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Equalization for Multirate Transmission in a CDMA Overlaid Cellular System

by

Shahid R. Chaudry

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for degree of

Master of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
Carleton University
Ottawa, Ontario
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CDMA Overlaid Cellular System”**

submitted by Shahid R. Chaudry, B.Sc.
in partial fulfillment of the requirements for
the degree of Master of Engineering

Thesis Supervisor
Professor A.U.H. Sheikh

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October, 1994

Abstract

Radio communication has gone through a phenomenal change in the recent years. A lot of research work has been done for the upcoming PCS which will provide many services to the users through a single handset. One of the access schemes which is actively considered for PCS is CDMA; a CDMA system has been standardized and licensed by FCC in United States.

This thesis research considers a CDMA overlaid cellular system, containing microcells overlaid over larger macrocells, to enhance capacity and to provide multirate services. This architecture has the advantage that it does not require a large number of handoffs which are necessary in a microcellular system. Also, the users in microcell can accommodate higher data rates because of the smaller delay spread in the microcells. The use of CDMA is suitable in such an architecture as it has the inherent ability to handle different data rates - the users being separated from each other by the spreading codes only.

A simple DFE receiver architecture for the proposed system is simulated for two different data rates. It will be shown that this receiver gives an adequate performance with only average power control used in the system. The performance is shown to improve when users are transmitting over Ricean channels. It will also be shown that the performance of the system is still satisfactory even when the average power control is imperfect. Simulations of the system when the *average* power of interference varies between -2 dB to +2 dB around the desired user's average power, suggest that the DFE receiver is near - far resistant.

to my parents

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Table of Contents

Abstract	iii
Acknowledgments	v
Table of Contents	vi
List of Figures	viii
List of Tables	xi
 Chapter 1	
Introduction	1
1.1 Mobile Communication	1
1.2 Thesis Motivation	2
1.3 Thesis Description	3
1.4 Thesis Organization	3
 Chapter 2	
Mobile Radio Communication	5
2.1 Mobile Radio Channels	5
2.1.1 Rayleigh Fading Channel	6
2.1.2 Ricean Fading Channel	7
2.1.3 Shadowing	8
2.1.4 Average Power Delay Profile	8
2.1.5 Fading Multipath Channel Characteristics	9
2.2 Code Division Multiple Access	11
2.3 Multiuser DS-CDMA	14
2.3.1 Rake Receiver	19
2.3.2 Adaptive Equalization	22
2.4 Service Integration Issues	25

Chapter 3	
System Description and Simulation Design	31
3.1 Transmitter	31
3.2 Channel Model	34
3.3 Receiver	39
3.4 Overlaid Cellular Scenarios	43
 Chapter 4	
Simulation Results	47
4.1 Initialization of Receiver Parameters	47
4.2 Results for Different Overlaid Scenarios	51
4.2.1 All Users in Macrocell	52
4.2.2 Desired User in Macrocell, Interference from Micro-cells	57
4.2.3 Desired User in Microcell, Interference from Macro-cells	61
4.2.4 All Users in Microcell	62
4.3 Effect of Transmission over Ricean Channel	65
4.4 Effect of the Spreading Code of Users	73
4.5 Near Far Resistance of DFE receiver	75
 Chapter 5	
Conclusions	85
5.1 Proposals for Future Work	87
References	89

List of Figures

Figure 2.1	Overlaid Cellular Architecture	28
Figure 3.1	Transmitter and Channel Model	33
Figure 3.2	Data Symbol and Transmitted Symbol	35
Figure 3.3	3 Ray Channel Model	37
Figure 3.4	Receiver Structure	40
Figure 4.1	DFE performance as a function of number of feedforward taps for a single user in microcell.	49
Figure 4.2	DFE performance as a function of number of feedforward taps for a single user in macrocell.	49
Figure 4.3	mse performance of DFE in scenario 1: when all users are in macrocell	54
Figure 4.4	Outage of DFE in scenario 1: when all users are in macrocell	54
Figure 4.5	BER of DFE in scenario 1: when all users are in macrocell	56
Figure 4.6	Example of a bad channel	56
Figure 4.7	mse performance of DFE in scenario 2: when desired user is in macrocell and interference from microcell	58
Figure 4.8	Outage of DFE in scenario 2: when desired user is in macrocell and interference from microcell	58
Figure 4.9	BER of DFE in scenario 2: when desired user is in macrocell and interference from microcell	60
Figure 4.10	mse performance of DFE and Rake in scenario 4: when desired user is in microcell and interference from macrocell	60
Figure 4.11	Outage of DFE in scenario 4: when desired user is in microcell and interference from macrocell	63

Figure 4.12	BER of DFE in scenario 4: when desired user is in microcell and interference from macrocell	63
Figure 4.13	mse performance of DFE in scenario 6: when all users are in microcell	64
Figure 4.14	Outage of DFE in scenario 6: when all users are in microcell	64
Figure 4.15	BER of DFE in scenario 6: when all users are in microcell	66
Figure 4.16	mse performance of DFE in scenario 6: when all users are in microcell with some users over Ricean channel	68
Figure 4.17	Outage of DFE in scenario 6: when all users are in microcell with some users over Ricean channel	68
Figure 4.18	mse performance of DFE in scenario 2 with some users over Ricean channel	70
Figure 4.19	Outage of DFE in scenario 2 with some users over Ricean channel	70
Figure 4.20	mse performance of DFE in scenario 4 with some users over Ricean channel	72
Figure 4.21	Outage of DFE in scenario 4 with some users over Ricean channel	72
Figure 4.22	mse performance of DFE in scenario 6: when all users are in microcell and desired user is using different codes	74
Figure 4.23	Outage of DFE in scenario 6: when all users are in microcell and desired user is using different codes	74
Figure 4.24	mse performance of DFE in scenario 2: when desired user is in macrocell and interference from microcell with power varying from -2 to +2 dB with respect to desired user	77
Figure 4.25	Outage of DFE in scenario 2: when desired user is in macrocell and interference from microcell with power varying from -2 to +2 dB with respect to desired user	77
Figure 4.26	BER of DFE in scenario 2: when desired user is in macrocell and interference from microcell with power varying from -2 to	

	+2 dB with respect to desired user	78
Figure 4.27	mse performance of DFE in scenario 4: when desired user is in microcell and interference from macrocell with power varying from -2 to +2 dB with respect to desired user	78
Figure 4.28	Outage of DFE in scenario 4: when desired user is in microcell and interference from macrocell with power varying from -2 to +2 dB with respect to desired user	80
Figure 4.29	BER of DFE in scenario 4: when desired user is in microcell and interference from macrocell with power varying from -2 to +2 dB with respect to desired user	80
Figure 4.30	mse performance of DFE in scenario 6: when all users are in microcell and power of interferers varies from -2 to +2 dB with respect to desired user	82
Figure 4.31	Outage of DFE in scenario 6: when all users are in microcell and power of interferers varies from -2 to +2 dB with respect to desired user	82
Figure 4.32	BER of DFE in scenario 6: when all users are in microcell and power of interferers varies from -2 to +2 dB with respect to desired user	83

List of Tables

Table 3.1:	Overlaid Cellular Scenarios	45
Table 4.1:	Confidence Intervals for scenario 1	55
Table 4.2:	Confidence Intervals for scenario 2	59
Table 4.3:	Scenario 6 with some users over Ricean channels	69
Table 4.4:	Scenario 4 with some users over Ricean channels	71
Table 4.5:	SIR at the receiver for scenario 2	79
Table 4.6:	SIR at the receiver for scenario 4	81
Table 4.7:	SIR at the receiver for scenario 6	81

List of Acronyms

Acronym	Meaning
AMPS	Advanced Mobile Phone System
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CDMA	Code Division Multiple Access
dB	Decibels
DECT	Digital European Cordless Telephone
DFE	Decision Feedback Equalizer
DS-CDMA	Direct Sequence Code Division Multiple Access
FDMA	Frequency Division Multiple Access
FPLMTS	Future Public Land Mobile Telecommunications Systems
GSM	Global System for Mobile Communication
ISI	Inter Symbol Interference
LMS	Least Mean Square
LOS	Line of Sight
MLSE	Maximum Likelihood Sequence Estimator
mmse	Minimum Mean Square Error
MS	Mobile Station
mse	Mean Square Error
NLMS	Normalized LMS
PCS	Personal Communication Services
pdf	Probability Density Function
PG	Processing Gain
PN	Pseudo Noise
PRMA	Packet Reservation Multiple Access
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
RLS	Recursive Least Squares

Acronym	Meaning
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SSMA	Spread Spectrum Multiple Access
TACS	Total Access Communications System
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunication Systems
VMCS	Vehicular Mobile Communication System
WSSUS	Wide Sense Stationary Uncorrelated Scattering

Chapter 1

Introduction

1.1 Mobile Communication

Radio communication has gone through a number of changes in the last decade particularly in the area of mobile communication. Rapid development in wireless communication for mobile cellular radio has seen replacement of the analogue system by a more flexible digital system in less than a decade. Mobile communication services have recently got a major boost by the allocation of nearly 160 MHz [1] of new spectrum in U.S. for the upcoming PCS network providing multitude of services.

The number of subscribers using mobile communication has been rapidly increasing since the service was first introduced. In U.S. alone the number of cellular subscribers are expected to reach 22 million by the year 1995 while the new PCS services are projected to have nearly 31 million domestic PCS subscribers by the year 2003. The bright future foreseen for mobile communication has given huge momentum to provide many supplementary services with quality exceeding that of existing mobile services.

The first generation of cellular systems, AMPS (Advanced Mobile Phone System) in U.S., a system similar to AMPS in Japan, TACS (Total Access Communications System) in U.K. and Nordic System in Scandinavian countries, use analog transmission employing FDMA technique. These systems are now being replaced by second generation digital systems. The second generation systems, GSM (Global System for Mobile Communica-

tion) in Europe, IS-54 standard based on TDMA and IS-95 standard based on CDMA in U.S. are now being deployed. The second generation systems are more flexible in introducing new services.

Work has already started for the development of third generation mobile systems which should support indoor and outdoor communication and allow for worldwide roaming. These systems include FPLMTS (Future Public Land Mobile Telecommunications Systems) in U.S. and UMTS (Universal Mobile Telecommunication Systems) [2] in Europe. In a couple of years users in U.S. are expected to have PCS available to them in 900 and 1900 MHz band.

1.2 Thesis Motivation

Universal Personal Communication system was first proposed by D.C. Cox [3] about seven years ago. Since then a lot of new ideas have been proposed aiding evolution of the new system, but the main objectives are essentially the same. These objectives include, but are not limited to, provision of secure and good quality portable communications - voice, data and video, reduction in size and weight of handset and more efficient use of frequency spectrum. The other desired attributes are high reliability, power economy and ability to provide communication from anywhere to everywhere. The services that are provided by this system are called Personal Communication Services or PCS.

In PCS system, users will have the flexibility of selecting a data rate for the service they want to use. So a system employing different data rate signals forms the backbone of PCS. It is well known that microcells can support data rates higher than is possible in macrocells because of relatively smaller delay spread in microcells. Therefore an overlaid cellular structure, with microcells overlaying macrocells, provides a practical environment to

study different data rate signals. In such an architecture, it may be assumed that users can transmit at a higher data rate in microcells compared to macrocells. The main motivation behind this thesis is to see whether CDMA signals transmitted at different data rates can coexist in an overlaid cellular system.

1.3 Thesis Description

In this thesis, a CDMA overlaid cellular system [6] [7] employing different data rate transmissions and decision feedback equalization is simulated. This system contains microcells to provide improved capacity [4] and underlaying macrocells to allow highly mobile users to receive continuous service by avoiding excessive handoffs. It is assumed that users in microcells transmit at higher rate than the ones in macrocells as the propagation environment in microcells is favorable to higher rates than in macrocells. Two system approaches can be considered here - a CDMA system which has same processing gain (PG) for all the users results in higher bandwidth for microcell users or alternately, a system employing PG which varies inversely with the user data rate results in the same spread bandwidth. The latter approach is used in this thesis. A simple receiver employing decision feedback equalizer DFE is used to cancel the interference, arising from the same and different data rate users and intersymbol interference ISI due to multipath channels. It has been shown that a DFE can be very effective against ISI and multiuser interference [8].

1.4 Thesis Organization

The following chapters of the thesis are organized as follows

Chapter 2 describes the characteristics of mobile radio channels detailing the types of fading which can occur in mobile cellular environment. CDMA systems are also discussed

describing Rake receivers and equalizers. The last section describes the overlaid cellular architecture and its use for service integration in PCS.

Chapter 3 gives the system description including the kind of modulation scheme used, channels, spreading codes, transmitter and the receiver structures used in the simulation. The RLS algorithm used for updating the taps of the equalizer in receiver is described. In the last section different scenarios employing multirate transmission in overlaid cellular system are discussed

Chapter 4 gives the results of the simulations for the different scenarios described in chapter 3. The results are discussed first for the case of Rayleigh fading for some scenarios. The change in performance for Ricean fading is discussed in the next section. The effect of spreading code of users on performance is also discussed. The last section describes the performance of DFE receiver in a near - far environment.

Chapter 5 summarizes the results of chapter 4. Conclusions are drawn and some proposals are presented for future work.

