On the other hand increasing the drop timer t_{DROP} from 14 to 30 decreases NAUs by 11.3% (from 6.97 to 6.18) but at a cost of increase in ASA by 12% (from 2.0 to 2.24). Because of this small increase in ASA we have very small reduction in required TxPDL (decrease of 0.05dB or 1.16% approx.) and TxPUL (decrease of 0.044dB or 1.0% approx.). Again like relative T_{DROP} we notice that t_{DROP} affects the system performance to a large extent in terms of NAUs and ASA and to a very small extent in terms of transmit powers TxPDL and TxPUL. Another point we noticed while comparing system performance at three different operating points is that the operating points in the lower part of the optimum operating range have more pronounced adverse effect on the system performance than the points in the higher part of the optimum operating range have. Thus as was the case with relative T_{DROP} the network signalling load (NAUs) is quite sensitive to parameter drop timer t_{DROP} and can be reduced by selecting an adequately large drop timer t_{DROP} value.

To achieve the optimum system performance the system must be operated at some t_{DROP} value that lies in the optimum operating range of 2 to 20 samples for the given operational environment. The optimum operating range might be slightly different for different terrains and might depend if the system is operating in urban or suburban environment. From the above discussed results we have seen that parameter t_{DROP} reduces the signalling load on the CDMA network by reducing the NAUs. We have also seen that we might not gain substantially, compared to the gains we realized in case of parameter T_{ADD} , in terms of link quality or reduced required Tx-powers on both Up and Down links. Thus best way to optimize the performance of the system is to first find an optimum operating point in terms of T_{ADD} from its trade-off curves (figure 4-14 or figure 4-15) which will give us a system operating at optimum link quality or optimum transmit power levels. Later the system performance in terms of NAUs can be optimized by obtaining optimum operating points in terms of relative T_{DROP} and drop timer t_{DROP} from their respective trade-off curves (figures 4-24 and 4-33 respectively).

Figure 4-25: Effect of t_{DROP} on Probability of inclusion of BS1 in the AS (Prob1) Figure 4-26: Effect of t_{DROP} on Probability of inclusion of BS2 in the AS (Prob2)

Figure 4-27: Effect of t_{DROP} on Probability of inclusion of 3rd BS in the AS (Prob3)

Figure 4-28: Effect of t_{DROP} on Fraction of distance MS in SHO (F_{SHO}), in 2-Cell SHO Distance (F_{2SHO}) and in 3-Cell SHO Distance (F_{3SHO})

Figure 4-29: Effect of t_{DROP} on Average Size of Active Set (ASA)

Figure 4-30: Effect of t_{DROP} on Mean Number of Active Set Updates (NAUs)

Figure 4-31: Effect of t_{DROP} on Required Down Link Transmit Power per Active Channel (TxPDL)

Figure 4-32: Effect of t_{DROP} on Required Up Link Transmit Power (TxPUL)

Figure 4-33: Trade-off between the Average Size of the Active Set (ASA) and Number of Active Set Updates (NAUs)

4.4 Effect of Averaging Interval, d_{avg} , on SHO Performance

The d_{avg} , is the length of averaging interval in *meters*, which is used to average out some of the effect of long-term fading or shadowing. The d_{avg} is the distance over which the *average received signals* from different BSs are averaged to obtain C/I ratios of candidate BSs which later are used by the SHO algorithm to update the AS of the mobile. The reason why we mentioned above *average received signals* and not just the *received signals* is that the signals received from different BSs have already been sampled and averaged over an interval 400 msec long in order to average out short-term fading. These average received signals are further averaged over an interval d_{avg} meters long in order to average out some of the long-term fading effects. We'll see shortly that like SHO parameters d_{avg} also affects the performance of a system quite significantly. Increasing d_{avg} means more and more past samples are taken into consideration while averaging the received signal. Though adequately long d_{avg} interval removes long-term shadowing more effectively, yet if d_{avg} interval chosen is too long then pathloss starts affecting the estimates of received signal strengths of different BSs which in turn affects the received C/I ratios. Figures 4-34, 4-36 and 4-38 show the effect of increasing d_{avg} on received average C/I ratios of BS1, BS2 and BS3 that have been averaged over 120 iterations.

Figure 4-34: Effect of d_{avg} on received average C/I ratios for BS1

Figure 4-35: Closer look at the received average C/I ratios for BS1 around T_{DROP}

Figure 4-36: Effect of d_{avg} on received average C/I ratios for BS2

Figure 4-37: Closer look at received average C/I ratios for BS2 around T_{ADD}

Figure 4-38: Effect of d_{avg} on received average C/I ratios for BS3/BS4 Figure 4-39: Closer look at received average C/I ratios for BS3/BS4 around T_{ADD}

Figure 4-40: Closer look at received average C/I ratios for BS3/BS4 around T_{DROP}

Let us zoom onto these figures around the two thresholds, i.e., T_{ADD} and absolute T_{DROP} . Zooming onto figures 4-34 and 4-38 around threshold absolute T_{DROP} we obtain figures 4-35 and 4-40 that provide us with the microscopic views of the effect of parameter d_{avg} on the received average C/I ratios of BS1 and BS3 respectively in the second half of the travel. In both figures 4-35 and 4-40 we notice that increase in d_{avg} raises the estimates of received average C/I ratios for BS1 and 3rd BS in the second half of travel, consequently the SHO algorithm tries to retain them in the AS for periods longer than before. As a result of which we see a slight increase in Probabilities of inclusion of BS1 and 3rd BS in the AS (please note a very slight right shift in the falling right sides of the curves of figures 4-41 and 4-43). Similarly zooming onto figures 4-36 and 4-38 around threshold T_{ADD} we obtain figures 4-37 and 4-39 that provide us with the microscopic views of the effect of parameter d_{avg} on the received average C/I ratios of BS2 and BS3 respectively in the first half of the travel. In both figures 4-37 and 4-39 we notice that increase in d_{avg} lowers the estimates of received C/I ratios for BS1 and 3rd BS near the beginning of travel, consequently there is more and more delay in adding them to the AS. As a result of which we see substantial decrease in the Probabilities of inclusion of BS2 and 3rd BS in the AS (please note a substantial right shift in the rising left sides of the curves of figures 4-42 and 4-43). It is quite clear from figures 4-41, 4-42 and 4-43 that effect of increasing d_{avg} is more pronounced on Probability of inclusion of 3rd BS (Prob3) than that on probabilities Prob1 and Prob2. The reason being that since C/I ratios

of BS3 and BS4 hover around the SHO thresholds thus lower estimates of their received C/I ratios not only delay the addition of 3rd BS to the AS but also reduce their chances of being included in the AS which in turn reduces the probability Prob3. Unlike Prob3 the probabilities Prob1 and Prob2 are not affected (reduced) much by this later effect of d_{avg} because despite of the underestimation of C/I ratios of BS1 and BS2 they are still quite high relative to the SHO thresholds. Another thing we notice that probability Prob2 (figure 4-42) is affected more than probability Prob1 (figure 4-43). The reason being that in case of BS2 its inclusion into the AS is being delayed because of under estimation of its C/I ratios as d_{avg} is increased. On the other hand in case of BS1 some of the gain we get, because of over estimation of its C/I ratios, is offset by its decreasing C/I ratios as MS is moving away from the BS1. Now the combined effect of the changes in these probabilities of inclusion of different BSs is that the Fraction of total travel distance the MS is in Soft Handoff (F_{SHO}) and that the MS is in 3-Cell Soft Handoff (F_{3SHO}) decrease where as the Fraction of total travel distance the MS is in 2-Cell Soft Handoff (F_{2SHO}) increases as shown in figure 4-44. This results into a net decrease in the ASA as shown in figure 4-45. Decrease in ASA means that we have smaller spatial diversity for smaller periods which in turn reduces the quality of signal in terms of higher BERs on both Down and Up Links. This reduced quality of received signal gets translated into higher required TxPDL and TxPUL by means of Down and Up Link Power Control algorithms. The effect of increasing d_{avg} on required TxPDL and TxPUL has been shown in figures 4-47 and 4-48.