Chapter 2

Mobile Radio Communication

The communication channel defines the limits of performance that can be achieved in a system. It is therefore necessary to select a suitable model for the channel so that computer simulations can be used to predict system performance.

In this chapter, a review of the channel characteristics is presented which will help in determining a suitable model in the next chapter. Other important aspects of the system such as multiple access scheme and cellular architecture are discussed. Some research work done in the area of multiuser CDMA is also presented. The need for service integration is stressed which requires transmission and reception of multirate signals.

2.1 Mobile Radio Channels

The main impairment in mobile communications is the rapidly changing channel state. The radio waves reach the receiver via many paths after reflections by different scatterers. The presence of scatterers and movement of mobile constitute a constantly varying environment resulting in different signal paths that arrive at the receiving antenna displaced with respect to each other in time and space. This results in lengthening of the transmitted signal, a phenomenon known as delay spread. If a base station transmits an impulse signal $\delta(t)$ to the mobile unit, then due to multipath scattering the lowpass signal received at the mobile is given by

$$r(t) = \sum_l \alpha_l(t) e^{j\phi_l(t)} \delta(t - \tau_l(t)) \quad (2.1)$$

where $\alpha_l(t)$ is the attenuation factor for the signal received on the l th path, $\phi_l(t)$ is the time varying phase corresponding to the l th path and $\tau_l(t)$ is the propagation delay for l th path. As the number of scatterers increase the received discrete impulses become continuous pulse with a pulse length T_m equal to the composite delay spread. The delay spread dictates the time when the next pulse can be transmitted in order to avoid ISI. It is required that the signalling rate should be much less than $1/T_m$ to prevent intersymbol interference in a Rayleigh fading environment. The delay spread is generally larger in urban areas than in the suburban areas. The delay spread in urban areas can be up to 9 to 10 μs [9] while the mean delay spread for a suburban area is typically 0.5 μs [10]. The impulse response of the channel can be expressed as [11]

$$h(\tau; t) = \sum_l \alpha_l(t) e^{j\phi_l(t)} \delta(t - \tau_l(t)) \quad (2.2)$$

This multipath channel model results in fading which is primarily a result of time variation in phases. The time varying phases result in the vectors adding constructively at times giving large signal amplitudes and destructively at other times resulting in small signal amplitudes. Thus the amplitude variations in the received signal are due to time varying multipath characteristics of the channel. Depending upon the type of scatterers the envelope of the channel can be Rayleigh or Ricean distributed resulting in Rayleigh fading channel or Ricean fading channel.

2.1.1 Rayleigh Fading Channel

Whenever there is no line of sight (LOS) component in the signal arriving at the receiver then the small scale amplitude variations are considered to have Rayleigh distribution. The signal component arriving at the receiver through different paths have complex signal

strength given by

$$\alpha_l(t) e^{j\phi_l(t)} = X + jY \quad (2.3)$$

As the number of signal components arriving at the receiver is large so the central limit theorem suggests that X and Y are Gaussian distributed. Since X and Y are uncorrelated so they are also independent. In the absence of LOS component the mean of these Gaussian random variables is zero and the variance of each of the Gaussian distributed variable is σ^2 . The envelope $\alpha_l(t) = \sqrt{X^2 + Y^2}$ is a random variable with pdf given by [11]

$$p_{\alpha_l(t)}(r) = \frac{r}{\sigma^2} e^{-r^2/2\sigma^2} \quad r \geq 0 \quad (2.4)$$

which is known as Rayleigh distribution. The phase $\phi_l(t)$ is a function of path length, changing by order of 2π rad as the path length changes by a wavelength, so it can be modelled as uniformly distributed random variable over $(0, 2\pi)$.

2.1.2 Ricean Fading Channel

Ricean distribution is assumed for the amplitude variations whenever there is a LOS component arriving at the receiver. In this case channel consists of sum of a dominant non fading component and Rayleigh faded components. This results in complex Gaussian random variable having a non zero mean and common variance σ^2 for each Gaussian variable. The pdf of envelope is Ricean distributed and is given by [11]

$$p_{\alpha_l(t)}(r) = \frac{r}{\sigma^2} e^{-(r^2+s^2)/2\sigma^2} I_0\left(\frac{rs}{\sigma^2}\right) \quad r \geq 0 \quad (2.5)$$

where $\frac{s^2}{2}$ is the mean power in non fading component and I_0 is the zeroth order modified Bessel function of the first kind.

2.1.3 Shadowing

It has been repeatedly found that transmitted signals attenuate over smooth earth as a power of the distance from the transmitter. The small scale signal losses are shown to have Rayleigh or Ricean distribution. It is seen that although the local statistics may be Rayleigh [12] or Ricean the local mean varies because of the terrain and effects of other obstacles.

The local mean of the signal envelope is fairly constant over a few tenths of wavelengths. However, as the user moves over a large distance in the service area, the local mean varies due to the changes in the environment surrounding the user. Measurements taken in 800 - 900 MHz range suggest that the local mean follows log normal distribution [12]. These variations in the signal due to changes in environment surrounding the user are called shadowing effects or shadow fading. A cellular area may contain a number of shadow zones which extend over large area. As a mobile enters a shadow zone the mean signal strength decreases, increasing again as the mobile comes out of it. Shadow fading can only be averted by macro diversity, which uses signal from a group of nearby ports [13].

2.1.4 Average Power Delay Profile

For N power delay profiles the average power delay profile $P(\tau_l)$ is given by [9]

$$P(\tau_l) = \frac{1}{N} \sum_{i=1}^N p_i(\tau_l) = \langle |h(\tau_l; t)|^2 \rangle \quad (2.6)$$

where $p_i(\tau_l)$ is the i th power delay profile. All the profiles in a given profile set have the same specified delay τ_l . The average excess delay τ_e is measured by the first moment of the profile with respect to the first arrival delay and is given by

$$\tau_c = \frac{\sum_{l=1}^M \tau_l P(\tau_l)}{\sum_{l=1}^M P(\tau_l)} - \tau_A \quad (2.7)$$

where M is the index of the last sample along the delay axis which has significant amplitude and $l=1$ is a point before the minimum arrival delay τ_A at which the amplitude of profile is insignificant. The location of samples at $l=1$ and M is selected in such a way that moving the sample at $l=1$ to smaller delays and the sample at $l=M$ to larger delays does not affect the value of τ_c . The square root of second central moment of the power delay profile gives the rms delay spread

$$\tau_{rms} = \sqrt{\frac{\sum_{l=1}^M (\tau_l - \tau_c)^2 P(\tau_l)}{\sum_{l=1}^M P(\tau_l)}} \quad (2.8)$$

The average excess delay at a location in New York is reported [9] to be $1.9\mu s$ with the average absolute delay equal to $3.6\mu s$. The rms delay spread is reported to be $2.53\mu s$.

2.1.5 Fading Multipath Channel Characteristics

The impulse response of the channel $h(\tau; t)$ is generally assumed to be wide sense stationary, so the autocorrelation function of the impulse response is defined as

$$\phi_h(\tau_1, \tau_2; \Delta t) = \frac{1}{2} E [h^*(\tau_1; t) h(\tau_2; t + \Delta t)] \quad (2.9)$$

In mobile radio environment, the attenuation and phase shift of the channel associated with one path delay is uncorrelated with the attenuation and phase shift associated with another path delay. This type of scattering is called uncorrelated scattering. The uncorrelated scattering assumption gives

$$\frac{1}{2} E \{ h^* (\tau_1; t) h (\tau_2; t + \Delta t) \} = \varphi_h (\tau_1; \Delta t) \delta (\tau_1 - \tau_2) \quad (2.10)$$

This type of model is known as *wide sense stationary uncorrelated scattering WSSUS model*. When $\Delta t = 0$ in the above equation then the autocorrelation function $\varphi_h (\tau; 0) = \varphi_h (\tau)$ is the average power of the channel as a function of delay τ . $\varphi_h (\tau)$ is known as the delay power spectrum of the channel. The range of values of τ for which $\varphi_h (\tau)$ is nonzero is called the delay spread of the channel T_m .

The Fourier transform of the delay power spectrum is denoted by $\varphi_h (\Delta f; \Delta t)$ and is known as the spaced frequency spaced time correlation function of the channel. When $\Delta t = 0$ then $\varphi_h (\Delta f)$ defines the frequency coherence of the channel. This Fourier transform relationship between $\varphi_h (\Delta f)$ and $\varphi_h (\tau)$ suggests that the coherence bandwidth of the channel is given by reciprocal of the delay spread. i.e.

$$(\Delta f)_h = \frac{1}{T_m}. \quad (2.11)$$

When the frequency separation between the two signals is greater than $(\Delta f)_h$ they are affected differently by the channel. If $(\Delta f)_h$ for a channel is small compared to the bandwidth of the information signal transmitted through the channel then the channel is said to be frequency selective. i.e.

$$W \gg (\Delta f)_h \quad (2.12)$$

where W is the bandwidth of information signal. If $W \approx 1/T$ where T is the signalling interval then the frequency selective channel implies that

$$\frac{1}{T} \gg (\Delta f)_h$$

$$\text{or } T \ll T_m \quad (2.13)$$

If $(\Delta f)_h$ is large compared to the bandwidth of the information signal transmitted the channel is said to be frequency nonselective.

When Δt is nonzero, the time variations in the channel are a measure of Doppler shift. Consider that $S_h(\Delta f; \lambda)$ represents the Fourier transform of $\phi_h(\Delta f; \Delta t)$ with respect to Δt . When $\Delta f = 0$ then $S_h(\Delta f; \lambda) = S_h(\lambda)$ which is called the Doppler power spectrum of the channel. The range of values of λ for which $S_h(\lambda)$ is nonzero is called the Doppler spread of the channel denoted by B_d . The coherence time $(\Delta t)_h$ of the channel is given by the reciprocal of B_d . When channel is time invariant i.e. $\phi_h(\Delta t) = 1$ then $S_h(\lambda)$ is equal to the delta function $\delta(t)$. So a slowly fading channel has a larger coherence time and hence smaller Doppler spread.

It should be noted that the criteria that defines frequency nonselective fading, $T \gg T_m$, also makes intersymbol interference negligibly small. In this case the symbol energy extends only over a small leading portion of the next symbol interval. So, in frequency nonselective case, there is a duration $T - T_m$ for each received symbol which is free of intersymbol interference as it contains energy of that symbol only.

2.2 Code Division Multiple Access

Three access technologies are currently in common use in the wireless systems namely FDMA, TDMA and CDMA. Until 1990 FDMA was the most prevalent access scheme. In FDMA the entire bandwidth is divided into channels and these channels are distributed among the cells using a certain frequency reuse pattern. The bandwidth of these channels has been decreasing over the years, currently the channel bandwidth of 30kHz is mostly used. To use higher data rate services channels with higher bandwidth are needed, so certain channels have to be assigned which have a different bandwidth. However such a

scheme is spectrally inefficient, therefore, it can be assumed that in FDMA a scheme to integrate services having different data rates is inflexible and inefficient.

In order to get better flexibility frequency division multiplexing is combined with TDMA or CDMA to give FDM/TDMA and FDM/CDMA access systems. A TDMA system maintains the orthogonality of channels by separating them in time. If three channels are time multiplexed in one channel bandwidth of an FDM system then the system capacity increases by three times, however higher sampling rates are required to achieve this time orthogonality. TDMA system also has the inherent capability of integrating different data rate services by demanding multiple slots in a frame thus increasing the bandwidth. This approach is used in second generation mobile systems like GSM and IS-54. The main drawback of TDMA is the requirement of accurate timing clock. TDMA transmission also undergoes severe time dispersion. However the use of diversity schemes and adaptive equalization can increase the performance of the system.

The use of CDMA has gained popularity in the recent years, in this scheme each user in the system has a particular code with which the data is spread over a much wider band. Other users, using different codes, are also spread over the same band but do not significantly interfere with each other because of the orthogonality of codes. The receiver despreads the desired user by using the same code which was used to spread it at the transmitter. Other users however are not affected and remain spreaded thus decreasing the interference in the information bandwidth. The interference from other users depend on the processing gain (PG) which is defined as the ratio of spread bandwidth to the information bandwidth. Larger is the processing gain smaller is the interference encountered for a given number of users. The spreading of the signal reduces the amplitude of the signal by the factor of PG so that the signal becomes more closer to the noise sequence and hence becomes difficult to intercept. This advantage of spreading a sequence not only has con-

siderable importance for military application but also offers some gain for mobile communication where unscrambled signal can easily be intercepted by anyone.

In practice the codes are not perfectly orthogonal, however codes can be devised which give low cross correlation and auto correlation properties [14] so that several orthogonal carriers are created. An implication of the property of low cross correlation of the codes is that unlike TDMA or FDMA there is no hard limit to the number of users allowed in the system at a time. As the number of users increases, the signal quality degrades gracefully placing a soft limit on the number of users [15].

Two main reasons for the use of CDMA are (i) resistance to multipath fading and (ii) greater capacity [16]. Ideally, the signature sequence, as the spreading code is more commonly known, is completely random and has no correlation with its shifted version. So in the ideal case the correlation between two shifted versions of the code is zero. Therefore if the delay between two replicas of a signal is more than one chip the correlation between them is ideally zero and multipath fading is effectively removed. In practice such ideal spreading codes do not exist so a spreading code has some correlation with its shifted version resulting in intersymbol interference, but, CDMA greatly reduces it.

The capacity improvement [17] [18] [19] in CDMA systems can be evident by considering certain issues. Firstly, the use of CDMA allows improved frequency reuse. Cellular systems cannot use same transmission frequency in the adjacent cells because of interference problems but CDMA is inherently resistant to interference so the same spectrum can be used in every cell. This results in increase of frequency reuse efficiency by a factor of 4-6. The second consideration is the voice activity factor. When CDMA is used to transmit voice signals, capacity can be improved by exploiting the fact that voice activity is typically lower than 40%. In CDMA all the users share the same channel, so when some

of the users on that channel are not talking then all the other users on the channel benefit from less interference. Thus voice activity factor reduces the mutual interference by more than 60% and the capacity increases by more than 2.5 times. Another factor which translates directly into capacity improvement is sectorization in a cell. For a 120° beamwidth the interference sources seen by any antenna are approximately one third of those seen by omnidirectional antenna. As CDMA is interference limited so this reduction in interference results in three times increase in capacity.

One of the major system design problems in mobile cellular communication systems particularly in case of microcells is handoff. In CDMA as every cell uses the same spectrum so the only difference in going from one cell to the other is the code sequence. Therefore handoff from one frequency to another while moving from one cell to another is not required. So CDMA systems do not require hard handoff instead soft handoff is used [20]. The use of same spectrum in every cell also has the advantage that CDMA does not require complex frequency management schemes needed for FDMA and TDMA systems.

2.3 Multiuser DS-CDMA

A lot of research has been done in the field of CDMA in the recent years. This section presents some of the research done for multiuser Direct Sequence CDMA (DS-CDMA) for mobile communication.

A DS-CDMA system proposed by QUALCOMM [21] [17] is shown to give a many fold increase in capacity over FDMA and TDMA systems. The system capacity is shown for ten percent of the spectrum allocated for a cellular service provider. The forward link signals in the system share a quadrature pair of Pseudo Noise (PN) codes. Time offsets from the basic code are used to distinguish signals from different cells and sectors using the

autocorrelation property of the code. Signals transmitted from a single antenna in a CDMA radio channel are distinguished at the mobile receiver using 64 chip Hadamard or Walsh codes. The transmitted information is convolutionally encoded and scrambled. The reverse link design employs same PN sequence pair as used for the forward link. To identify signals from different mobile stations very long PN sequences are used with user address determined time offset. The information is convolutionally encoded and combined with 64 chip Walsh functions. The Walsh functions for the reverse channel are selected in a different way from the forward link. The capacity of this CDMA system is given by [21]

$$N = \frac{W}{R} \frac{1}{E_b/N_o} \frac{1}{d} \cdot F \cdot G \quad (2.14)$$

where N = calls per cell
 W = spread spectrum bandwidth (1.25 MHz)
 R = data rates in kbps (9.6 kbps)
 E_b/N_o = bit energy to noise power spectral density ratio (6 dB)
 d = voice duty cycle (50%)
 F = frequency reuse efficiency (60%)
 G = number of sectors in the cell (3 for 120° antenna beamwidth)

the above values give a capacity of 120 CDMA channels in 1.25 MHz bandwidth. In [17] the capacity is shown to be 108 channels in the same bandwidth for $R = 8$ kbps and $E_b/N_o = 7$ dB. This capacity is 18 times that of FDMA and 6 times that of TDMA assuming three users sharing a channel.

The single most important system requirement is identified to be power control. The power control scheme used at forward link of each cell reduces the interference to adjacent cells. The less the interference generated in a cell, the more the number of users

which can be accommodated. The power control issue is more sensitive on the reverse link. If all the mobiles are transmitting at the same power then a strong signal received from a mobile near the base station will mask the weak signal from a mobile far from the base station. To reduce this near far interference a power control scheme is required at the reverse link.

M. B. Pursley [22] gives criteria for selection of code sequences for phase coded (DS) SSMA system. An upper bound on the worst case error probability is derived which may be useful for some SSMA systems. However, unless the period of code sequences is much larger than the number of users, these bounds are of no value and the maximum error probability is not a useful performance parameter. An alternate approach is to treat interference terms as additional noise. The signal to noise ratio at the output of the correlation receiver is used as a criterion for code selection and can be computed with reasonable amount of computation. A formula is derived which can be used to determine what code sequence length, bit energy and noise density are required to achieve certain signal to noise ratio for a given number of users. Another formula derived can be used to determine the performance given by a specific code sequence.

D.E. Borth and M. B. Pursley [23] give the analysis of DS-SSMA systems over channels which have sufficient amplitude of specular components so that the effects of fading on the performance can be neglected. Signal to noise ratio is considered as the measure of performance over WSSUS channels for the two specialized cases of time selective and frequency selective fading channels. The analysis assumes that frequency selectivity is such that it results in intersymbol interference only due to two adjacent data symbols. It is shown that signal to noise ratio degrades in proportion to the intensity of fading, which is to be expected. An assumption which follows would be that a SNR higher than that obtainable for a given E_b/N_o can be obtained by increasing E_b/N_o . However, it is shown

that this approach is not valid as SNR curve flattens out as E_b/N_o increases. The performance of DS-SSMA is shown to be much better than that of biphase PSK. Most of this improvement is attributed to multipath rejection capability of a spread spectrum system. It is also shown that there can be significant difference in performance depending upon whether a good set of signature sequences is used or not.

J.S. Lehnert and M.B. Pursley [24] have derived upper and lower bounds on the average probability of error for random signature sequences. The bounds derived are tight and can be used for a system with large number of users. The results are compared for the case when Gaussian assumption is used for multiple access interference. It is shown that for a small number of users Gaussian assumption is only good for a small value of E_b/N_o . However, the Gaussian assumption becomes better as the number of users increases and the dependence on E_b/N_o reduces as the length of spreading sequence increases for a given average probability of error.

The authors in [25] derive the average probability of bit error for the case of multipath environment which is not considered in [24]. An approximation to average probability of bit error is derived by modelling the decision statistics as Gaussian. It is also assumed that variance of number of paths received from each user is small which is necessary to achieve good results. Each user is assumed to have a number of spreading sequences one of which is used for every few bits. This reduces the correlation between two successive sequences sent. It is shown that better performance results as the spreading gain increases and the Gaussian approximation becomes more realistic with increase in the number of users. The assumption is more accurate when spreading gain is very large as for this case multiple access interference and intersymbol interference become small compared to the Gaussian noise at the receiver. Another approximation is considered which is appropriate for a wider range of system conditions, this approximation applies Gaussian assumption to

the conditional density of decision statistics and requires more computation than the first one. It is shown that channel parameters have to be known to achieve large gains with this system. The knowledge of channel parameters is however very difficult to achieve in a typical mobile environment where the channel is continuously changing.

The near far problem which is considered the main shortcoming of code division multiple access system is not an inherent characteristics of CDMA systems rather it is the inability of the conventional single user receiver to exploit the structure of multiple access interference. Some researchers like Lupas and Verdu [26] have studied multiuser detectors for synchronous CDMA which are near far resistant under mild conditions. Linear transformations are used to obtain various multiuser detectors. A decorrelating detector is presented which does not require knowledge of the energies of any of the other active users. The decorrelating detector has a linear complexity in the number of users when used in a fixed energy environment otherwise complexity is exponential. The performance of the decorrelating detector is shown to be either the same or quite similar to the optimum linear detector depending on the energies and correlations. The optimum linear detector has exponential complexity in the number of users. The only requirement for the reliable detection of user signal regardless of the level of multiple access interference is that it does not belong to the subspace spanned by the other signals.

The research in [26] is later generalized for asynchronous CDMA systems by the same authors [27]. It is shown that the decorrelating detector is also near far resistant in asynchronous CDMA system and gives a performance which is equal to the worst case performance of the optimum detector. The receiver in both cases has the knowledge of the spreading sequence of all the users. It is also suggested that if a filter is a good enough approximation of the decorrelating receiver then it will not be near far resistant in the worst case sense defined above, however, the bit error rate will be very insensitive to the

energy level of the interferers. So the near far problem can be preserved within any desired energy range.

In [28] Duel-Hallen describes a decorrelating decision feedback multiuser detector for synchronous CDMA. This approach requires the knowledge of user energies in addition to their spreading sequences. Decisions for the users are made in the order of decreasing received energies. Thus the receiver for the strongest signal does not involve feedback and is equivalent to decorrelator. The detector for the weakest user utilizes decisions for all others and if all the feedback symbols are correct it achieves the performance of the single user system.

After having described some important research done for multiuser CDMA we would like to review two types of receiver structures which we consider important for CDMA systems. These are the Rake receiver and adaptive equalizer receiver.

2.3.1 Rake Receiver

Rake receiver is a simple and efficient method of obtaining diversity in a wideband signaling environment like CDMA. A multipath channel is simply the one where energy arrives at the receiver via several paths. Most analyses in a fading environment assume a receiver which attempts to demodulate the signal received over one fixed path or the strongest path only. Signals over other paths are suppressed by the receiver and hence the information and energy contained in those paths is discarded. A unique capability of spread spectrum is the exploitation of multipath to provide path diversity. A receiver which makes use of this inherent diversity was invented by Price and Green [29] and is called a Rake receiver because of its resemblance to a garden rake.

Consider a signal transmission which is received via K paths, where K is a random vari-

able which varies from one transmission to another. The k th path can be completely characterized by the path strength a_k , path delay t_k and its carrier phase shift θ_k . In spread spectrum we can assume that all paths are resolvable provided

$$(|t_k - t_l| > 1/W) \quad \text{for all } k \neq l$$

where W is the transmission bandwidth, that is when the separation between paths is greater than one chip period. The signal paths that do not satisfy the above equation are considered as a single path with delay given by $t_k \approx t_{k_1} \approx t_{k_2}$ and strength and phase given by

$$a_k e^{j\theta_k} = a_{k_1} e^{j\theta_{k_1}} + a_{k_2} e^{j\theta_{k_2}}$$

Assume that we can accurately estimate atleast the path strength and path delay. In the mobile environment the changes in phase shift occur too rapidly to be tracked so we can neglect the phase estimates. In case the paths are strong enough with respect to noise so that they can be measured accurately, the optimal combining of the samples is given by[16]

$$w \approx \frac{2}{N_o} \sum_{k=0}^{K-1} \hat{a}_k \hat{x}_k \quad (2.15)$$

where N_o is the noise power spectral density, $\hat{a}_k$ is the estimate of the strength of k th path and $\hat{x}_k$ is a sample of match filter output envelope at $t = T + \hat{t}_k$, $\hat{t}_k$ being the estimate of k th path's delay.

The linear combiner can be realized using a transversal filter whose input is the output of the envelope detector. The filter consists of a delay line which is T_m seconds long where T_m is the delay spread of the channel. The delay line is tapped every $1/W$ seconds for a

total of WT_m taps. Only those paths contribute to the output which have a significant path strength. The estimates $\hat{\tau}_k$ are used to determine these significant paths, the taps for which these estimates are equal to the tap delays measured from the right hand end of the line are turned on. The tap coefficients are set to be proportional to the corresponding path strength estimates $\hat{a}_k$. Therefore the output of the transversal filter is a weighted sum of certain tap outputs. The output of the Rake receiver as defined above is equivalent to a maximal ratio combiner in the system [11].

It should be however noted that ISI cannot be avoided, even in spread spectrum systems, with data rates greater than $1/T_m$ bits per second. When PG is very large only a few percentage of the taps is activated at one time and the probability that multipath pulses from predecessor and successor symbols would appear at the taps which are activated is small [16]. So the intersymbol interference is considerably reduced. However, for smaller PGs equalization is required to cancel ISI.

In [30] Turin gives the performance of the Rake receiver by considering two cases. In the first case it is assumed that each signal follows only one path over non fading link and that each user has equal power. In the second case it is assumed that each link has multiple paths that might be fading. In both cases the interference from other simultaneous users is modelled as Gaussian noise. It is shown that performance degrades five to twenty folds in going from first case to the second one. The decrease in the performance is attributed to the fact that fading of interferers by multipath causes a version of near far problem with the desired user undergoing a deep fade while the one or more interferers might present an unusually strong signal.

Rake receiver and similar adaptive channel estimators can be used in a multistage algorithm for interference rejection. Such a structure is shown in [31] where Rake is used to

simultaneously estimate received data and channel impulse response for each user. The estimate signal is then reconstructed and subtracted from the received signal as it forms the interference. The new received signal is used to perform another stage of estimation. This iterative approach is used to eliminate the multiuser interference. In [32] the authors present a multistage Rake receiver for CDMA systems. The receiver does not require knowledge of signal power of users or the channel parameters. The Rake receiver simultaneously estimates the multiple access interference and channel impulse response of the multipath channel. The estimation and interference cancellation process can be repeated for an arbitrary number of stages as in the previous research work. The authors have simulated the receiver for the case of two stages and shown that the performance of the receiver with 2 stages and 7 users is better than the performance when there are 2 users and a single stage receiver for a BER of 10^{-4} .

Most of the receiver structures discussed up to now require the knowledge of users' energies, channel parameters or their spreading codes. The knowledge of energies and channel parameters of all the users is very difficult in mobile environment. Moreover, the use of all the spreading codes in a receiver structure makes it complex. Also the knowledge of spreading code of other users may cause a security problem. However, the knowledge of these parameters is not required if adaptive equalizers are used in the receiver.