Now looking at effect on NAUs which is a signalling overhead on the network we see in figure 4-46 that the larger the d_{avg} interval the lower the NAUs are. The reason being that increasing d_{avg} smoothens out fluctuations in received C/Is because of long-term shadowing. This helps in reducing the frequency of AS updates thus this averaging helps in reducing the unnecessary NAUs caused by shadowing which in turn reduces the signalling load on the network. This implies that we are gaining in terms of lower NAUs at the cost of higher required TxPDL and TxPUL. Thus a trade-off has to be made between the NAUs and TxPDL or between NAUs and TxPUL. Figures 4-49 and 4-50 show the trade-off curves for parameter d_{avg} . The optimum operating range lies at the knees of the trade-off curves which corresponds to approximate d_{avg} range of 20 to 60 meters.

Let us compare quantitatively the system performance at three operating points with one having the d_{avg} averaging length of 40 meters that lies right in the middle of the optimum operating range, second having the d_{avg} averaging length of 80 meters that lies above the optimum operating range and third having the d_{avg} averaging length of 10 meters that lies below the optimum operating range. By increasing d_{avg} interval from 10 to 40 meters we can reduce the NAUs by 30.6% (from 12.4 to 8.6) at a very small cost of increasing the transmit powers TxPDL by 0.07dB (1.62%) and TxPUL by 0.065dB (1.51%). On the other hand if d_{avg} interval is increased to as high as 80 meters though there is a reduction in NAUs by 26.5% (8.6 to 6.8) but at a relatively high cost of increasing the transmit powers TxPDL by 0.62dB (15.34%) and TxPUL by 0.65dB (16.14%). Again like SHO

parameters relative T_{DROP} and drop timer t_{DROP} the parameter d_{avg} affects the system performance to a large extent in terms of NAUs and to some extent in terms of transmit powers TxPDL and TxPUL. Thus as was the case with relative T_{DROP} and drop timer t_{DROP} the network signalling load (NAUs) is also quite sensitive to parameter d_{avg} and proper choice of d_{avg} can substantially reduce the signalling load of the network without affecting much the Tx-powers on both Up and Down links.

Thus to achieve the optimum system performance the system must be operated at some d_{avg} length that lies in the optimum operating range of 20 to 60 meters for given operational environment. From the above discussion we have seen that parameter d_{avg} reduces the signalling load on the CDMA network by reducing the NAUs at the cost of a very small increase in transmit powers. Thus best way to optimize the performance of the system is to first find an optimum operating point in terms of T_{ADD} from its trade-off curves (figure 4-14 or figure 4-15) which will give us a system operating at optimum link quality or optimum transmit power levels and at some associated cost in terms of network signalling load, NAUs. Now by selecting optimally the parameters relative T_{DROP} and drop timer t_{DROP} by means of their respective trade-off curves (figures 4-24 & 4-33) we not only can reduce this cost optimally but also gain in terms of a small reduction in TxPDL and TxPUL. Further by the optimal selection of parameter d_{avg} by means of its trade-off curves (figures 4-49 & 4-50) we further reduce the network signalling cost at a very small penalty in terms of slightly increased transmit powers TxPDL and TxPUL.

Figure 4-41: Effect of d_{avg} on Probability of inclusion of BS1 in the AS (Prob1)

Figure 4-42: Effect of d_{avg} on Probability of inclusion of BS2 in the AS (Prob2)

Figure 4-43: Effect of d_{avg} on Probability of inclusion of 3rd BS in the AS (Prob3)

Figure 4-44: Effect of d_{avg} on Fraction of distance MS is in SHO (F_{SHO}), in 2-Cell SHO Distance (F_{2SHO}) and in 3-Cell SHO Distance (F_{3SHO})

Figure 4-45: Effect of d_{avg} on Average Size of Active Set (ASA)

Figure 4-46: Effect of d_{avg} on Mean Number of Active Set Updates (NAUs)

Figure 4-47: Effect of d_{avg} on Required Down Link Transmit Power per Active Channel (TxPDL)

Figure 4-48: Effect of d_{avg} on Required Up Link Transmit Power (TxPUL)

Figure 4-49: Trade-off between Mean Num Updates (NAUs) and Mean Down Link Transmit power (TxPDL)

Figure 4-50: Trade-off between Mean Num Updates (NAUs) and Mean Up Link Transmit power (TxPUL)

4.5 Identifying Parameter affecting Performance the most

In sections 4.3 and 4.4 by finding the optimum operating ranges for SHO parameters and the averaging parameter we accomplished our first objective of the thesis. In the current section again looking at these results we will try to identify the parameter that affects the performance of the system the most. We know that the capacity thus the performance of the system is affected the most by the amount of interference caused by other users to the desired user. The amount of interference in turn depends upon the average powers at which different BSs and users are transmitting. Thus the parameter that affects the average transmit powers of the system affects the performance of the system the most. Let us look at figures 4-12, 4-22, 4-31 and 4-47 to compare the effect of four parameters on Down Link transmit powers (TxPDL). We observe from the above figures that the variation in TxPDL due to variation in parameter T_{ADD} is 4dB approximately whereas that due to T_{DROP} and t_{DROP} is 0.2-0.25dB only, and that due to d_{avg} is 0.6-0.7dB only. Same is true for Up Link transmit powers (TxPUL) as we see from figures 4-13, 4-23, 4-32 and 4-48. This implies that T_{ADD} is the parameter that influences the performance of the system the most. In the next chapter extending our simulation scenario to ten paths that cover all possible RSS scenarios in a cell we will study further the effect of parameter T_{ADD} on the performance of the system. Later these results will be used to estimate the effect of SHO on the capacity of CDMA system.

5

Impact of SHO on Capacity

From sections 4.3 and 4.4 of chapter 4 we have seen that of all the parameters we studied in Scenario I parameter T_{ADD} affects the system performance the most. It not only affects the link quality of the system in terms of quite a large variations in required transmit powers TxPDL and TxPUL but also the network signalling load in terms of large variations in NAUs. As T_{ADD} is lowered the required transmit powers TxPDL and TxPUL get lowered because of increased available diversity. This in turn reduces interference not only to other users of the same cell but also to those of neighboring cells which improves the average E_b/N_T of the system. This, as we will see in this chapter, enables the system to support additional users thus increasing the system capacity. The other parameters relative T_{DROP} , t_{DROP} and d_{avg} do not affect the link quality (thus capacity) as much but their effect in tuning the network signalling load is quite substantial. Since T_{ADD} is the parameter that affects the system capacity the most let us extend our study of the effects of parameter T_{ADD} on system performance in Scenario II. With Scenario II we will be able to study the performance of soft handoff in almost all possible

received signal strength representative scenarios in the cell. From Scenario II results we can compute average results that are valid along one side of the hexagonal cell. Later because of symmetry associated with hexagonal cells we can use these results for the whole cell and in fact for the whole network of hexagonal cells to estimate the capacity of the CDMA system.

5.1 Soft handoff Performance in Scenario II

Scenario II has been described in section 4.2.2 and shown in figure 5-1. In Scenario II a mobile's travels are observed along 10 different routes. These travel routes are parallel to the one in Scenario I with same starting and stopping X-coordinates but are conveniently located at 51-52 meters from the adjacent routes along Y-axis. This gives us 10 routes as shown in figure 5-1 that are parallel to X-axis with their Y-coordinates fixed at 0, 52, 104, 156, 207, 258, 309, 360, 411 and 462 respectively. For the sake of convenience we'll denote these routes by Y0, Y52, Y104, Y156, Y207, Y258, Y309, Y360, Y411 and Y462 respectively. The route Y0 is the one that is identical to the mobile path of Scenario I and route Y462 is the mobile path that passes through the weakest point of the cell which is also the common corner point of the 3 neighboring hexagonal cells. Thus these 10 routes are representative of all possible received signal strength scenarios along one side of the hexagonal cell.

Figure 5-1: Zoomed top view of the CDMA Network showing the mobile paths in Scenarios II

In Scenario II, keeping all other SHO parameters and averaging interval constant, we will vary parameter T_{ADD} from -7 to -22dB and observe its effect on the performance of the system along each of these 10 travel routes. The system performance is being monitored by means of the subset of the performance indicators used in Scenario I. Again the required Transmit powers TxPUL and TxPDL have been used as link quality indicators. Whereas ASA, NAUs and F_{SHO} have been used as resource allocation indicators. Now as we move from route Y0 towards Y462 we move away from BSs BS1, BS2 and BS4 whereas we move closer to BS3. As a result of that the average signal strengths received at the mobile from BS1, BS2 and BS4 gradually get weaker whereas that from BS3 strengthens. Which results into the received Pilot strength (C/I_s ratios or E_c/I_T) of BSs BS1, BS2 and BS4 decreasing gradually whereas the received Pilot strength of BS3 increasing gradually. After performing simulations similar to Scenario I the following results for Scenario II were obtained.