2.3.2 Adaptive Equalization

One of the important category of interference rejection techniques used in CDMA is adaptive equalization. It has already been stated that when the transmission rate is greater than the inverse of the delay spread the spread spectrum system suffers from intersymbol interference apart from the multi access interference caused by a number of users operating in the same band.

There are two main classes of equalizers - linear equalizers and nonlinear equalizers. Linear equalizers work on the principle of zero forcing or minimization of mean square error. Zero forcing equalization, first suggested by Lucky [33], requires that the equalizer taps are adjusted to force the ISI to zero without regard to any noise enhancement. The mean square error (mse) criterion, on the other hand, chooses equalizer coefficients which minimize the equalizer output mse due to both residual, ISI and noise. A method to update the equalizer coefficients recursively known as Least Mean Square (LMS) algorithm using the mse criterion was first proposed by Widrow and Hoff [34]. The linear mse equalizer also suffers from the noise enhancement problem. The noise enhancement is unacceptable when the channel experiences severe amplitude distortion. The linear equalizer is therefore not suitable for mobile radio communication where deep fades often occur.

The nonlinear equalizers are less susceptible to noise enhancement problem as they do not attempt to invert the folded channel spectrum like the linear equalizers. A decision feedback equalizer (DFE) is a nonlinear equalizer which consists of a feedforward filter similar to a linear equalizer and a feedback filter whose input is the sequence of decisions on previously detected symbols. The feedforward and feedback taps of DFE can be adjusted simultaneously using the minimum mse criterion. The feedforward filter of the DFE eliminates precursor ISI while the feedback filter removes the postcursor ISI by removing exactly the ISI contributed by already detected symbols to the present estimates if all the past decisions are assumed to be correct [35].

Monsen [36] [37] has shown that the performance of a DFE is better in the presence of multipaths because of the implicit diversity gain obtained which is larger than the ISI degradation. As a DFE removes ISI without inverting the spectrum and hence without excessive noise enhancement so it performs superior to a linear equalizer in deep fading environment. It is shown [38] [39] that the performance of DFE is nearly as good as that

of MLSE as long as decision error propagation is not severe. The DFE on the other hand has a complexity which is much less than that of a MLSE. Also as the feedback filter eliminates all the postcursor ISI, the number of forward filter taps in DFE can be reduced relative to the number of equalizer coefficients required in a linear equalizer. This results in lesser coefficient noise for the same convergence rate as the coefficient noise increases with the number of taps.

The advantages offered by equalizers have led many researchers to look into receiver structures employing equalizers for CDMA systems. In [8] the authors describe the use of DFE for indoor CDMA systems. It is shown that DFE combines the advantages of Rake by exploiting the inherent diversity resulting from multipath and performs cancellation of ISI and multiaccess interference. Two configurations of the DFE receiver are discussed, one configuration uses information about the desired user's spreading code while the other assumes no such knowledge. Both configurations assume no knowledge of channel parameters, a training sequence is however used to train the equalizer. The DFE receiver is shown to perform much better than a single stage Rake receiver. A gear shifting normalized least mean square (NLMS) algorithm is used to update the equalizer coefficients which gives better convergence rate and a mse slightly better than conventional LMS algorithm. It is shown that the two configurations give comparable performance for small number of users, however, the first configuration, which employs knowledge of desired user's spreading code by using a filter matched to desired user's spreading code, gives better performance for larger numbers of users than the second configuration which uses no information of desired user's spreading code. The second configuration uses a low pass filter at the receiver input to band limit noise. The power control in the system is assumed to be imperfect and is only applied in an average sense. The receiver is shown to accommodate a number of users equal to half the PG for a system employing very low process-

ing gain.

Madhow and Honig [40] consider interference suppression schemes for DS-CDMA systems using mmse criterion. The schemes are simple to implement and use linear filters employing mmse adaptive algorithms. One scheme uses N -tap filter where N is equal to the PG. As N could be large requiring large number of taps increasing coefficient noise, so two other schemes are proposed with fewer adaptive parameters. The schemes are compared using three user system and PG of 31 and are shown to give low error probability no matter how strong is the interference.

Rapajic and Vucetic [41] describe a receiver for an asynchronous CDMA system in which the receiver uses LMS algorithm for each user. The receiver is assumed to have no knowledge of signature waveforms or timing information of other users. The receiver is simulated by using a set of Gold sequences of length 31 and is shown to have considerable improvement with respect to conventional single user receiver. Wilson and Cioffi [42] have shown a linear equalizer to perform much better than a Rake detector in a multichannel environment in the presence of near far problem.

2.4 Service Integration Issues

All sections of wireless communication are going through a phenomenally rapid growth which started almost a decade ago. Apparently, the growth in voice related application has benefitted from better publicity since it relates to the ordinary person on the street. However, the applications involving data have not lagged behind. Recently, the system operators are making provisions to transmit data over the cellular systems which were primarily designed for voice. This has resulted in a high increase in demand for more spectrum. To accommodate ever increasing number of subscribers within the assigned spectrum, exten-

sive frequency reuse has to be employed. To cover densely populated areas small cell operation becomes necessary. This requires low transmit power to limit intercell interference which incidentally meet the two important acceptability criteria for the user - small terminal and low power transmission.

The small cell operation has the disadvantage of large number of handoffs [5] when the mobile terminal moves rapidly through the coverage area. Thus larger cells are more appropriate from the point of view of handling fast moving terminals. However, the large cell operation has an important implication on the cellular system's data handling capability. This is due to the relatively large channel delay spread. It is well known that maximum reliable transmission rate over a channel is inversely proportional to the channel delay spread. Over uniform terrain conditions delay spread is proportional to cell size i.e. small cells with shorter delay spread are capable of handling high rate transmission and vice versa. Thus as the cell size increases, the maximum transmission rate decreases and the use of channel equalizers becomes necessary if the large cell radio channel is to support higher data rates.

The subscribers of today demand a large category of services. These include voice, paging, variable data rate services and both low and high definition images. A desire to access all these services or a chosen subset of these with only one Universal terminal is of great importance to Personal Communications. In Europe a modified approach based on TDM/TDD technology to deliver PCS services is being debated. GSM, DECT, CT2 and DCS1800 are the few examples of systems which have been standardized. GSM is quietly emerging as an international standard. DCS1800 modified for small cell operation is based on GSM, the latter was designed for VMCS. This is well thought strategy because related baseline systems for GSM, DCS1800 and DECT make integration of these systems relatively easier. Thus, in Europe the dream of using a single terminal to access a multitude of

services is much closer to fulfillment than in North America.

In North America the PCS scene is quite chaotic. The desire to reduce the effects of environmental vagaries led to several systems, designed for particular applications and operating environments. Distinct systems have been proposed and designed for indoors, outdoor microcells, VMCS and satellites. The various standards have created dilemmas for both service providers and users. The IS-54 system primarily designed for voice services may be used to support low data rate services but is unable to provide medium to high speed data services. In microcellular and indoor applications where higher data rate services could be provided TDM/TDD or CDMA technologies are being considered. Thus, short of developing a new standard, a baseline system facilitating service integration is currently not available.

Two strategies can be adopted to provide service integration. A universal terminal can be developed which would integrate several systems distinct in transmission bandwidth, modulation format, data rates, coding and decoding. The development of this terminal may be a short term solution. Besides, such terminals can only integrate a limited number of systems and thus services while being comparatively large and power hungry. The second strategy involves development of a suitable baseline system facilitating integration of a multitude of services. This strategy will have to progress through standardization process which is usually difficult and expensive.

It is likely that a need to standardize an entirely new wireless integrated system will be felt in near future. Therefore, a flexible integrated PCS system using CDMA overlaid concept is proposed. The flexibility in the system is achieved by varying burst rate which commensurates with selected service. The same transmission bandwidth is used for all services. On selecting a low rate service the terminal lowers the burst rate which increases with

Figure 2.1 Overlaid Cellular Architecture

high rate services. Thus, the integration is more flexible. The choice of spreading bandwidth is important because it ultimately defines the services. For example narrower bandwidth in IS-95 system limits the data rate to 9.6 kbits/sec. The flexibility in service selection can be increased by either using wider bandwidth CDMA or defining a relatively narrow bandwidth CDMA within TDM or TDD. The choice of TDD or TDM depends upon the application. For example, for microcells TDD is better while for interlinking satellites TDM is more attractive.

An overlaid cellular structure combines the advantages of microcells and macrocells. Microcells provide increase in the capacity of the system while macrocells allow fast moving terminals without excessive handoffs thus improving communication quality. This architecture is described in [6] [7] and is shown in Figure 2.1. An algorithm has to be developed by which a mobile station MS chooses whether to select a microcell channel or a macrocell channel. Typically, it is desired that microcell channels be assigned to only stationary or quasi stationary MS so as to avoid excessive handoffs. A mobile station may not be allowed to select a microcell channel unless it receives the signal from microcell base station BS for a certain minimum amount of time. This insures that the mobile is not moving fast enough that a microcell channel can be allocated.

CDMA has been proposed as a method to provide expanded capacity and PCS features by overlaying existing cellular systems [43] or fixed microwave service [44]. It has also been proposed to provide microcells underlying existing cellular macrocells [45]. A structure similar to the one shown in Figure 2.1 is compared in [46] for two different access schemes packet reservation multiple access PRMA and CDMA. The performance of the two access schemes in overlaid cellular environment is compared from the point of view of spectrum efficiency as the two schemes cannot be compared in terms of interference probability. The authors show a better performance for PRMA for the same value of E_b/N_o .

used for both schemes. However it is suggested that no definite conclusion can be drawn at this early stage of research as some factors if taken into account can change the picture completely. These factors are channel coding which is totally free in CDMA and the fact that fixed reuse pattern can hardly be identified in microcellular environment. This causes problems in PRMA which cannot follow a solution like in classical schemes.

Chapter 3

System Description and Simulation Design

This chapter describes the details of the system used in the simulation. A description of the transmitter and receiver architecture including the receiver filter and DFE is given. Different scenarios which are possible in an overlaid cellular environment are presented and channel models used in the simulation are described.

3.1 Transmitter

In a multiuser system, a number of users are transmitting at the same time. The output of the i th user is given by

$$x_i = \sqrt{2} \operatorname{Re} \left\{ \sum_{k=1}^{\infty} x_{i,k} c_i(t - knT_c - \tau_i) e^{j\omega_c t + \phi_i} \right\} \quad (3.1)$$

Each user has the same carrier frequency $\omega_c = 2\pi f_c$ and ϕ_i is the phase angle of the i th user. τ_i is the delay for the i th user and T_c is the chip period. BPSK modulation is used for each user. It is suggested in [47] that BPSK gives performance similar to QPSK and is preferable as it uses one spreading code per user compared to two spreading codes (in I and Q channels) per user needed for QPSK. This advantage leads to the use of a smaller set of codes. Each user encodes a binary data stream into BPSK (1,-1) code stream $\{x_{i,1}, x_{i,2}, x_{i,3}, x_{i,4}, \dots\}$. The data symbols $x_{i,k}$ are assumed to be independent and identically distributed random variables for which $Pr\{x_{i,k} = 1\} = Pr\{x_{i,k} = -1\} = 1/2$. The equivalent baseband equation is given by

$$x_i = \sum_{k=1}^{\infty} x_{i,k} c_i(t - knT_c - \tau_i) \quad (3.2)$$

It is convenient to use equ. (3.2) representing the baseband equivalent of equ. (3.1) for simulations. Each user is assigned a n -chip code sequence

$$c_i(t) = \sum_{j=1}^n c_{ij} \Psi(t - jT_c) \quad (3.3)$$

where $c_{ij} \in \{\pm 1\}$ are independent identically distributed random variables each occurring with a probability of 1/2. It is assumed that each code spans one symbol period i.e. the number of chips $n = T/T_c$ where T is one symbol period. $\Psi(t)$ is chip pulse shape given by

$$\Psi(t) = \begin{cases} 1 & \text{for } 0 \leq t \leq T_c \\ 0 & \text{everywhere else} \end{cases} \quad (3.4)$$

The simulation uses four samples per chip with the chip waveform normalized to one, this means that each sample in the chip has a height of 0.5 giving a rectangular pulse shape and $T_c = 1$. The transmitter model considered in the system is shown in Figure 3.1 along with the channel model and noise.

The spreading code used for a user in the simulation is a row of Hadamard matrix containing equal number of +1's and -1's. The Hadamard codes have the property that every code in the Hadamard matrix is orthogonal to the other. The delay spread in microcell channel is less than that in larger cell because of lower transmitted power. As the maximum possible transmission rate is inversely proportional to delay spread so a user in microcell can support higher data rates than a macrocell user. In the simulation a user using a macrocell channel is assumed to have a data rate which is half that of the user using a microcell channel.

Figure 3.1 Transmitter and Channel Model

Same transmission bandwidth is assumed for all the users with two different PGs employed in the system. The transmission bandwidth of a user is defined by the chip period T_c with bandwidth $W = 1/T_c$, therefore, it is assumed that T_c is same for microcell and macrocell users. This means that the users using the microcell channels have a PG which is half that of users using macrocell channels. The situation is shown in Figure 3.2.