Figure 5-4 shows that as the Y-coordinate of mobile's travel route is increased the network signalling load in terms of NAUs decreases very fast which is more visible at lower T_{ADD} levels. The reason being that as we move from route Y0 towards route Y462 the pilot strength of BS4 starts declining and beyond the route Y156 the BS4 has become so weak that it can't contest anymore with BS3 for 3rd spot in the AS. This results into smaller NAUs thus smaller network signalling load. In figures 5-3 and 5-2 we observe that as we move from route Y0 towards Y462 there is a gradual increase in Average Size of

AS (ASA) and Fraction of total travel distance mobile is in Soft Handoff (F_{SHO}). The reason being that as we move from route Y0 towards Y462 we move closer to BS3 that enables the gradually strengthening BS3 be a member of AS for increasingly longer travel periods. This not only increases F_{SHO} but ASA too. Now because of increasing ASA we have larger spacial diversity for longer periods which in turn improves the link quality. The improvement in link quality gets translated into reduced required Transmit power on down link as shown by slight downward shift in the required Tx-power curves in figure 5-8. The performance improvement on Up link is not obvious from figure 5-6. The reason being that IS-95 defined Up link power control algorithm is quite different from the Down link power control algorithm (please refer to section 3.6 for details). In Up link power control algorithm because of Open Loop power control mobile increases or decreases its transmit power by the amount the total received power decreases or increases. Now as we move from path Y0 to Y462 we move away from two stronger BSs BS1 and BS2. Because of that total power received at the mobile on each route decreases gradually which has been shown in figure 5-5 in terms of change in average received power for each travel route relative to that of travel route Y0. Figure 5-6 shows Up link performance in terms of actual required MS transmit powers ($TxPUL$) which is the resultant of two opposing phenomena. First being an increase in the required Up link Tx-Power ($TxPUL$) because of Open Loop power control algorithm. The second being the reduction in required $TxPUL$ due to increased available diversity. Figure 5-5 in fact gives an estimate of the factor for each travel route by which the average transmit power of the mobile has been changed on

that route by the Up link Open Loop Power control algorithm. To look at the actual performance of SHO algorithm on Up link we have to take out the effect of Open Loop power control algorithm by shifting downwards the curves of figure 5-6 by the values shown in figure 5-5 for each travel route. That results into figure 5-7 which reflects the actual performance of SHO on up link and is quite similar to the down link performance as shown in figure 5-8.

To understand the behavior of TxPDL and TxPUL curves in figures 5-7 and 5-8 we'll have to look at them in conjunction with figure 5-3 for ASA curves. Let us first try to understand the behavior of figure 5-3 alone. It is quite clear from figure 5-1 that as we move from a travel route with lower Y-coordinate (say Y0) to that with higher Y-coordinate (say Y156) we in fact are moving closer to BS3 which implies that the Pilot strength of BS3 is getting stronger. This implies that as we move towards travel routes with Y-coordinates of higher values the fraction of total travel distance/period for which the 3rd BS (i.e., BS3) gets included in the AS grows gradually. This implies there must be a gradual increase or upward shift in the Average Size of AS (ASA) curves as we move from travel route with lower Y-coordinates to those with higher Y-coordinates. Now looking at figure 5-3 carefully we certainly see that kind of behavior for T_{ADD} levels lower than -11dB. The ASA curves coincide for travel routes Y0, Y52 and Y104 in the T_{ADD} range of -7 to -11dB; for routes Y0 to Y156 in the T_{ADD} range of -7 to -10dB; for routes Y0 to Y207 in the T_{ADD} range of -7 to -9dB; and for routes Y0 to Y258 at T_{ADD} level of -7dB. The reason being that even though by moving from route Y0 towards routes

with higher Y-coordinates the 3rd BS is becoming stronger yet not strong enough to be included in the AS for above mentioned travel routes in the above specified ranges of threshold T_{ADD} . Another reason for this behavior is that at high T_{ADD} levels of -7 to -9dB even 2nd BS is member of AS only for very small fraction of travel. Which is indicated by ASA curve values of around 1 to 1.2 for travel route Y0 to Y360. The travel routes ranging from Y360 to Y462 are so close to BS3 that it is strong enough to be included in the AS for substantial part of the travel over these routes for most of the range of T_{ADD} threshold.

Let us now look at figures 5-7 and 5-8 together with ASA curves of figure 5-3 to understand the behavior of TxPDL and TxPUL curves for different travel routes. In figure 5-3 for T_{ADD} levels lower than -12dB we noticed that as we move from travel route with lower Y-coordinates to those with higher Y-coordinates there is an increase in ASA which implies that there is an increase in the amount of available diversity. This in turn improves the quality of both Down and Up links and thus lowers the required transmit powers TxPDL and TxPUL as seen in figures 5-7 and 5-8. Again looking at figures 5-7 and 5-8 we notice that the behavior of TxPDL and TxPUL curves of different travel routes is not as expected for T_{ADD} levels greater than -12dB, i.e., for this T_{ADD} range the required transmit powers TxPDL and TxPUL do not decrease as we move from lower travel route to higher travel route. We notice a number of crossover points among the TxPDL and TxPUL curves of figures 5-7 and 5-8. Again we can understand these crossover points and the fore mentioned behavior by looking at ASA curves of figure 5-3. In figure 5-3 we

notice that ASA curves of travel routes Y0, Y52 and Y104 coincide for T_{ADD} levels above -12dB. This implies that as we move from route Y0 to Y52 or Y104 or from Y52 to Y104 there is no gain in terms of diversity because the T_{ADD} levels are too high for 3rd BS to be included in the AS. Not only that there is no increase in diversity but also we are moving away from BS1 and BS2 as we move from the travel route Y0 towards Y52 and Y104. Because of the weakening of BSs BS1 and BS2 and no additional diversity the link quality worsens making required transmit powers TxPDL and TxPUL increase as we move from Y0 to Y52 or Y104 or from Y52 to Y104 for T_{ADD} levels above -12dB. This reversal of behavior for routes Y52 and Y104, relative to the behavior of route Y0, occurs somewhere between the T_{ADD} range of -11dB to -12dB which we'll call as crossover point. For similar reasons we observe a crossover point around -10.6dB for travel routes Y156 and Y207, and that around -9.5dB for travel route Y258. The transmit powers TxPDL and TxPUL increase as we move from lower travel route to higher travel route while T_{ADD} levels are above the respective crossover points. The reason being that above crossover points 3rd BS doesn't contribute to the performance at all. This implies that the link performance for any travel route above the crossover point is fully dependent upon BS1 and BS2. Now as we move from lower travel route towards higher travel route these two BSs grow weaker thus worsening the link performance gradually. In figure 5-3 we notice that for travel routes from Y360 to Y462 the ASA curves are always increasing over the whole T_{ADD} range as we move from lower to higher route. Thus performance of both links is always improving as we move from route Y360 to higher travel route Y462

though the amount of improvement is not the same as expected because of the weakening of BSs BS1 and BS2. Since route Y462 compared to route Y411, and route Y411 compared to route Y360 are closer to BS3 thus the down link performances are better for Y462 and Y411 compared to those of Y411 and Y360 respectively.

In Scenario II by observing the SHO performance on different possible travel routes with their Y-coordinates ranging from $Y=0$ (Y0) to $Y=462$ (Y462) we noticed that travel route Y0, which is same as the travel route of Scenario I, is indeed the most critical travel route because of the high network signalling load (NAUs) associated with it. Thus by choosing our SHO parameters, i.e., T_{ADD} , T_{DROP} and t_{DROP} , and averaging parameter d_{avg} for certain optimal system performance on travel route Y0 we have in fact ensured its optimal performance on all other possible travel routes or in fact anywhere in the cell. Thus the optimum operating ranges for SHO parameters and d_{avg} , we found in sections 4.3 and 4.4 for desired optimal system performance in terms of required Tx-powers and signalling load NAUs are perfectly valid all over the cell.

The purpose of studying SHO performance in Scenario II was not only to look at the performance of SHO over the whole range of different possible routes and to check the validity of the different optimal operating ranges we found in previous chapter over different possible scenarios in the cell, but also to have enough data to study the effect of SHO on the capacity of CDMA system which we will see in more detail in the next few sections.

Figure 5-2: Effect of T_{ADD} on Fraction of distance MS in Soft Handoff (F_{SHO}) for all ten travel routes of Scenario II

Figure 5-3: Effect of T_{ADD} on Average size of Active Set (ASA) for all ten travel routes of Scenario II

Figure 5-4: Effect of T_{ADD} on Mean Number of Active Set Updates (NAUs) for all ten travel routes of Scenario II

Figure 5-5: Change in the Average Received power at mobile with increase in Y-Coordinate (from 0 to 462 meters) relative to that received at Y-Coordinate = 0

Figure 5-6: Effect of T_{ADD} on Mean Up Link Tx-power (TxPUL) (including the effect of Up link Open Loop Power Control) for all ten travel routes of Scenario II

Figure 5-7: Effect of T_{ADD} on Mean Up Link Tx-power (TxPUL) (excluding the effect of Up link Open Loop Power Control) for all ten travel routes of Scenario II

Figure 5-8: Effect of T_{ADD} on Mean Down Link Tx-power (TxPDL) for all ten travel routes of Scenario II

5.2 Estimating the Impact of SHO on CDMA Capacity

From the preceding chapter we observed that while a mobile is in Soft Handoff (SHO) the communication link, between the mobile and the set of BSs the MS is in Soft Handoff with, requires lower transmit powers to maintain an average link quality. Which implies that it now causes lower in-cell as well as other-cell interference than it would have caused had it not been in Soft Handoff thus requiring very high transmit powers in the regions close to the boundary. This reduction in interference enables CDMA BSs to support additional users in the same fixed sized cell. In this chapter by working with the basic capacity equation for CDMA we will try to estimate this gain in terms of increase in the number of supported users. We know that the capacity of CDMA is asymmetric on Up and Down links with Up link limiting it. There are two fundamental reasons why Up link has this performance limitation compared to Down link. First reason being that the Down link has a Pilot channel so the MS can use coherent detection thus increasing the probability of detecting the signal. Secondly, all the users in the same cell are using orthogonal (Walsh) codes which reduce interference between the users. On the other hand Walsh codes on the Up link do not remain orthogonal because the path delay between the users and the BS is a random variable thus the frames do not arrive at the BS at the same time. Walsh functions are orthogonal only when frames from all users are time aligned at the receiver. Thus users on Up link are not on orthogonal channels. Moreover since there is no Pilot channel on Up link thus BS can use noncoherent detection only which has lower probability of detection compared to that of coherent detection which in turn makes Up link slightly inferior to

Down link. Because of this reason only Up link is being considered to assess the effect of SHO on the capacity of CDMA. In section 5.2.1 first of all we will compute the average performance indicators from the results obtained in section 5.1 by averaging them over all ten travel routes and show that they in fact represent the performance of network. Later using these results and the basic capacity equation of CDMA we will quantify the gain in the capacity of a SHO based CDMA network.

5.2.1 Average SHO Performance Across the Cell

Now referring to figure 5-2 that shows the Fraction of travel distance or time the mobile was in SHO (F_{SHO}) for all the ten travel routes over the T_{ADD} range of -7 to -22dB. By taking the average of the F_{SHO} from figure 5-2 over all ten travel routes and plotting over the T_{ADD} range we get figure 5-11. The ten travel routes of Scenario II basically cover the region IA of the a cell as shown in figure 5-14. Figure 5-11 shows the average Fraction of travel distance or time the mobile was in SHO (F_{SHO}) over the region IA of figure 5-14. In the similar fashion the Average size of AS (ASA) from figure 5-3 and Average number of AS Updates (NAUs) from figure 5-4 can be averaged over all ten travel routes to get average ASA and average NAUs over the SHO region IA of figure 5-14. Figures 5-10 and 5-12 respectively show the computed average ASA and NAUs over region IA of cell for the given range of T_{ADD} . Now referring to figure 5-6 that shows the required TxPUL for SHO for all the ten travel routes over the T_{ADD} range of -7 to -22dB. By taking the average of the TxPULs shown in figure 5-6 over all the travel routes and plotting over the

T_{ADD} range we get figure 5-9 which shows the average required Up link Transmit-power (TxPUL) over the SHO region IA of figure 5-14.

Now because of symmetry of a hexagonal cell the results of figures 5-9 to 5-12, that are valid over region IA of the cell, are also valid over region IB of the cell as shown in figure 5-14. This implies that the results of figures 5-9 to 5-12 are valid along one side of the hexagonal cell. By further symmetry of a hexagonal cell the results are applicable to all six sides of each cell of the network. Now using average F_{SHO} for a any desired level of T_{ADD} from figure 5-11 if we draw a line parallel to each side of each cell of the network we get a snapshot of the network as shown in figure 5-15. Figure 5-15 shows the network with dark shaded SHO region along the boundary of each cell for a particular level of T_{ADD} . The area covered by this SHO region (shaded portion) of each cell (thus that of whole network) varies with the value of average F_{SHO} which in turn varies with the level of threshold T_{ADD} as we see from figure 5-11.

The estimate of the area covered by the SHO region (shaded portion) of a cell for a particular T_{ADD} level can be computed as shown in the following discussion. Later from this estimate of area of SHO region and under the assumption that the user density being uniformly distributed across the cell we can estimate the fraction of users that are in SHO. Now for a desired T_{ADD} level the value for average F_{SHO} can be read directly from figure 5-11. As we already know that this value of F_{SHO} is the fraction of the total travel distance a mobile remains in SHO. Now the total travel distance is 800 meters with 400 meters on either side of the boundary. The SHO region is quite symmetric on both sides of the

boundary thus without loss of generality we can assume F_{SHO} to be representing the SHO distance in terms of the fraction of the travel distance on each side of the boundary. This implies that F_{SHO} represents the fraction of a distance of 400 meters on each side of the boundary where mobile was in SHO. Let k represents the fraction of the distance K where mobile was in SHO where K represents the distance between the center and the border of the cell, i.e., a distance of 800 meters from center to the border as shown in figures 5-14 and 5-15. Since F_{SHO} is the fraction over the distance $K/2$, thus k which is a fraction over distance K can be obtained from F_{SHO} using the following expression

$$k = 0.5 \cdot F_{SHO} \quad (5.1)$$

Now let R be the radius of the whole hexagonal cell and r be the radius of non-SHO (unshaded hexagonal) portion of the cell as shown in figure 5-15. The radii R and r can be expressed in terms of K and k as below

$$R = \frac{2}{\sqrt{3}}K = 1.1547K \quad (5.2)$$

and

$$r = \frac{2}{\sqrt{3}}K(1-k) = 1.1547K(1-k) \quad (5.3)$$

Substituting for k from Equation (5.1) into (5.3) we get

$$r = 1.1547K(1 - (0.5 \cdot F_{SHO})) \quad (5.4)$$

We know that area of a hexagon can be obtained from the expression

$$Area_{Hex} = 2.5981 Radius^2 \quad (5.5)$$

Thus substituting equations (5.2) and (5.4) for *Radius* in equation (5.5) we get the expressions for the area of the cell itself, and the areas of the SHO and non-SHO portions of the cell as shown below.

$$Area_{Cell} = 2.5981R^2 = 3.4641K^2 \quad (5.6)$$

$$Area_{nonSHO} = 2.5981r^2 = 3.4641K^2(1 - (0.5 \cdot F_{SHO}))^2 \quad (5.7)$$

and

$$Area_{SHO} = Area_{Cell} - Area_{nonSHO} = 3.4641K^2\{1 - (1 - (0.5 \cdot F_{SHO}))^2\} \quad (5.8)$$

Assuming that the mobile users are uniformly distributed over the cell area then the ratio $Area_{SHO}/Area_{Cell}$ gives us the fraction of users in SHO (N_{SHO}). Thus from equations (5.6) and (5.8) the fraction of users in SHO (N_{SHO}) can be expressed in terms of F_{SHO} as below

$$N_{SHO} = 1 - (1 - (0.5 \cdot F_{SHO}))^2 \quad (5.9)$$

Since F_{SHO} is a function of T_{ADD} level thus N_{SHO} is also a function of T_{ADD} and can be rewritten as

$$N_{SHO}(x) = 1 - (1 - (0.5 \cdot F_{SHO}(x)))^2 \quad (5.10)$$

where $F_{SHO}(x)$ and $N_{SHO}(x)$ are the fraction of distance MS in SHO and fraction of users in SHO respectively for T_{ADD} level of x dB where $-22dB \leq x \leq -7dB$.