The PGs used in the system are 16 and 32. The data symbol waveform shown in Figure 3.2 (a) has a data rate which is twice that of the waveform in Figure 3.2 (b). In both cases the coded signal is shown below the data symbol waveform for the spreading code corresponding to second row of the Hadamard matrix, this code consists of alternating +1's and -1's in both cases - for PGs of 16 and 32. This code will be used for the desired user in the simulations unless otherwise specified. The codes corresponding to microcell and macrocell users have a PG of 16 and 32 respectively resulting in the same transmission bandwidth.

3.2 Channel Model

The channel model used in the simulation is a WSSUS channel model. The channel has a fixed number of paths and is given by

$$h(t) = \sum_{l=1}^L \alpha_l(t) e^{j\phi_l(t)} \delta(t - \tau_l) \quad (3.5)$$

where $\alpha_l(t)$ is Rayleigh or Ricean distributed amplitude of the l th path and $\phi_l(t)$ is the phase shift associated with the path. L is the number of paths used and is equal to three for the simulation and τ_l is the delay of the l th path. The delay spread in the system is assumed to be equal to six chip periods. As the transmitted bandwidth is much larger than the coherence bandwidth, the channel is frequency selective. Therefore, the channel con-

(a) for microcellular users

(b) for macrocellular users

Figure 3.2 Data Symbol and Transmitted Symbol

sists of three paths occurring randomly within a period of $6T_c$. In order to give an illustrative example of the delay spread used in the simulation, assume that delay spread is equal to $5.86 \mu s$ which is a typical delay spread in an urban environment. This gives a transmission rate of 32 ksymbols/sec for the macrocell users and 64 ksymbols/sec for the microcell users. The transmitted bandwidth for this delay spread is approximately 1 MHz which is close to the bandwidth used in the QUALCOMM system.

The three ray channel model is shown in Figure 3.3 with T_A equal to arrival time of a path in terms of chip period with respect to first path. The complex tap coefficient vector $[h_{i,0} \ h_{i,1} \ h_{i,2}]^T$ gives the amplitude and phase of each path. All the users are assumed to start their transmissions at the same time. Therefore, the delay τ_i in equ. (3.1) is assumed to be zero with the first path of all the users occurring at the first chip so that all the users' transmissions are synchronized. The second and third paths are randomly selected to occur within the next five chip periods with the second path occurring within T_A to $3T_A$ and the third path occurring within $3T_A$ to $5T_A$. It can be seen that both the 2nd and 3rd paths can occur at $3T_A$ with respect to the first path, however, the simulation is designed in such a way that if the 2nd path occurs at $3T_A$ with respect to the first path then the third path will occur at $4T_A$ or $5T_A$ with respect to the first one. Each path consists of a complex Gaussian variable given by equ. (2.3). In case the envelope $\alpha_i(t)$ is Rayleigh distributed the variance of the envelope satisfies the relation

$$\frac{1}{2}E(\alpha_i^2(t)) = E(X^2) = E(Y^2) \quad (3.6)$$

A Ricean distributed envelope consists of a dc component added to the complex Gaussian variable [48]. The ratio of power of the dc or LOS component to the power of multipath signal is denoted by 'k' and gives the strength of the LOS component relative to the Rayleigh faded component.

Figure 3.3 3 Ray Channel Model

The variance of each path of Rayleigh channel and the Rayleigh faded component in Ricean channel is considered to decay according to the relation $e^{-(T_A/3)}$. Therefore, the variance of each path is exponentially decreasing, this is the so called *exponential variance* model of [47]. The exponential variance model is shown in Figure 3.3 (b). The total variance of the three paths of the channel is equal to one which means that the channel profile is normalized. This means that the sum of power of the three paths at a given time may not be equal to one but the average over a long time will be equal to one. This type of channel model will result in only an imprecise power control as the power of various users at the receiver will only be equal in the average sense if the transmitted power is same. Although the average power of users is same but the power of different users at a particular instant of time may be different. This type of power control is called *average power control* [47].

The effects of shadowing are not considered in the simulation. The signal after passing through the channel is given by

$$d_i = \sum_{k=1}^{\infty} x_{i,k} \sum_{l=1}^L \alpha_l(t) e^{j\phi_l(t)} c_i(t - knT_c - \tau_i - \tau_l) \quad (3.7)$$

The noise is added to the signal before the receiver. The noise is additive, white and Gaussian AWGN with two sided power spectral density equal to $N_0/2$. The noise is modelled as a zero mean complex Gaussian variable. The real and imaginary components of noise are independent and uncorrelated, this is also true for samples of noise at different time as the autocorrelation of AWGN is a delta function.¹

¹. The fact that autocorrelation of AWGN is a delta function implies that different samples of noise are uncorrelated. Since noise is modelled as a Gaussian process so the samples will also be independent.

3.3 Receiver

The signal arriving at the receiver is given by

$$d(t) = \sum_{i=1}^N d_i(t) + n(t) \quad (3.8)$$

where N is the number of users and $n(t)$ is the additive white Gaussian noise. As the white noise process has a two sided power spectral density of $N_0/2$ for all frequencies so the average noise power, or noise variance as noise has zero mean, is infinite. Therefore, the received signal has to be passed through a receiver filter to bandlimit noise. The variance of noise at the output of receiver filter is finite. The receiver filter used in the system consists of a filter which is matched to the spreading code and the pulse shape of the desired user. The output of this matched filter is a function of autocorrelation with the desired user and crosscorrelation with the other users. As the crosscorrelation between the desired user and other users is less than the autocorrelation function this receiver filter helps in reducing the effects of interfering users on the desired user. The output of the filter is sampled at the chip rate before being fed to the forward filter of the decision feedback equalizer.

Direct form of the Recursive Least Square (RLS) algorithm is used to update the taps of the DFE. The main advantage offered by the RLS algorithm is its fast convergence rate which may be necessary to track the rapid changes taking place in an outdoor environment. The RLS algorithm is relatively insensitive to variations in the eigenvalue spread of the correlation matrix of the tap input vector which is a problem with the Least Mean Square (LMS) algorithm. The LMS algorithm has a much slower convergence rate than the RLS algorithm, the convergence rate is specially slow when the eigenvalue spread is large. The RLS algorithm is, however, computationally complex (the number of computations required to compute the variables to update the taps is proportional to M^2 where M is

Figure 3.4 Receiver Structure

the number of taps) compared to the LMS algorithm - a compromise to pay to achieve fast convergence.

The receiver structure is shown in Figure 3.4. The output of the receive filter is denoted by $v(t)$ while v_i denotes the sample taken at time iT_c . These chip spaced samples constitute the input to the feedforward filter while the feedback filter gets the output of the decision device every symbol. The tap input vector is given by

$$\mathbf{y}_k = [v_{i+f} \ v_{i+f-1} \ v_{i+f-2} \dots \ v_{i+1} \ v_i \ \tilde{x}_{1,k-1} \ \tilde{x}_{1,k-2} \dots \ \tilde{x}_{1,k-b}]^T \quad (3.9)$$

$\mathbf{y}_k$ indicates the tap input vector needed to make decision for the k th symbol. The feedback filter taps have the past decisions corresponding to the first user at their inputs as user 1 is assumed to be the desired user. The number of feedforward taps is $(f + 1)$ and feedback taps is ' b ' giving a total of $M = f + b + 1$ taps. The input to the decision device is given by

$$\hat{x}_{1,k} = \mathbf{y}_k^T \mathbf{w}_{k-1} \quad (3.10)$$

where $\mathbf{w}_{k-1}$ is the column vector of equalizer coefficients updated at time $(k - 1)$ and used at time k . The vector $\mathbf{w}_{k-1}$ is given by

$$\mathbf{w}_{k-1} = [w_{k-1}(-f) \ w_{k-1}(-f+1) \dots w_{k-1}(0) \ w_{k-1}(1) \dots w_{k-1}(b)]^T \quad (3.11)$$

A decay factor λ is used which has a value slightly less than one. This weighting factor helps to forget the past data which is suitable for a time varying channel characteristics. The equalizer coefficient vector is determined so as to minimize the time averaged weighted square error. The following set of equations summarize the algorithm used to update the coefficients [11]

$$\begin{aligned}
e_k &= \tilde{x}_{1,k} - \hat{x}_{1,k} \\
k_k &= p_k y_k^* \\
&= \frac{p_{k-1} y_k^*}{\lambda + y_k^T p_{k-1} y_k} \\
p_k &= \frac{1}{\lambda} [p_{k-1} - k_k y_k^T p_{k-1}] \\
w_k &= w_{k-1} + k_k e_k
\end{aligned} \tag{3.12}$$

e_k is the equalizer output error at time k , $p_k = R_k^{-1}$ is the inverse of the correlation matrix R_k ¹. Since it is computationally complex to calculate the inverse of matrix in each iteration so the matrix p_k is computed recursively as in equ. (3.12). It is necessary that an initial value is set for p_k , this value is set at²

$$p_o = \delta^{-1} I \tag{3.13}$$

where I is a $(M \times M)$ identity matrix, the value of δ is selected to ensure nonsingularity of R_k . The $(M \times 1)$ order matrix k_k is called the Kalman gain vector. The fast convergence speed of the RLS algorithm is due to the fact that each tap is controlled by one element of k_k which is adjusted every iteration. This gives RLS algorithm M adjustable parameters compared to only one adjustable parameter, the step size, available in LMS algorithm.

It is customary to set the initial value of equalizer coefficient vector equal to a null vector. Therefore

$$w_o = 0. \tag{3.14}$$

The equations 3.12-3.14 define the RLS algorithm used in the simulations.

¹. The correlation matrix R_k is defined as $\sum_{n=1}^k \lambda^{k-n} y_n^* y_n^T + \delta \lambda^k I$ where δ is a small positive constant.

². The value of $R_o = \delta I$, therefore the value of $p_o = \delta^{-1} I$

3.4 Overlaid Cellular Scenarios

The overlaid cellular structure is shown in Figure 2.1. A number of different scenarios emerge in such an overlaid structure as the mobile station moves around. It is assumed that a Ricean channel will be available for most of the time to a user when located in a microcell. However such a condition will not occur after the MS turns a corner. In a macrocell, most of the time a user has a Rayleigh channel available unless it is very close to the BS and has a direct LOS path. So depending upon whether a user is in a microcell or a macrocell the channel characteristics will be different.

Different scenarios can occur when the user is in a microcell and may be using a microcell channel or a macrocell channel. If the user in a microcell is using a channel from the macrocell then it will experience the desired signal over a Rayleigh channel with the interference coming over Rayleigh and Ricean channels from the BSs in the macrocell and microcell respectively. This will be the case of the forward channel, in the reverse channel the desired user and interference will be over Rayleigh channel. The interference from the microcell users will be negligible at the macrocell BS as the power of the users in the microcell is much smaller than that in the macrocell. An appreciable amount of interference from microcell users will only be able to reach the macrocell BS if the microcell is close to the macrocell BS. Such a scenario is however not considered because of the high interference from the macrocell users to the microcells which will occur.

In the scenario when a user in the microcell is using a microcell channel then the desired signal will reach the MS on the forward channel and the BS on the reverse channel over Ricean channel for most of the time. The user will experience interference coming over Rayleigh and Ricean channels from macrocell and microcell BSs on the forward channel. For the reverse channel the interference from microcell users will be over Ricean channel

while the interference from the macrocell users will be over Rayleigh and Ricean channels depending on whether the macrocell user is outside the boundary of the microcell or not. It should be noted that although the microcell users will experience Ricean interference, this may not be the case always. It has already been mentioned that at some locations within the microcell a LOS path may not occur so a transmission over Ricean channel implies that this will be the case for most part of the transmission.

The user in the macrocell will receive the desired signal over a Rayleigh channel unless it is very close to the BS - a case that occurs less frequently. In case of forward channel, the interference coming to the user will also be over Rayleigh channels. The interference from the microcell will only be appreciable if the user is close to the microcell boundary. For the reverse channel the interference coming from microcell will be negligible because of the assumption that microcell BS are not close to the macrocell BS. The interference will consist of other users in the macrocell.

From the above discussion it is clear that there are a number of possible scenarios which can occur with different number of users using channels from macrocells and microcells and causing interference to the other users. In order to reduce the possible number of scenarios interference from only one type of interferers is considered, either the ones using macrocells or the ones using microcells. The performance for the scenario when both types of interferers are present can be concluded from the two separate scenarios with only one type of interferers present. With this simplification, the different possible scenarios can be presented as in Table 3.1.

When all the users are in the macrocell (cell A in Figure 2.1), all users experience Rayleigh fading. Second scenario is the situation in which desired user is in the macrocell but out of the boundary of any microcells such as cell B and C shown in Figure 2.1. In the

third scenario the desired user is within the boundary of microcell but is still using a macrocell channel. This is indicated in the table by putting micro in brackets. In both scenarios, 2 and 3, interference is considered coming from users in microcells. As the desired user moves towards the microcell boundary it is moving away from the macrocell BS, therefore, for the forward channel the interference power will increase as the user moves into microcell where for the most part it will experience interference coming over Ricean fading channels while in scenario 2 interfering users will be using Rayleigh fading channels. For the reverse channel the two scenarios present almost the same situation with both the desired user and interferers experiencing Rayleigh fading.