For instance for T_{ADD} levels of -7, -12 and -16dB we obtain the corresponding average

$F_{SHO}(x)$ values of 0.09, 0.43 and 0.72 from the curve of figure 5-11. Then from equation (5.10) for each value of $F_{SHO}(x)$ we can compute the fraction of users in SHO ($N_{SHO}(x)$) which comes out to be 0.088, 0.38 and 0.59 respectively. Thus we notice that as T_{ADD} level is lowered the number of users in SHO, $N_{SHO}(x)$, increase. The reason being that lowering T_{ADD} level increases $F_{SHO}(x)$ which means that lowering T_{ADD} brings in more cell area under the SHO region.

Again referring back to figure 5-9, that shows the average required TxPUL over the SHO region for the given T_{ADD} range of -7dB to -22dB, we observe the required Tx-power decreasing as the T_{ADD} level is lowered from -7dB to -22dB. From previous paragraph the value of N_{SHO} at T_{ADD} level of -7dB is 0.088 which implies only 8.8% of the users in SHO which means a very small portion of users are in SHO at this level of T_{ADD} . Thus fixing the TxPUL of T_{ADD} level -7dB as our base. We will be comparing our gains in TxPUL thus capacity relative to this base. For that purpose we need to take ratios of required TxPUL for each T_{ADD} level relative to that for T_{ADD} level of -7dB from figure 5-9. Doing that we obtain figure 5-13 that shows the average gain G (in dB) in the TxPUL at each T_{ADD} level relative to the TxPUL at T_{ADD} level of -7dB. Since results of figure 5-9 are valid over the SHO region of the whole cell thus the results of figure 5-13 must also be valid for the SHO region of whole hexagonal cell.

Later in section 5.2.2 by using equation (5.10) and results of figures 5-11 and 5-13 we'll quantitatively evaluate the effect of SHO on the capacity of CDMA network in terms of the number of users it can support.

Figure 5-9: Required Average Up Link Tx-power (TxPUL) averaged over all ten travel routes

Figure 5-10: Average Size of AS (ASA) averaged over all ten travel routes

Figure 5-11: Mean Fraction of distance MS in Soft Handoff (F_{SHO}) averaged over all ten travel routes

Figure 5-12: Mean Signalling Load per User (NAUs) averaged over all ten travel routes

Figure 5-13: Average gain G (dB) in required Up Link Tx-powers for each T_{ADD} level relative to that for T_{ADD} level of -7dB

Figure 5-14: Zoomed top view of the Network showing the region IA and IB

Figure 5-15: Top view of the CDMA Network with Soft Handoff region shown as shaded area

5.2.2 Impact of SHO on Network Performance

Before we look at the impact of SHO on the capacity of CDMA let us first look at the basic equation for capacity of CDMA. The basic equation for capacity of CDMA that has been derived in section A.1 of Appendix is given below

$$M = \left(\frac{1}{1+f} \right) \left(\frac{T_b/T_c}{E_b/N_T \alpha} + 1 \right) \quad (5.11)$$

where M is the maximum number of users that can be supported by a CDMA BS, and ratio T_b/T_c and the factor $\frac{1}{1+f}$ are the processing gain and reuse efficiency of the CDMA system. T_b is the bit interval for the user data and T_c the chip interval. E_b/N_T is the minimum required ratio between bit energy and the total interference density, and α is the voice activity factor.

The characteristic values of different parameters of equation (5.11) for IS-95 based system are processing gain $T_b/T_c = 128$, required $E_b/N_T = 7.0dB = 5.012$, voice activity factor $\alpha = 0.5$ and other-cell Interference factor $f = 0.5$. Substituting these values in equation (5.11) we get $M = 35$ as the maximum number of supported users. Considering a loading factor¹ of $\mu = 0.8$ the maximum number of users that can be supported without overloading the BS is obtained as $M \times \mu = 35 \times 0.8 = 28$.

Now in equation (5.11) we notice that it doesn't include any factor that represents the impact of Soft handoff on the capacity of CDMA. In the rest of the chapter we'll modify

1. For discussion on loading factor, μ , please refer to section A.2 of Appendix.

the basic capacity equation, i.e. equation (5.11), to reflect the impact of SHO on CDMA capacity. Later using the new equation we'll estimate the impact of SHO on the capacity of CDMA system. From figure 5-11 that shows the fraction of distance MS is in SHO ($F_{SHO(x)}$) we notice that at T_{ADD} level of -7dB (or for $x = -7dB$) the $F_{SHO(x)}$ is only 0.09. This implies that the distance or time for which MS is in SHO is very small (only 9%) at T_{ADD} level of -7dB. This implies that at T_{ADD} level of -7dB there is a very small impact of SHO on the capacity of system. Thus without loss of generality we can assume that equation (5.11) provides us with the capacity of the system at T_{ADD} level of -7dB. Now substituting values of average $F_{SHO(x)}$ as shown in figure 5-11 into equation (5.10) we can estimate the fraction of users in SHO ($N_{SHO(x)}$) at each level of T_{ADD} . Later using gains $G(x)$ (dB) in TxPUL at each T_{ADD} level of x relative to TxPUL at T_{ADD} level of -7dB, as shown in figure 5-13, and the $N_{SHO(x)}$, we obtained from figure 5-11 into equation (5.10), we can modify the capacity equation (5.11) to reflect the impact of SHO on capacity.

In order to bring in the effect of Soft handoff into the capacity equation let us rewrite equation (4), from Appendix, in terms of the Transmit Power (TxP) gains, $g(x)$, where $g(x)$ is the ratio between the Up Link Transmit Power (TxPUL) of a CDMA system operating at T_{ADD} level of x dB relative to that in the system that is operating at T_{ADD} level of -7dB where x lies in the range $-22dB \leq x \leq -7dB$. The ratio $g(x)$ is computed as

$$g(x) = 10^{(G(x)/10)} \quad (5.12)$$

where gain $G(x)$ (dB) that is obtained from figure 5-13 for any desired level of x . Thus

rewriting equation (A.4) of Appendix we get

$$E_b/N_T = \frac{ST_b}{N_0 + \alpha\{(M_{Tot} - M_{SHO} - 1)ST_c + M_{SHO}g(x)ST_c + f(M_{Tot} - M_{SHO})ST_c + fM_{SHO}g(x)ST_c\}} \quad (5.13)$$

where M_{SHO} is the number of users in SHO region, $g(x)$ is the TxP gain as described before and M_{Tot} is the total number of users supported by the SHO based CDMA system. Dividing both numerator as well as denominator of above equation by ST_c , ignoring the first term of denominator and rearranging it we get

$$M_{Tot} - M_{SHO} - (M_{SHO} \cdot g(x)) = \left(\frac{1}{1+f} \right) \left(\frac{T_b/T_c}{E_b/N_T \alpha} + 1 \right) \quad (5.14)$$

Now M_{SHO} can be expressed in terms of M_{Tot} and $N_{SHO}(x)$, and can be written as function of T_{ADD} level x as below,

$$M_{SHO}(x) = N_{SHO}(x) \cdot M_{Tot} \quad (5.15)$$

where $N_{SHO}(x)$ which is the Fraction of users in SHO is obtained from equation (5.10) and values for $F_{SHO}(x)$ obtained from figure 5-11 for any x dB level of threshold T_{ADD} . After substituting for M_{SHO} in equation (5.14) and solving for M_{Tot} we get,

$$M_{Tot}(x) = \left(\frac{1}{1 - \{1 - g(x)\}N_{SHO}(x)} \right) \left(\frac{1}{1+f} \right) \left(\frac{T_b/T_c}{E_b/N_T \alpha} + 1 \right) \quad (5.16)$$

In the above equation since the two variable quantities, i.e., $g(x)$ and $N_{SHO}(x)$, are functions of T_{ADD} level x thus M_{Tot} has been expressed as function of x . We notice from this equation that the smaller the gain $g(x)$ and/or larger the factor $N_{SHO}(x)$ the larger will be the

value of the total number of supported users M_{Tot} . Above equation can be rewritten as below,

$$M_{Tot}(x) = S(x) \left(\frac{1}{1+f} \right) \left(\frac{T_b/T_c}{E_b/N_T \alpha} + 1 \right) \quad (5.17)$$

where the Soft Handoff Gain Factor, $S(x)$ is given by

$$S(x) = \frac{1}{1 - \{1 - g(x)\} N_{SHO}(x)} \quad (5.18)$$

Now using equations (5.10) and (5.12) along with values of $F_{SHO}(x)$ and gains $G(x)$ from figures 5-11 and 5-13 respectively we obtain $N_{SHO}(x)$ and $g(x)$ respectively for any T_{ADD} level x in the desired range $-22dB \leq x \leq -7dB$. Using these values of $N_{SHO}(x)$ and $g(x)$ in equation (5.18) we can obtain average gain in capacity due to soft handoff at each level of T_{ADD} relative to that at T_{ADD} level of -7 dB. Figure 5-16 shows average gain (dB) in performance of SHO based CDMA system due to soft handoff at each level of T_{ADD} and we observe an improvement in the performance of the system as threshold T_{ADD} is lowered. This improvement in performance is very small for T_{ADD} levels of -9 to -7dB. The reason being that because of high T_{ADD} levels the SHO region shown in figure 5-15 is very small. Thus there are very small number of users that are in SHO as well as the gain in terms of reduction in Tx-powers is not much. Between T_{ADD} levels of -17 to -10dB the slope of the performance improvement curve increases. The reason being that we are not only gaining in terms of reduced Tx-powers but also there is a larger fraction of

users, $N_{SHO}(x)$, that are in SHO and thus are operating at lower Tx-powers. The combined effect of these two factors is an increase in performance gain, $s(x)$. For T_{ADD} levels below -17dB the marginal increase in performance or the slope of the performance improvement curve decreases. The reason being that at T_{ADD} levels below -17dB though larger fractions of users are falling in SHO region but there is not much relative gain in Tx-powers, i.e., $G(x)$ thus $g(x)$, as shown by almost flat curve for this range of T_{ADD} in figure 5-13.

Using the values of performance gains obtained from equation (5.18) in equation (5.17) we can compute the number of users that can be supported by the SHO based CDMA system over the desired range of T_{ADD} levels. Assuming system parameters values of processing gain $T_b/T_c = 128$, required $E_b/N_T = 7.0dB = 5.012$, voice activity factor $\alpha = 0.5$, other-cell Interference factor $f = 0.5$ and loading factor $\mu = 0.8$ number of supported users have been computed and plotted in figure 5-17 over the desired range of T_{ADD} levels. Figure 5-17 shows that the capacity of SHO based CDMA system increases as threshold T_{ADD} is lowered. This increase in capacity is quite small at high T_{ADD} levels since performance gain, $s(x)$, is small in the beginning. The capacity increases substantially between T_{ADD} levels of -9 to -17dB because of increasing performance gain as we saw before in figure 5-16. For T_{ADD} levels below -17dB the marginal increase in capacity decreases because of decrease in performance gain. Average performance gain obtained from equation (5.18) can be expressed in terms of Percent improvement in the capacity of

Soft Handoff based CDMA system and has been shown in figure 5-18 for the T_{ADD} range of -7 to -22dB. We notice that increase in capacity with the lowering of T_{ADD} level is quite substantial and is as high as 93% at T_{ADD} level of -22dB relative to that at T_{ADD} level of -7dB.

As a Network Operator we would also like to know how much infrastructure cost we would have to incur in order to attain this gain in capacity. Part of the infrastructure cost is a one time cost of providing number of Channel Elements or Cell-site Modems required to support all the users. The number of Channel Elements (CEs) or Cell-site Modems required can be estimated from the Average Size of AS (ASA) of each user. We know that each user in the non-SHO region of a cell of figure 5-15 has an ASA of one thus requires one CE per user. Whereas each users in the SHO region has an ASA as shown in figure 5-10 thus requires average number of CEs equal to the value of ASA at any given level of T_{ADD} . Thus for each level of T_{ADD} , x , we can compute the Average Number of required CEs, $ANCEs(x)$, as below

$$ANCEs(x) = M_{SHO}(x) \times ASA(x) + \{M_{Tot}(x) - M_{SHO}(x)\} \quad (5.19)$$

where the number of users in SHO, $M_{SHO}(x)$, and total number of supported users, $M_{Tot}(x)$, can be obtained from equations (5.15) and (5.17) respectively. Average Size of the AS in SHO region at any T_{ADD} level x , i.e., $ASA(x)$ can be obtained from figure 5-10. Thus using equation (5.19) we can compute for each T_{ADD} level x the ANCEs. Percent increase in the Average total Number of required CEs (ANCEs) can be computed

as below,

$$\text{Percent Increase in ANCEs at level } x = \frac{ANCEs(x) - ANCEs(x = -7dB)}{ANCEs(x = -7dB)} \cdot 100 \quad (5.20)$$

Now plotting the Percent Increase in Capacity obtained from equation (5.18) (as shown in figure 5-18) versus Percent Increase in ANCEs obtained from above expression we get figure 5-19. In figure 5-19 we notice that curve is almost linear over the whole T_{ADD} range. This shows that the infrastructure cost in terms of Average total required Number of CEs (ANCEs) grows almost linearly with the increase in the Capacity. This increase in ANCEs is not only to account for more than one CE to a single user that is in SHO but also to support the additional number of users due to capacity gain because of Soft Handoff. As already mentioned this is a one time cost and has to be incurred in order to provide necessary hardware to take advantage of this increased capacity.

Apart from increase in fixed infrastructure cost there is also an increase in the operating cost in terms of increased signalling load. Like we did for ANCEs in the previous paragraph we can also estimate the Total Number of AS Updates (TNAUs) for each level of T_{ADD} , x , from the NAUs of each user as shown in figure 5-12. Assuming that each user in the non-SHO region of a cell of figure 5-15 generates only one AS update and each users in the SHO region generates NAUs as shown in figure 5-12. Thus for each level of T_{ADD} , x , we can compute the average Total NAUs, $TNAUs(x)$, as below

$$TNAUs(x) = M_{SHO}(x) \times NAUs(x) + \{M_{Tot}(x) - M_{SHO}(x)\} \quad (5.21)$$

where the number of users in SHO, $M_{SHO}(x)$, and total number of supported users, $M_{Tot}(x)$, can be obtained from equations (5.15) and (5.17) respectively. Average Number of AS Updates in SHO region at any T_{ADD} level x , i.e., $NAUs(x)$ can be obtained from figure 5-12. Thus using equation (5.21) we can compute for each T_{ADD} level x the TNAUs. Percent increase in the Total signalling load in terms of average Total NAUs can be computed as below,

$$\text{Percent Increase in TNAUs at level } x = \frac{TNAUs(x) - TNAUs(x = -7dB)}{TNAUs(x = -7dB)} \cdot 100 \quad (5.22)$$

This gives us an estimate of average increase in the network signalling load due to Soft Handoff. Now as we did in section 4.3.1 of chapter 4, we can also look at it as a Trade-off problem between Percent Increase in Network Signalling Load (Percent Increase in TNAUs) and Percent Increase in Capacity in order to arrive at an Optimum operating range for the system. Again plotting Percent Increase in Capacity obtained from equation (5.18) (as shown in figure 5-18) versus Percent Increase in TNAUs or Total Signalling Load obtained from equation (5.22) we get figure 5-20. In figure 5-20 we notice that while T_{ADD} is lowered from -7 to approximately -12dB the cell capacity increases without any significant increase in average total signalling load as shown by the sharp rise in the curve. If T_{ADD} level is lowered any further there is an increase in capacity along with a substantial increase in average total signalling load as shown by decreasing slope of the curve. For T_{ADD} levels below -17dB the curve starts flattening out very quickly thus signifying the region of non-optimal operation where very small increase in capacity is

associated with very large increase in network signalling load. The knee of the curve provides us with the optimum operating range where we achieve the optimum capacity of the system without being burdened much with the unnecessary signalling load. The knee of the curve in figure 5-20 lies in the T_{ADD} range of -12 to -17dB. We must recall from our discussion of results in section 4.3.1 that the optimum operating range we found there was also from -12 to -17dB in terms of T_{ADD} threshold. Thus we have seen that the optimum operating range we found for parameter T_{ADD} in section 4.3.1 not only gives us a system operating at optimum level of network signalling load but also assures us with a system that is operating at its optimal capacity.