Scenario#	Desired User / Interferer
1	Macrocell / Macrocell
2	Macrocell / Microcell
3	Macrocell(micro) / Microcell
4	Microcell / Macrocell
5	Microcell / Macrocell(micro)
6	Microcell / Microcell

Table 3.1: Overlaid Cellular Scenarios

The reverse channel is assumed to be on a different carrier, so there is no interference between signals on forward channel and reverse channel. Although different scenarios are described on the basis of type of channel used by the user, an important difference between the macrocell and microcell users is that the microcell users have twice the data rate and half the PG of the users in macrocell.

The power received at the MS and BS for all the users in the cell is controlled using the average power control. The power received at the MS from the users in another cell is a system design parameter and is generally kept small due to greater propagation loss. In the

results presented in the next chapter the average power of all the users is assumed equal whether the interference is coming from users in the same cell or other cells. The average power of interference from neighboring cells can be the same as that of average power of the user at certain points, the most typical would be the case when the desired user is at the cell boundary. Section 4.5 will describe the case when the average powers received from the users are not same. This is indicative of low accuracy average power control.

In the fourth scenario the desired user transmits over a microcell channel while the interferers are using macrocell channels from outside the boundary of microcell. The desired user experiences Ricean fading for the forward channel while interference experiences Rayleigh fading. The situation for the forward channel is same for scenario 5 where the desired user is using microcell channel and interference is from macrocell user within the boundary of microcell. For the reverse channel, the desired user experiences Ricean fading while interference in scenario 4 experiences Rayleigh fading environment. In the reverse channel for scenario 5 the desired user is again over a Ricean channel while interference also experiences Ricean fading. Scenario 6 consists of desired user and interferers using microcell channels. All the users in this scenario have the same data rate which is twice that of macrocell users in scenario 1.

Chapter 4

Simulation Results

The results of the simulations are presented in this chapter. Suitable values of receiver parameters are investigated e.g. the effect of feedforward and feedback filter length on the performance of the receiver. Several scenarios are chosen for the simulations and results of simulations pertaining to each scenario are presented. The later sections of the chapter present the effect of choosing different spreading codes and different channel models on the performance which is measured in terms of mse, BER and outage probability. In the final section the effect of imperfect average power control on the performance is considered.

4.1 Initialization of Receiver Parameters

Before discussing the simulation results, several suitable parameters for the receiver need to be determined e.g. size of feedforward and feedback filters and the number of training bits used. The feedforward filter of the DFE is used to cancel the precursor ISI while the feedback filter is used to cancel the postcursor ISI.

For the RLS algorithm the computational complexity is proportional to the square of number of taps so it is necessary to adjust the equalizer length properly. The system consists of users transmitting at different data rates and PGs keeping the transmission bandwidth same. For service integration, however, it is suitable to determine an equalizer length which is same for all users no matter what the data rate. In simulations, the value of E_s/N_0

is 12 dB for all the users, where E_c is defined as the chip energy and N_0 the two sided noise power spectral density. The value of bit energy to noise power spectral density is then given by E_b/N_0 (dB) = E_c/N_0 (dB) + 10logPG. As the aim in this research is to study the performance degradation which results due to multiple access interference so the system is simulated in the high signal to noise region.

In order to determine the optimum length of the forward filter the system is simulated with one user for the two cases

1. desired user is in microcell communicating at data rate twice that of macrocell user and half PG (16)
2. desired user is a macrocell user with PG of 32 and half the data rate of micro-cell user.

The simulation follows the structure shown in Figure 3.1, 3.3 and 3.4. The data transmitted by the user is multiplied with the spreading code and arrives at the receiver via three paths containing AWGN. To determine the length of the filter, each path is assumed to undergo Rayleigh fading. The received signal is passed through the receiver filter matched to the spreading code of the desired user and the chip spaced samples are fed to the DFE. In order to determine the feedforward filter length, the DFE is simulated with 2 feedback filter taps which is sufficient as will be shown shortly. The receiver in this case is trained using a training sequence of 20 symbols. It is assumed that the receiver has an accurate carrier recovery.

The results of the simulation are shown in Figure 4.1 and 4.2. In both the figures the mean square error, in decibels, at the output of the equalizer is plotted as a function of the number of feedforward filter taps. It can be seen from these plots that no improvement in mse is obtained if the number of taps is increased beyond 16. The reason for this is that the feedforward filter tries to cancel the precursor ISI for which it needs to have a length

Figure 4.1 DFE performance as a function of number of feedforward taps for a single user in microcell.

Figure 4.2 DFE performance as a function of number of feedforward taps for a single user in macrocell.

longer than the delay spread of the channel. So the length of the feedforward filter is determined by the channel delay spread which in our case is 6 chip periods.

A length of 16 taps is therefore reasonable for the feedforward filter. In mobile cellular environment the channel parameters change rapidly and are unpredictable so it may be advantageous to have a slightly longer length of feedforward filter. However, increasing the filter length beyond a certain limit may result in reduction in performance as the tap coefficients add to the noise at the output. A longer filter length also adds to the computational complexity of the tap coefficient update algorithm. Therefore, a length of 19 taps will be used for the feedforward filter in the later simulations.

After fixing the length of feedforward filter to 19 taps the performance of DFE is simulated for feedback filter lengths of 1, 2 and 3 taps. It is found that the mse(dB) is equal to the values shown in Figure 4.1 and 4.2 for 19 feedforward and 2 feedback taps for the three cases. The reason is that the ISI is mostly due to the neighboring symbol, so a feedback filter length of one tap is sufficient. However, a length of two feedback taps will be employed in all the following simulations for the same reason as discussed for the feedforward tap.

The RLS algorithm converges in the mean square sense in a number of iterations equal to twice the number of equalizer taps [49]. As the total length of equalizer filter used in the simulations is 21 taps so a training sequence of 40 symbols is used for all the following simulations. The value of $\lambda = 0.95$ is used in all the simulations. Four samples per chip are used and the receiver is adjusted to the best sampling phase and delay for the plots shown in this chapter. For all the cases in which average power of users is equal the signal to interference ratio is $1/(N-1)$ where N is the total number of users accessing the system.

4.2 Results for Different Overlaid Scenarios

In chapter 3, several scenarios possible in the proposed overlaid system were discussed. Significant differences between the scenarios are the result of cell size and fading statistics.

The scenarios shown in Table 3.1 may be further classified into smaller number of scenarios. The third scenario can be considered as a special case of second scenario. In both the scenarios the desired user uses a macrocell channel with a PG of 32 while the interfering signals are via microcell channels with twice data rate and PG of 16. In the second scenario all users have transmission over Rayleigh channels for the forward and reverse channels. The reverse channel in the third case is also Rayleigh for all users while the forward channel bearing desired user is Rayleigh, however, the interference signal (in forward direction) propagates over Ricean channel. It should be remembered that the reverse channel contributes no interference to the forward channel and vice versa as both are assumed to be on different carriers with no overlap between their transmitted spectrum. Therefore, the difference between the second and third scenarios from simulation point of view is that the forward channel in the third scenario has interference over the Ricean channel compared to interference over Rayleigh channel in the other cases. The interference coming over Ricean channel is less severe than the interference coming over Rayleigh channel (this will be described in detail in section 4.3) so the performance will be worse in scenario 2 than in scenario 3. Therefore, the performance of the receiver is simulated in detail for scenario 2 only. This will present a worst case scenario.

Similarly, scenario 5 can be considered as a special case of scenario 4. In scenario 5 the desired user signal propagates through a microcell channel with twice the data rate and PG of 16 over Ricean channel and interference is using a macrocell channel (from outside the

boundary of microcell) with a PG of 32. In scenario 5 all the conditions are same as that of scenario 4 except that the interference is accessing microcell channel from within the boundary of microcell. So, for scenario 4 and 5 desired user will always have twice the data rate of interference and $PG = 16$ while interference has $PG = 32$. With these conditions applying to both cases, the forward and reverse channels of scenario 4 have desired user undergoing Ricean fading while interference propagates over Rayleigh channels. The same conditions occur for the forward channel in scenario 5 where desired user propagates over Ricean channel and interference signal undergoes Rayleigh fading. In the reverse channel of scenario 5, however, both desired and interfering users undergo Ricean fading.

It can be seen that the only difference in these cases is the type of fading experienced by the user and interference. The worst case will occur when both the desired user and interference have their transmission over Rayleigh channels. This is the case which is discussed in detail in section 4.2.3, the results for the case of Ricean channel are presented in section 4.3.

Scenario 6 is also discussed in detail for the desired and interfering users using Rayleigh channels. The results for the case of transmission over Ricean channels are discussed in section 4.3.

4.2.1 All Users in Macrocell

This scenario presents the case in which all users are in the macrocell transmitting over three path Rayleigh channels with a PG of 32. The performance of the receiver is simulated in terms of mean square error (mse), outage probability and BER. In order to obtain the plots, the system is simulated for 500 randomly generated channels for each user. Each simulation run lasts for 400 symbols and is preceded by a training sequence of 40 symbols. The plots for the case when all the users are in macrocell are shown in Figure 4.3,

4.4 and 4.5.

Before discussing the results, the values of the performance parameters required at the output of the receiver need to be determined. The minimum mse at output of the DFE is given by $\text{mmse (dB)} = -\text{SNR (dB)}$ where a SNR of 6 dB is considered satisfactory for the performance of a coded coherent system [47]. It can be seen from Figure 4.3 that the value of mse in decibels is much less than -6 dB for different number of users. The performance of the system degrades as the number of users increases which is expected. It should be noted that the DFE here performs the function of a Rake by combining the energies in the multipaths and also cancels the cochannel interference and ISI. This advantage of DFE over Rake is shown in [47] for same data rate users and will be shown for different data rate users in section 4.2.3. It can also be observed in Figure 4.3 that the value of mse (dB) does not vary by more than 3 dB after 40 symbols which form the training sequence. So the length of the training sequence used in the simulation is adequate.

Although the value of mse is much better than the expected value but still some channels may not be giving good performance. This can be seen by calculating the outage probability of the system. The outage probability is defined as the ratio of number of channels for which the value of square error 'se' is greater than the acceptable value of -6 dB to the total number of channels. Figure 4.4 shows the outage probability of the system for scenario 1. In order to draw the outage plot, the value of outage is determined every 10th symbol after the training sequence so the first symbol in the plot is the first symbol after the training sequence. It can be seen in the figure that the plot for outage shows larger variations for smaller number of users and becomes smoother as the number of users increases. This is because for smaller number of users the number of channels which are considered 'out' is small and therefore provides a less confident estimate of outage probability compared to the case of large number of users where there is relatively more outage.

Figure 4.3 mse performance of DFE in scenario 1: when all users are in macrocell

Figure 4.4 Outage of DFE in scenario 1: when all users are in macrocell

The estimate is improved, to some extent, by repeating each of the 500 channels five times resulting in a total of 2500 channels. The same number of channels is used for mse and BER plots. The value of outage in Figure 4.4 is less than 3% for up to 15 users. This means that the system has an acceptable performance for more than 97% of channels when up to 15 users are transmitting simultaneously.

Figure 4.5 shows the BER at the output of DFE. It is observed that some channels in the simulation have a large number of errors. Such channels may occur in the simulation when the channel over which the desired user is transmitting has a power much smaller than the channels of the interferers and with severe ISI. When calculating the BER such channels are eliminated assuming that they will not occur in actual environment which is carefully planned. One such channel is shown in Figure 4.6 where the power of channel is much less than one which is the average power of each user. These channels are only neglected to compute the BER performance. In all the simulations the number of such channels is not more than 2%, the figure of 2% occurring only for large number of users in a few scenarios. It can be seen that the BER for upto 15 users is less than the acceptable value of 10^{-3} where the BER = 1.1×10^{-3} for the case of 16 users accessing the channel at the same time.

The following table lists the values of confidence intervals for the mse and BER plots.

No. of users	estimated mse	90% Confidence Interval	estimated BER	90% Confidence Interval
14	-22.2 dB	(-22.6, -21.8) dB	4.7×10^{-4}	(9.4×10^{-5} , 8.4×10^{-4})
15	-21.3 dB	(-21.7, -20.9) dB	6.0×10^{-4}	(2.7×10^{-4} , 9.3×10^{-4})
16	-19.5 dB	(-19.9, -19.1) dB	1.1×10^{-3}	(5.7×10^{-4} , 1.7×10^{-3})

Table 4.1: Confidence Intervals for scenario 1

Figure 4.5 BER of DFE in scenario 1: when all users are in macrocell

Figure 4.6 Example of a bad channel

So for 16 users the true mse (dB) will be in the interval $(-19.9, -19.1)$ dB with a probability of 0.9 and the true BER will be in the interval $(5.7 \times 10^{-4}, 1.7 \times 10^{-3})$ with the same probability.

It is shown in [47] that 4 users can access a channel with satisfactory performance when all the users have the same data rate and PG of 8. In this thesis, the PG is 32 so it is expected that the number of users which can access the system at the same time will also be four times, therefore an adequate performance with 15 users seems to be reasonable.

4.2.2 Desired User in Macrocell, Interference from Microcells

This is scenario 2 in Table 3.1 where the desired user transmits over a macrocell channel with a PG of 32 and the interference is coming from users transmitting in microcell with twice the data rate as macrocell users and $PG = 16$ so that all the users occupy the same bandwidth. The desired user in this case is assumed to have the same spreading code as that used in the previous scenario. It should be noted that the performance changes with the spreading codes used, however, care is taken to use codes which give neither too bad nor too good a performance. The difference in performance will be shown in section 4.4 for one scenario. As the problem of finding optimum codes is not the aim of this research so the effects of codes will not be discussed in detail.

Each interfering user in this scenario is also assumed to have power equal in the average sense to the power of the desired user as in the previous scenario. Figure 4.7 shows that 16 users can be easily accommodated in the system. It is also observed here that the variation in the mse in going from 8 users to 16 users is less here than the variation in Figure 4.3 for a similar increase in the number of users. The reason for this could be effect of the spreading codes of the interference signals which are not the same as those used for results in Figure 4.3. The data rate of the interference signals in scenario 2 is higher than the data

Figure 4.7 mse performance of DFE in scenario 2: when desired user is in macrocell and interference from microcell

Figure 4.8 Outage of DFE in scenario 2: when desired user is in macrocell and interference from microcell

rate of interference used in scenario 1 so the PG used in the former case is lower. This implies that the spreading codes used for interference in scenario 2 are rows of a Hadamard matrix of size 16 compared to Hadamard codes of size 32 used in scenario 1. This results in different spreading codes used for interfering signals in scenario 1 and 2.

Figure 4.8 also shows an acceptable performance for 16 users. It can be observed here, as well, that the variation of outage as the number of users increases from 8 to 16 is less than the variation in Figure 4.4. The BER curve is shown in Figure 4.9 which also shows an acceptable performance for up to 16 users. It should be noted that the circles in the plots for BER indicate the number of users which are used to obtain the plots. This is not true for the other plots where different geometrical figures are put in the plot to identify different curves. The concern here is to determine of the maximum number of users which can perform satisfactorily in different scenarios - a reason why the system has been simulated for higher number of users.

The following table lists the values of confidence intervals for the mse and BER plots.

No. of users	estimated mse	90% Confidence Interval	estimated BER	90% Confidence Interval
14	-22.6 dB	(-23.0, -22.2) dB	7.1×10^{-4}	$(5.3 \times 10^{-4}, 8.9 \times 10^{-4})$
15	-21.3 dB	(-21.7, -20.8) dB	8.2×10^{-4}	$(1.8 \times 10^{-4}, 1.5 \times 10^{-3})$
16	-20.9 dB	(-21.4, -20.5) dB	9.5×10^{-4}	$(5.2 \times 10^{-4}, 1.4 \times 10^{-3})$

Table 4.2: Confidence Intervals for scenario 2

The values indicate that, for 16 users, the true mse(dB) will be in the interval (-21.4, -20.5) dB with a probability of 0.9 and the true BER will be in the interval $(5.2 \times 10^{-4}, 1.4 \times 10^{-3})$ with the same probability.

Figure 4.9 BER of DFE in scenario 2: when desired user is in macrocell and interference from microcell

Figure 4.10 mse performance of DFE and Rake in scenario 4: when desired user is in microcell and interference from macrocell

The results of this section indicate that the performance of DFE is satisfactory even when the data rate of interference is twice that of the desired user.

4.2.3 Desired User in Microcell, Interference from Macrocells

This section presents the results of scenario 4 where the desired user accesses a channel from microcell while the interference occurs from users in macrocell. The microcell users have a data rate twice that of macrocell users and a PG of 16 compared to PG of 32 for the macrocell users. This case presents a scenario which is the reverse of the one discussed in section 4.2.2 where the desired user is using a macrocell channel and interference is from microcell users. All the users are assumed to be transmitting over Rayleigh channels.

The result of the mse performance of DFE in this scenario are shown in Figure 4.10. The results show a good performance for the DFE for different number of users. The DFE shows some fluctuations in the mse for upto 50 symbols after the training sequence. These fluctuations increase as the number of users increases however they do not have any drastic effect on the performance. The performance of DFE for this case is compared with that of a single stage Rake receiver which shows a much worse performance. The Rake is like an equalizer with only feedforward taps. The Rake receiver, however, estimates the channel response for desired user only. As it does not adjust its taps according to interference signal so the performance gets worse as the number of interfering users increases. Where as an equalizer, linear or nonlinear, keeps on updating its taps as the number of users increases resulting in less interference at the output and, thus, much better performance compared to Rake. The equalizer, therefore, does the job of a Rake as well as cancel ISI and interference from other users resulting in a much better performance. This is shown in [47] for the same data rate system. It is reasonable to assume that the performance of DFE will be much better than Rake in other scenarios as well.

The outage performance of DFE in this scenario is shown in Figure 4.11. It can be seen that the performance is acceptable for up to 10 users. The outage for the Rake receiver, not shown in the plot, is greater than 22% even for 4 user case. 10 users can easily be accommodated in terms of BER as shown in Figure 4.12 where the 11 users case gives a BER higher than the acceptable value of 10^{-3} . The performance of Rake under similar conditions gives a BER of more than 3×10^{-3} even when 4 users are transmitting simultaneously. It can be seen from the BER curve that the change in BER when an additional user is added in to the system is not smooth. The reason is that the system no longer exhibits the graceful degradation behavior which is a characteristic of CDMA systems.

Therefore a total of 10 users can be accommodated in this case which is a very good performance considering that the PG of the desired user is 16 in this case which means that an efficiency of more than 60% is achieved compared to 50% efficiency when the desired user has a data rate half that of the interfering users. Some of this performance gain may be attributed to the spreading codes of the users which cannot be kept the same considering the different PGs used in the two scenarios. Nevertheless, the performance of the DFE is considerable when the data rate of the desired user is twice that of the interference.

4.2.4 All Users in Microcell

This scenario is similar to the first scenario in which all the users have the same data rate and transmit over Rayleigh channels. However, the PG of the users in this scenario is 16 instead of 32 and the data rate is twice that of the users in scenario 1.

The mse curves for different number of users are shown in Figure 4.13 where 8 users can be easily accommodated in the system. It can be seen in the plot that the change in mse in going from 6 to 7 users is larger than the change observed in going from 7 to 8 users. This is due to the structure of the spreading codes assigned to the interfering users. If the inter-

Figure 4.11 Outage of DFE in scenario 4: when desired user is in microcell and interference from macrocell

Figure 4.12 BER of DFE in scenario 4: when desired user is in microcell and interference from macrocell

Figure 4.13 mse performance of DFE in scenario 6: when all users are in microcell

Figure 4.14 Outage of DFE in scenario 6: when all users are in microcell

ference signal code has a large crosscorrelation with the desired user code, the performance will degrade more. This variation in performance upon adding one user can also be observed in the outage plot of Figure 4.14. It can be seen in the figure that the DFE performs satisfactorily for 8 simultaneous users.

The BER curve shown in Figure 4.15 also demonstrates satisfactory performance for up to eight users. This result is expected as the PG in this scenario is half that of scenario 1, hence, half the number of users are accommodated compared to that in scenario 1 where adequate performance is achieved for 15 users accessing the channel at the same time.

The performance shown here is a typical worst case as in actual practice a number of users operating in microcell have their transmission over Ricean channel which results in an improvement in the performance of DFE because of energy contained in the non fading line of sight path. This is also true for scenario 2 and 4 where some users may be using Ricean channels. The performance for Ricean fading channels will be discussed in detail in next section.

4.3 Effect of Transmission over Ricean Channel

The results shown in the previous section were given for all the users transmitting over Rayleigh channels. As mentioned earlier, the users in some scenarios may be transmitting over Ricean channels which gives different performance. This section discusses the effect of Ricean channels on the performance of DFE. To study the effect of the Ricean channel on the performance, some scenarios shown in previous section are simulated using Ricean channel in place of Rayleigh channel with all the other parameters unchanged. This means that same PG and set of spreading codes used in the previous section are simulated.

In scenario 6, when all the users are in microcell, the desired and interfering signals prop-

Figure 4.15 BER of DFE in scenario 6: when all users are in microcell

agate over Ricean channels. At some points in the cell a direct LOS path may, however, not be possible resulting in a Rayleigh channel. The possible cases are

- a. when desired and interfering users are transmitting over Rayleigh channel
- b. when desired user is transmitting over Ricean channel and interference is over Rayleigh channel
- c. when desired user is transmitting over Rayleigh channel and interference is over Ricean channel and
- d. when desired user and interference are transmitting over Ricean channel

The PG in all these cases is 16. The performance of the DFE in these cases is compared in Figure 4.16 and 4.17. A reasonable variation of 'k' in a mobile environment is from 0 to 9.9 [48] where 0 refers to no LOS. In this section the aim is to demonstrate the improvement in performance which results when Ricean fading occurs instead of Rayleigh fading. A value of $k = 4$ is assumed in the simulations which results in the power of LOS component equal to 4 times the power of non LOS component in the channel. This value of k results in a strong enough LOS path to show the improvement in performance due to Ricean fading. Higher values of k will result in further performance improvement. The simulation is done for the maximum number of users which can be accommodated in the case when all users are operating over Rayleigh channels. It is found in section 4.2.4 that 8 users can easily be accommodated in scenario 6, so the performance of case a - d is compared for 8 simultaneous users.

It can be seen in the figures that the performance of the DFE is better than in the case (a) when either the desired user or interference is propagating over Ricean channel. The performance is best when all the users are operating over Ricean channel. When the desired user is over Ricean channel, with interference signal propagating over Rayleigh or Ricean channel, there is very little ISI because most of the power is in the LOS path and the performance is better than that for the desired user undergoing Rayleigh fading. In the case

Figure 4.16 mse performance of DFE in scenario 6: when all users are in microcell with some users over Ricean channel

Figure 4.17 Outage of DFE in scenario 6: when all users are in microcell with some users over Ricean channel

when the interference is over Ricean channel the equalizer can easily track the interference and cancel it because it is mostly concentrated in one path. However, when the interference is over Rayleigh channel then the power is spread more uniformly among the three paths even with exponential variance model compared to Ricean channel where most of the power is concentrated in LOS path. This makes it harder to track all the interference and cancel leaving more residual interference at the output of DFE. Thus, the performance of the DFE improves when the interference is over Ricean channel compared to Rayleigh channel. The BER for the different cases is shown in Table 4.3

Case #	BER
a	9.05×10^{-4}
b	6.90×10^{-4}
c	6.75×10^{-4}
d	2.30×10^{-5}

Table 4.3: Scenario 6 with some users over Ricean channels

The BER also shows that the performance improves if desired user or interference is propagating over Ricean channel with the worst performance occurring when all users are transmitting over Rayleigh channels.

In section 4.2.2, scenario 3 was considered a special case of scenario 2. In scenario 3 the desired user is in a macrocell but located within the boundary of microcell. This results in the interference reaching the receiver undergoing Ricean fading for the forward channel. The results for the forward channel in scenario 3 are shown in Figure 4.18 and 4.19 for the case of 16 simultaneous users. It can be seen from the figures that the performance is much better for the case when the interference is over Ricean channel. It should be noted that $k = 4$ here, for higher values of k a further improvement in performance is expected

Figure 4.18 mse performance of DFE in scenario 2 with some users over Ricean channel

Figure 4.19 Outage of DFE in scenario 2 with some users over Ricean channel

since DFE will cancel it more effectively. The BER is 5.06×10^{-4} for the case when interference is over Ricean channel which is much better than the BER of 9.95×10^{-4} shown in Figure 4.9.

Section 4.2.3 shows the performance of scenario 4 and 5 when all users are transmitting over Rayleigh channels. In actual practice the desired and interfering users can be over Ricean channel depending on their location and the direction of link (forward or reverse) as discussed in section 3.4. This will also result in four similar cases, case a-d, as discussed for scenario 6. The desired user in scenario 4 and 5 transmits at a rate twice that of the interference i.e. PG of 16 for desired user compared to the PG of 32 for interference. It can be seen from Figure 4.20 and 4.21 that the performance of DFE, with 11 users transmitting simultaneously, improves when either or both the desired user and interference are transmitting over Ricean channels. The BER performance is given in Table 4.4

Case #	BER
a	1.2×10^{-3}
b	1.17×10^{-4}
c	4.60×10^{-4}
d	5.00×10^{-6}

Table 4.4: Scenario 4 with some users over Ricean channels

It can be seen that while 11 users cannot be accommodated satisfactorily on a single carrier when all the users are transmitting over Rayleigh channel in this scenario but the performance is adequate when either the desired user or interference is received over Ricean channel. The best performance is again achieved for the case when all the users are transmitting over Ricean channels.

Figure 4.20 mse performance of DFE in scenario 4 with some users over Ricean channel

Figure 4.21 Outage of DFE in scenario 4 with some users over Ricean channel

It can be concluded from the results presented in this section that a transmission over Ricean channel results in an improvement of performance with respect to Rayleigh channel in all the cases irrespective of their data rate (or PG) i.e. whether the data rate of all users is same or differs by a factor of two.

4.4 Effect of the Spreading Code of Users

Section 4.2 mentioned the importance of using proper spreading codes for the desired and interfering users. It is desired that a spreading code has a periodic autocorrelation which is close to a delta function and its periodic cross correlation with other codes is minimum [14]. A lot of research has been done on devising better codes for the improving the performance of CDMA systems. The problem of designing optimum codes is not considered in this thesis, however, the effect of changing the spreading code of the desired user in the simulations needs to be mentioned.