Figure 5-16: Average Gain in Performance due to SHO at each T_{ADD} level relative that for T_{ADD} level of -7dB

Figure 5-17: Average number of supported Users at each T_{ADD} level

Figure 5-18: Percent increase in capacity at each T_{ADD} level relative that for T_{ADD} level of -7dB

Figure 5-19: Percent increase in Capacity Vs. Percent increase in the required Number of Channel Elements or Cell-site Modems

Figure 5-20: Percent increase in Capacity Vs. Percent Increase in Network Signalling Load

6

Conclusion

6.1 Conclusion

In this thesis the performance of Soft Handoff in PCS environment has been studied. PCS environment is characterized by small cells called microcells with antennas heights at street lamps elevation. Because of low heights of antennas a line-of-sight component exists for within-cell transmissions thus desired signal was modeled as Rician faded whereas undesired signals were modeled as Rayleigh faded. CDMA being a wideband system also encounters frequency-selective multipath fading. A 3-path Exponential-variance model was used to implement the effect of frequency-selective fading. Log-normal shadowing with standard deviation of 6dB was modeled and superimposed as suggested by Lee [22]. Spatial correlation between the log-normal samples was implemented using Gudmundson's model [8].

A CDMA network of 10 cells was simulated and the performance of Soft Handoff (SHO) was studied in terms of following indicators, namely, required Up-Link and Down-Link average Transmit Powers (TxPUL and TxPDL), Average Size of AS (ASA), Average Number of AS Updates (NAUs) and Fraction of travel distance the Mobile Station (MS)

was in SHO (F_{SHO}). TxPUL is the minimum average Transmit Power of a MS that is required to achieve a minimum desired link quality of 0.001 to 0.002 in terms of BER. In the similar fashion TxPDL is the minimum required average Transmit Power of each BS's channel, involved in SHO, to achieve a BER of 0.001 to 0.002. Obviously lower TxPUL is desirable because it not only would increase the battery life of a MS but shall also reduce the interference to other users of same cell. Similarly lower TxPDL is desirable as it would reduce interference to the users of other cells. Now F_{SHO} being an indicator of the percent of travel time the MS is in SHO and ASA being an indicator of the average number of channels that are tied for the duration of a single call thus low values of both F_{SHO} and ASA are desirable. Similarly NAUs being the indicator of network signalling load is also desired to be low. Ideally we would like to have all the above mentioned resources or cost indicators to be as low as possible yet we have seen in chapter 4 that it is not possible. Resources allocation indicators ASA, NAUs and F_{SHO} are the costs that we have to incur in order to gain in terms of lower values of transmit powers TxPUL and TxPDL. We have to make a trade-off between one or all of ASA, NAUs and F_{SHO} with both TxPUL and TxPDL. In some cases as we saw in sections 4.3.2– & 4.3.3 the trade-off has to be made between ASA and NAUs.

The SHO algorithm consists of three main parameters namely add threshold T_{ADD} , drop threshold T_{DROP} , and drop timer t_{DROP} which affect its performance. In chapter 4 by monitoring the travel of a MS from one BS to another along the line joining their centers we studied the effects of the SHO parameters T_{ADD} , T_{DROP} , and t_{DROP} , and the

averaging parameter d_{avg} on the performance of the system. In section 4.3.1 we found that lowering the 1st parameter T_{ADD} reduces the required transmit powers TxPUL and TxPDL but at the cost of higher values of F_{SHO} , ASA and NAUs. The reduction in required TxPUL and TxPDL was quite substantial (in the range of 2 to 4dB) at a substantial increase in the network signalling load NAUs (by a factor of between 2 to 5). Thus a trade-off was studied between NAUs and transmit powers TxPUL and TxPDL (figures 4-14 & 4-15) in order to find an optimum operating range for SHO parameter T_{ADD} . A range of -12 to -17dB was found to be the optimum operating range for the SHO algorithm in terms of parameter T_{ADD} . In section 4.3.2 effect of 2nd parameter T_{DROP} on the performance of SHO was studied and it was found that increasing the *relative* T_{DROP} (or lowering *absolute* T_{DROP}) reduces the cost in terms of resource indicator NAUs and required transmit powers TxPUL and TxPDL but at the cost of higher values of F_{SHO} and ASA. Since in this case reduction in TxPUL and TxPDL was insignificant (between 0.2 to 0.3dB) whereas reduction in the signalling load NAUs (by a factor between 2 to 3) and increase in ASA (by a factor between 1.5 to 1.6) was quite significant. Thus a trade-off between NAUs and ASA (instead of between NAUs and Transmit powers) was studied in order to find an optimum operating range for SHO parameter T_{DROP} . A range of 1 to 6dB was found to be the optimum operating range for the SHO algorithm in terms of parameter *relative* T_{DROP} . In section 4.3.3 effect of 3rd parameter t_{DROP} on the performance of SHO was studied. Like *relative* T_{DROP} it was found that increasing t_{DROP} also reduces the cost in terms of resource indicator NAUs and required transmit powers TxPUL and

TxPDL but at the cost of higher values of F_{SHO} and ASA. Again since reduction in TxPUL and TxPDL was insignificant (between 0.2 to 0.25dB) whereas reduction in NAUs (by a factor between 1.8 to 2.5) and increase in ASA (by a factor between 1.35 to 1.45) was quite significant. Thus a trade-off between NAUs and ASA (instead of between NAUs and Transmit powers) was studied in order to find an optimum operating range for SHO parameter t_{DROP} . A range of 2 to 20 Samples was found to be the optimum operating range for the SHO algorithm in terms of parameter t_{DROP} . In section 4.4 effect of averaging parameter d_{avg} on the performance of SHO was studied and it was found that increasing d_{avg} reduces the cost in terms of parameter NAUs but at the cost of higher required transmit powers TxPUL and TxPDL. A trade-off was studied between NAUs and transmit powers TxPUL and TxPDL (figures 4-49 & 4-50) in order to find an optimum operating range for the SHO algorithm. A range of 20 to 60 meters was found to be the optimum operating range for the SHO algorithm in terms of averaging parameter d_{avg} .

From sections 4.3.1–4.3.3 and 4.4 we noticed that SHO performance is most sensitive to parameter T_{ADD} . Thus parameter T_{ADD} was further studied in section 5.1 on ten different parallel travel routes differing only in their locations along Y-axis (mobile travels in the direction of X-axis) as shown in figure 5-1 and following results were observed. For a fixed value of threshold T_{ADD} as we move from lower Y-axis to higher Y-axis travel route we incur more cost in terms of higher F_{SHO} and ASA where as we gain in terms of lower NAUs and Transmit powers TxPUL and TxPDL. Comparing NAUs and Transmit powers (TxPUL and TxPDL) for all ten travel routes we found that the travel route with Y-axis

value of zero (the travel route we studied in sections 4.3–4.4 as Scenario I) is indeed the most critical one. Thus the operating range of -12 to -17dB we obtained for threshold T_{ADD} is the most optimal for SHO algorithm all across the cell.

In section 5.2.1 the results obtained in section 5.1 were averaged over all ten travel routes and because of the symmetry of hexagonal cells we showed that these average results represent the performance of soft handoff over the whole SHO region as shown in figure 5-15. Since at T_{ADD} level of -7dB the MS is in soft handoff only for a very short period thus from the average results obtained in section 5.2.1 the average gains in Transmit powers at different T_{ADD} levels relative to that at T_{ADD} level of -7dB were obtained as shown in figure 5-13. Later in section 5.2.2 using these gains an equation for capacity of CDMA that includes the effect of SHO (equation (5.17)) and an equation for soft handoff gain factor (equation (5.18)) were derived. The results obtained from equation (5.18), that are depicted in figure 5-16, showed that the performance gain due to soft handoff varies from 0 to 2.85dB over the given T_{ADD} range. With the help of the results obtained from equation (5.17) we showed that there is an enhancement in capacity of CDMA system in terms of increased number of supported users. This enhancement in capacity as shown in figure 5-18 is as high as 93% over the T_{ADD} range of -7 to -22dB. This improvement in capacity is not free and requires use of more than one channel element by a MS that is in soft handoff. Thus SHO requires a network operator to provide more channel elements (CEs) at the BS which is a fixed hardware cost. SHO also requires the network operator to bear a variable operating cost in terms of network signalling load. Using equations (5.19)

and (5.20) an estimate of the Percent Increase in the required number of channel elements was obtained and plotted against Percent Increase in Capacity as shown in figure 5-19. Figure 5-19 shows increase in one time fixed cost in necessary hardware that has to be incurred in order to take advantage of the capacity gain from SHO. Later a trade-off between Percent Increase in the signalling load in terms of increase in average total NAUs and Percent Increase in Capacity for the given T_{ADD} range was studied and plotted in figure 5-20. From the knee of this curve an optimum operating range for the system was determined and was again found to be lying between -12 to -17dB. For this optimum operating range the capacity gain ranges from 25% to 75% approximately.

Thus in this thesis the two problems that are very important a network operator have been addressed. First problem was to find the optimum operating ranges for various SHO parameters so that the network can be operated at its optimal level of Transmit Powers without being overwhelmed with unavoidable network signalling load in terms of NAUs and resources cost in terms of Average Size of Active set (ASA). And we know that lower transmit powers reduce in-cell as well as other-cell interference which in turn enables the network to support additional users. Thus as a second problem we estimated the amount of improvement in the capacity of CDMA due to Soft Handoff for the given operational environment. From the point of view of a network operator both problems are very important. Not only the network should be operated at its optimal capacity but also the signalling network should not be overloaded with unnecessary signalling load.

From the results presented in chapter 4 we achieved first two of the three objectives that

were set for the thesis. The first objective was to study in detail the optimization process and to determine the optimum operating range for each of the four parameters in the given PCS environment. We found that the optimum operating ranges for the parameters are as follows. The optimum operating range for T_{ADD} is -12 to -17dB, that for T_{DROP} is 1 to 6dB, that for t_{DROP} is 2 to 20 samples, and that for d_{avg} is 20 to 60 meters. The second objective was to identify the parameter that affects the performance the most. In section 4.5 by comparing the effect of these parameters on Up and Down Link transmit powers we identified parameter T_{ADD} to be influencing the performance of the system the most. The third objective of the thesis of estimation of the enhancement in capacity of CDMA was achieved in chapter 5. We found a 25-75% (approximately) enhancement in the capacity of the CDMA system.

6.2 Suggested Future Work

In this thesis though an attempt was made to investigate the performance of 3-BS soft handoff extensively in as realistic environment as possible. A number of issues still remain unresolved and need further study. The simulations were performed assuming a log-normal shadowing with standard deviation of 6dB. It would be interesting to see the effect of different shadowing environments on the performance of SHO based system. It is expected that the optimum operating ranges for SHO parameters and averaging length parameter would change slightly as the shadowing environment changes.

In the simulations it was assumed that the signals from different BSs are uncorrelated. In real systems some correlation exists among signals from different users. It would be worth

while studying the effect of this correlation on the performance. Another assumption that was made in simulations was that multipaths model had exponentially decaying power delay profile. Whereas in some situations especially in big cities a uniform power delay profile has been observed. Thus, looking at performance with this variation in the model would be another interesting topic.

This thesis looked at the effect of SHO on Up Link capacity only. While the MS is in SHO with 2 or more BSs the MS is receiving signal from more than one BS. This implies that now there is increase in total received interference on Down Link. This suggests the effect on Down Link must be quite opposite to that what we saw in the case of Up Link. But we also see drop in the Down Link transmit powers on per channel basis. Thus the increase in the interference might be offset by this reduction in Down Link per channel transmit powers. It would another interesting problem to look at what is the resultant effect on the Down Link capacity.

Due to the consideration of 3-BS SHO in the presence of interferers and in multipath environment the problem of modeling becomes very complex. Thus developing an analytical model for SHO in this complex environment would be another very challenging and interesting topic.

Appendix

A.1 Basic Capacity Equation for CDMA

We know that capacity in CDMA is fundamentally asymmetric on Up and Down links with Up link performance limiting it. The theoretical upper bound for ideal noise free CDMA channel capacity is limited by the processing gain. In a real system the capacity being a function of many factors will be much lower. The factors that limit the CDMA channel capacity are the performance of receiver demodulator, the effectiveness of power control in solving the “near far” problem for both pathloss and fading, the interference from other users, the speaker activity and the cell sectorization. In this section we derive the basic capacity equation following the approach as shown in [21].

The current voice decoders provide adequate voice quality when the BER is below 10^{-3} , and requires $E_b/N_T = 6.6dB$ for 8Kbps and $E_b/N_T = 7.0dB$ for 13Kbps demodulators. This performance is far from the theoretical optimal detector, so capacity improvements are possible as technology for better demodulators improves. Power control accuracy directly affects the CDMA channel capacity. The better the power control algorithm equalizes all the mobile signals received at the BS the higher the CDMA channel capacity will be.

Co-channel interference from other-cell users appears as an increase in the receiver noise floor and reduces the capacity of CDMA channel. Thus CDMA channel capacity and effect of soft handoff on the capacity are tightly coupled with the fast closed loop power

control technique described in section 3.6.1.2. This technique of power control guarantees the controlling BS that received signal energy-to-interference for each user is normalized to be equal to that of all other users. This in turn limits interference received from each other-cell user to a normalized value less than unity. Thus CDMA capacity is then reduced by the sum total of all the relative energy received from other-cell users and is inversely proportional to $1 + f$ where

$$f = \frac{\text{average total interference from other-cell users}}{\text{average number of users per cell}} \quad (\text{A.1})$$

Thus CDMA is an interference limited system whose channel capacity is limited by the mutual interference from all users both in the same and neighboring cells. Assuming that all users are able to transmit enough power to just achieve the required E_b/N_T , then E_b/N_T is given by

$$E_b/N_T = \frac{\frac{S_1 T_b}{M}}{N_0 + \sum_{i=2}^M (S_i T_c) + f \sum_{i=1}^M (S_i T_c)} \quad (\text{A.2})$$

where M is the number of users per cell, S_i is the signal power from user i , T_b is the bit interval for the user data, T_c is the chip interval and N_0 is the receiver noise density. In the denominator of equation (A.2) the 2nd term accounts for the in-cell interference and the 3rd term accounts for other-cell interference and is modeled as a fraction f of the serving cell total received energy. The fraction f is the interference factor from the neighbors as defined in equation (A.1).

Most of the digital vocoders already have the capability to monitor the voice activity of a user. The IS-95 standard provides for turning off the transmitter or reducing the data rate when there is no speech to transmit. Studies have shown that on an average a speaker is active only 3/8 of the time. This reduces the interference from all other users by the *voice activity factor*, $\alpha = 3/8$ thus improving the capacity by a factor of 2 approximately. Thus including the voice activity factor α in equation (A.2) we get,

$$E_b/N_T = \frac{S_1 T_b}{N_0 + \alpha \left(\sum_{i=2}^M (S_i T_c) + f \sum_{i=1}^M (S_i T_c) \right)} \quad (\text{A.3})$$

Now assuming perfect power control, i.e., setting $S_i = S$, we obtain

$$E_b/N_T = \frac{S T_b}{N_0 + \alpha((M-1)S T_c + f M S T_c)} \quad (\text{A.4})$$

Factoring the user signal power S , we get

$$E_b/N_T = \frac{T_b/T_c}{N_0/(S T_c) + \alpha((1+f)M - 1)} \quad (\text{A.5})$$

Assuming that all users can transmit unlimited power so receiver noise floor is not a factor, i.e., $\lim_{S \rightarrow \infty} N_0/(S T_c) = 0$. Thus ignoring noise term in equation (A.5) and solving for the maximum CDMA channel capacity, M , that is limited only by the interference from all users we get

$$M = \left(\frac{1}{1+f} \right) \left(\frac{T_b/T_c}{E_b/N_T \alpha} + 1 \right) \quad (\text{A.6})$$

where T_b/T_c is also called as the processing gain, G , and the factor $\frac{1}{1+f}$ also called the

reuse efficiency, F .

The last factor that reduces the interference is cell sectorization since directional antennae reduce the interference from mobiles outside the sector. This increases the capacity of a cell by the number of sectors. We'll ignore the effect of sectorization on the capacity in our further discussions as we are considering an omnidirectional system.

A.2 Loading factor, μ

Since CDMA performance is limited by the total interference from in-cell and neighbor cells. As the number of users increase, the received interference at BS and MS increases correspondingly until the power control can no longer maintain the required E_b/N_T . Thus, the system must measure the BS activity and take action when the BS approaches overload limit to prevent degraded voice quality or dropped calls. The total received power above the background noise in an idle system is defined as the noise rise and is a measure of the number of active users and loading factor, μ . The BS uses a pair of thresholds, namely lower and upper reverse load thresholds normally set at 0.6 and 0.85 respectively, to limit the number of users in a cell so all active users have acceptable voice quality. The BS estimates the Up link loading factor, μ , by comparing the current received power to the power measured when the system is idle. The estimated μ is compared to the two thresholds. New calls and handoffs are allowed into the cell while μ is below the lower threshold. The system will deny access for new calls but allows emergency calls and handoff into the cell if μ is between the lower and upper threshold. The system denies all new calls and handoffs into the cell if μ exceeds the upper threshold.

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IMAGE EVALUATION TEST TARGET (QA-3)

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