Scenario 6 (desired user: PG=16, Rayleigh; interfering user: PG=16, Rayleigh, same data rate) is used to demonstrate the significance of selecting proper spreading codes for the users. Figure 4.22 and 4.23 show the change in performance when using different code for the desired user. The spreading codes used for the interference are the same in both cases. The curves show a marked improvement in performance when using better codes. The results for the 'moderate code' are the ones which are shown in the previous sections, therefore, the results presented in previous sections do not present an optimistic picture rather give a balanced view of a system employing Hadamard codes. The BER is equal to 2.42×10^{-4} for the case of good code compared with a BER of 9.05×10^{-4} shown in Figure 4.15 for the moderate code. This shows a gain of 3.75 times in BER performance achieved by using a better code. The corresponding improvement in mse performance shown in Figure 4.22 is 5 dB.

Figure 4.22 mse performance of DFE in scenario 6: when all users are in microcell and desired user is using different codes

Figure 4.23 Outage of DFE in scenario 6: when all users are in microcell and desired user is using different codes

Similar changes were also observed in other scenarios. The changes in performance upon varying the spreading codes indicate that the performance of the system will probably be good for codes like Gold code and Kasami code which are usually recommended for CDMA systems.

4.5 Near Far Resistance of DFE receiver

An accurate power control is an essential requirement in conventional mobile CDMA system. Imperfections in power control lead to poor performance and lower system capacity. Whenever the received power of the users is dissimilar the interference power at the output of the matched filter increases proportionally to the crosscorrelation between the spreading code of the user with that of the desired user and the performance of the system degrades. This is referred to as the near far problem. The near far problem is however not an inherent problem of the CDMA system rather it is a shortcoming of the current receiver structures employed for CDMA.

In the previous sections, all users are assumed to transmit with the same average power which is a loose form of power control known as average power control. Conventional CDMA systems require strict power control which is very hard to maintain because of rapid changes in the mobile environment. Therefore, there is a need for a receiver which is near far resistant. In this section, the DFE is demonstrated to give acceptable performance even when the average power of the users is not the same. The performance of DFE is simulated when the average power of interfering users differs -2dB to +2dB relative to the average power of desired user. The power level of interfering users is assumed to be uniformly distributed around the power level of desired user. The near far resistance properties of the DFE receiver are investigated for scenario 2, 4 and 6 when all the users are operating over the worst case scenario of Rayleigh channels. Scenario 1 which has same

data rate signals is not considered here as scenario 6 also gives the case of same data rate signals.

Figure 4.24, 4.25 and 4.26 give the performance of DFE when the average power of users is not same for scenario 2 (desired user: PG=32, Rayleigh; interfering user: PG=16, Rayleigh, twice data rate). Comparing these results to ones for the case of same average power for all users shown in Figure 4.7, 4.8 and 4.9 it can be seen that the performance of the receiver is still adequate for upto 15 users. The performance of DFE is a little worse for the case of 16 users, however, the DFE gives better performance for the case of 12, 14 and 15 users than that of system operating with average power control under similar conditions. The performance for 8 user case is not used for comparison as the simulation needs to be run for a much larger number of iterations in order to get a good estimate for BER for this case. The simulation is performed for 2 million symbols but the number of errors are too low to give enough confidence in BER, this will be the case for BERs lower than 0.5×10^{-4} . As the emphasis is on the maximum number of users which can be accommodated in the system with minimum acceptable BER, this case is not pursued any further.

As a matter of further investigation into the behavior of DFE in this near far environment the signal to interference ratio SIR at the input of receiver is examined in the two cases - when the average power is same and when it is changing. The SIR for different number of users in the two cases is listed in Table 4.5. It can be seen from the table that SIR is slightly higher in the case when the average power control is imperfect. It should also be noted that the SIR for the case of same average power is equal to $1/(N-1)$ where N is the total number of users transmitting, but the SIR shown in Table 4.1 is not exactly equal to this value. The reason is that the simulation is done for 500 channels for each user so that the average power of each user is equal to one approximately which means that the value

Figure 4.24 mse performance of DFE in scenario 2: when desired user is in macrocell and interference from microcell with power varying from -2 to +2 dB with respect to desired user

Figure 4.25 Outage of DFE in scenario 2: when desired user is in macrocell and interference from microcell with power varying from -2 to +2 dB with respect to desired user

Figure 4.26 BER of DFE in scenario 2: when desired user is in macrocell and interference from microcell with power varying from -2 to $+2$ dB with respect to desired user

Figure 4.27 mse performance of DFE in scenario 4: when desired user is in microcell and interference from macrocell with power varying from -2 to $+2$ dB with respect to desired user

of SIR at the input of receiver is only approximately $1/(N-1)$.

No. of users	SIR when users have same average power	SIR when users have different average powers
12	1/10.3	1/10.6
14	1/12.7	1/13.1
15	1/13	1/13.7
16	1/14.7	1/15.1

Table 4.5: SIR at the receiver for scenario 2

One reason for this improvement in performance, in case of interference power varying between -2dB to +2dB with respect to the desired user, can be that the users with spreading codes possessing low crosscorrelation with the spreading code of the desired user have the higher power compared to the users whose spreading code have higher crosscorrelation with the desired user's spreading code. Moreover the DFE adapts itself to the changes in the interference which means that the performance at the output of DFE is not affected as much as the changes in interference as it cancels out most of the interference.

The performance curves for scenario 4 (desired user: $P_G=16$, Rayleigh; interfering user: $P_G=32$, Rayleigh, half data rate) are shown in Figure 4.27, 4.28 and 4.29 for the case of imperfect average power control. A comparison of these plots with those in Figure 4.10, 4.11 and 4.12 show that the DFE still gives satisfactory performance for upto 10 users in this case. The SIRs for the two cases are shown in Table 4.6.

It can be seen from the plots that the performance is almost the same for the case of 8 users accessing the system simultaneously with imperfect average power control and is slightly worse for the case of 4 and 10 users compared to the average power control case. The SIR is worse for all the users when the power of interference is varied in the range of

Figure 4.28 Outage of DFE in scenario 4: when desired user is in microcell and interference from macrocell with power varying from -2 to $+2$ dB with respect to desired user

Figure 4.29 BER of DFE in scenario 4: when desired user is in microcell and interference from macrocell with power varying from -2 to $+2$ dB with respect to desired user

± 2 dB about the desired user than the average power control case. This shows that DFE receiver is near far resistant even when the user power varies within a range of 4 dB.

No. of users	SIR when users have same average power	SIR when users have different average powers
4	1/2.8	1/3
8	1/6.3	1/7
10	1/7.9	1/9

Table 4.6: SIR at the receiver for scenario 4

A similar behavior of DFE is observed in scenario 6 where all the users have the same data rate while accessing microcell channels with a PG of 16. The performance for the case of imperfect average power control is shown in Figure 4.30, 4.31 and 4.32. Comparing these figures with those obtained for the average power control case shown in Figure 4.13, 4.14 and 4.15, an adequate performance is observed for up to 8 users.

No. of users	SIR when users have same average power	SIR when users have different average powers
4	1/2.5	1/2.3
6	1/4.5	1/5.5
7	1/5.6	1/6.4
8	1/6.4	1/6.1

Table 4.7: SIR at the receiver for scenario 6

It can be seen that the performance with 7 users, when imperfect power control is used, is closer to that of 8 user case than in the average power control case. Some insight can be obtained by looking at the SIR values for the two cases shown in Table 4.7. It can be seen that the SIR in the case of 8 users is actually less than the 7 users case which may happen

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Figure 4.30 mse performance of DFE in scenario 6: when all users are in microcell and power of interferers varies from -2 to +2 dB with respect to desired user

Figure 4.31 Outage of DFE in scenario 6: when all users are in microcell and power of interferers varies from -2 to +2 dB with respect to desired user

Figure 4.32 BER of DFE in scenario 6: when all users are in microcell and power of interferers varies from -2 to +2 dB with respect to desired user

when there is imperfect average power control.

Although the SIR for the 8 user case is slightly lower than the 7 user case the performance is a little worse which may be because of some users with spreading code possessing high crosscorrelation with the desired user spreading code having higher power than the others.

The results and discussion in this section demonstrate the capabilities of the DFE in a near far environment. It is shown that the DFE gives a satisfactory performance even when the average power of the users is varying in a range of 4 dB. So the DFE structure performs well in a very loose power control environment, where the average powers are allowed to vary within a range of 4 dB.

Chapter 5

Conclusions

This thesis research was motivated by the current research and development towards implementation of PCS. There are two main competing approaches towards PCS- one using TDMA and other using CDMA. Some aspects of CDMA approach are investigated in this thesis which is gaining popularity and is attractive in many aspects, but the aim here was limited to service integration.

An overview of channel models which are found in the mobile environment was presented. Some related research done in the area of multiuser CDMA was reviewed in detail. Later the current research in cancellation of multi access interference using Rake and decision feedback equalizer structures was also highlighted. It was observed that equalizers can effectively cancel interference. Moreover, DFE structure used in this thesis has the advantage of being simple and requiring the knowledge of the desired user's spreading code only, whereas other structures proposed to date mostly need information about all users' codes, energies and their channel parameters for interference cancellation.

The issues involved in integration of different services were described which is the most important aspect of PCS. An approach was presented which employs the use of overlaid cellular architecture for using different data rates in CDMA. The smaller cells support higher data rates much easily than the larger cells because of their relatively shorter delay spread and are laid over larger delay spread macrocells supporting lower data rates.

CDMA uses a much wider spectrum than that needed for transmission of a signal but this spectrum is shared by many signals spread by unique spreading codes. As each user transmission does not need to be separated in frequency or time band from others so we have a scheme which has the natural ability to allow different data rate signals using same or different RF transmission bandwidths.

Chapter 3 described the system model used for the simulation study. It was decided to use the RLS algorithm for updating the taps of decision feedback equalizer because of its fast convergence rate which is needed in a mobile cellular environment. The power control scheme employed in the system assumes that the power of the users is only equal in the average sense resulting in only a loose power control. Different scenarios were drawn for the overlaid cellular environment and simplified to reduce the number of scenarios to four.

The first scenario has the desired user and interference transmitting at same data rate with PG of 32, the second has the interference at twice the data rate of the desired user and with $PG = 16$. Third scenario has the desired user at twice the data rate of interference and PG of 16 compared to PG of 32 for interference. Last scenario is similar to the first one with same data rate users but PG of 16 instead. It is shown that the DFE receiver performs well for all the scenarios accommodating number of users greater than or equal to 50% of PG. This conclusion is arrived at by measuring the mse, outage and BER at the output of the DFE for each scenario. It is, therefore, concluded that the DFE receiver structure is suitable for different data rate transmissions in a CDMA system. The BER curves show that the graceful degradation property of CDMA is lost when an equalizer is used at the receiver. However, this loss is outweighed by the improvement in performance which results with the use of equalizer.

All the scenarios were first simulated for Rayleigh channels. It was shown later that the

performance is better when either the desired user or interference are transmitting over Ricean channels. This means that the performance over Rayleigh channel case always gives worst performance. It was also shown by computer simulations that an improvement in performance can be achieved by using a better set of spreading codes for the users.

The last section of chapter 4 presents simulation performance of the DFE in a near far environment. It was seen that the performance of the DFE does not vary much when the average power of the interfering users varies in a range of -2 dB to +2 dB with respect to the desired user. Thus the proposed structure can even tolerate imperfect average power control. This result is important because the main problem with the current CDMA systems is that they do not perform well without power control.

The system assumes that different data rate interference is coming from different cells, however same results are expected if the interference is from the same cell users with different data rates. In the simulation it is assumed that interference has either the same data rate or data rate which is a factor of 2, however, it can be seen that in case the interference is coming from the same cell as well as the neighboring cell the DFE should perform well giving good efficiency for the channel. A thorough investigation of the system using distance power law and shadowing can be considered as a problem for future work.

5.1 Proposals for Future Work

Although many scenarios were investigated, a number of issues remain unresolved and require further study.

In the simulations, it was assumed that all the users are on the same frequency carrier using the same bandwidth by lowering the PG for higher data rate users. It would be interesting to see the results for the case when all users are transmitting with same PG but dif-

ferent data rates, that is different bandwidth signals are overlaid. This may be done by transmitting over the same carrier or transmitting over different carriers to have the same amount of interference in each band.

It will be worthwhile to derive an expression to determine the system performance in terms of BER or outage probability. This would require making some realistic but simplifying assumptions as the analysis could be mathematically involved because of multipath propagation. This would provide more insight into the system behavior under different conditions.

A simple synchronous system was simulated in this research, it would be worthwhile to see the performance for an asynchronous system in overlaid environment. The system could be made more realistic by incorporating the distance power law and shadowing effects into the simulation and considering the same cell and intercell interference at the same time. Also a more realistic channel model can be used employing doppler shifts.

It would also be interesting to look at the cyclostationarity of the signals and, if possible, exploit the spectral redundancy of the modulated signal for interference cancellation using frequency shift decision feedback equalizers [50]. These structures have been shown to give better performance than a conventional DFE for signals possessing cyclostationarity at the expense of complexity. Moreover, antenna diversity could also be employed into the system to improve the capacity.

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