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DFE for Interference and Multipath Suppression in a CDMA System

by

Majeed Abdulrahman, B.A.Sc., M.Eng.

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

Doctor of Philosophy

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
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Ottawa, Ontario, Canada, K1S 5B6

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Majeed Abdulrahman, B.A.Sc., M.Eng.

in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

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Abstract

Spread Spectrum techniques had been always adopted by the military for protection against interference and jamming. But the need of additional spectrum to meet growing demand compelled the researchers to evaluate these techniques for commercial use. It is expected that it will provide more users on newly-assigned or already-used bandwidth than that provided by other modulation techniques. *Direct Sequence Spread Spectrum (DS/SS)* is the preferred technique for commercial use where all users, each having a spreading sequence, share the same bandwidth. Much research work has been done on designing a DS/SS system that gives the best performance, but the resulting approaches were either implementationally complex or had some other drawbacks, e.g. requiring the spreading sequences of all users; thus, resulting in security concerns.

In this proposal, a *fractionally-spaced Decision Feedback Equalizer (DFE)* receiver is suggested that assumes knowledge of only the desired user's spreading sequence. An alternative receiver is also suggested where the matched filter of the desired user, placed at the input of the DFE, is replaced by a low pass filter. The DFE-receiver is analyzed and gives good performance, based on minimizing the mean square error, in a slow-fading multipath environment. A simulation of the receiver was also performed, and the results showed good convergence for 4 users when using a processing gain of 8. The NLMS algorithm was used for adapting the DFE coefficients. Good outage probability was also achieved for 4 users when studying the BER performance. It has also been shown that the proposed system does not require an instantaneous precise power control technique, because the DFE works to combine the desired user's paths and jointly minimizes the effects of fading, multipath, interference and Gaussian noise. An FDMA/CDMA system was also recommended to be used for indoor cellular environments, which potentially gives better capacity gains than other proposed CDMA systems.

To ***The One***

who gave me life, knowledge and patience

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List of Abbreviations

Abbreviation	Meaning
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase-Shift Keying
CDMA	Code Division Multiple Access
dB	decibel
DFE	Decision Feedback Equalizer
DS/SS	Direct Sequence Spread Spectrum
FDMA	Frequency Division Multiple Access
FH/SS	Frequency Hopping Spread Spectrum
FR-SP	Fractionally Spaced
FSE_2	Fractionally spaced equalizer at twice the chip rate
ISI	Intersymbol Interference
LMS	Least-Mean Square
LPF	Lowpass filter
MMSE	Minimum Mean Squared Error
MSE	Mean Squared Error
MSK	Minimum Shift Keying
NEXT	Near-End Crosstalk
NLMS	Normalized Least-Mean Square
NSERC	Natural Sciences and Engineering Research Council
OQPSK	Offset Quadrature Phase-Shift Keying
PG	Processing Gain
PN	Pseudo-random noise
QPSK	Quadrature Phase-Shift Keying

Abbreviation	Meaning
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SQRT (RC)	Square-root raised-cosine pulse
SS	Spread Spectrum
SSMA	Spread Spectrum Multiple Access
TDMA	Time Division Multiple Access

chapter 1

Introduction

1.1 Background

Spread Spectrum has always played a major role in military communication systems. It gives protection against interference and jamming from other users in the same frequency band. In civilian multiple-access radio systems the frequency spectrum is becoming more crowded because of accelerating demand of mobile and portable communications. This means that either more bandwidth should be allocated from government-controlled bands for commercial use, or the available spectrum be reorganized to improve efficiency. Spread spectrum offers a flexible solution for both suggestions, since it allows more users to share a newly-assigned or already-used bandwidth [1], [2].

In a spread spectrum (SS) system, each user has a specified code which is used to spread the transmitted signal's power over a wide band. The receiver of a specific user will use its code to despread the signal, while the signals from the other users will be spread again over the wide band thus decreasing the effect of interference within the information bandwidth (despread bandwidth) of the desired user. Therefore, the spread bandwidth should be many orders of magnitude larger than the information bandwidth in order to decrease the effect of interference.

SS also handles jamming the same way it does the multiple access users' interference. Now, the jamming power will be spread over the spread bandwidth thus reducing its effect within the information bandwidth. SS users could also be

added to share an already-used bandwidth by placing the spread signal under the noise floor of the non-spread signal, and achieve higher system capacity.

Signal fading and multipath channels are two of the major impairments of indoor and mobile environments. Fading could be frequency-selective where portions of the signal spectrum will have deep fades or nulls, and non-frequency selective where fading is uniform over the entire signal spectrum. SS provides protection against frequency-selective fading, because portions of the signal bandwidth remain unaffected by fading. It also improves the performance in multipath channels since these signal components can be resolved and constructively combined by a spread spectrum receiver of the RAKE type.

Two main techniques are used in spread spectrum communication: *direct sequence spread spectrum (DS/SS)* and *frequency hopping spread spectrum (FH/SS)*. DS/SS is based on amplitude modulation where the original transmitted data is multiplied by a higher rate sequence corresponding to a specific code of the intended user. The same sequence will be used at the receiver to despread the signal; thus recovering the transmitted data. FH/SS is based on frequency modulation where the information bandwidth hops over a wide range of frequencies in the spread spectrum band by changing the carrier frequency according to a specific sequence. This sequence of hops is a priori known at the receiver which uses it to recover the transmitted data.

Code Division Multiple Access (CDMA) is a spread spectrum system where a number of users, each with a unique code called the *spreading sequence*, communicate simultaneously over the same frequency band. Total interference in CDMA is dependent on the *processing gain (PG)* which is the ratio of spread bandwidth to information bandwidth. The larger the PG the lower is

the interference on a given user. Also, the more users share a given CDMA bandwidth the more interference a given user encounters.

For cellular systems, the capacity of a CDMA system may be larger than that of a T(time)DMA or F(frequency)DMA system since the CDMA system can readily exploit multipath resolution, voice activity and antenna sectorization to decrease the main impairment of CDMA- interference[1]. This also enables CDMA to reuse the same frequency spectrum in the adjacent cells. CDMA is less susceptible to fading than TDMA since with a suitable RAKE receiver multipath components can be resolved and added coherently. It has been shown for voice transmission that a user only talks 3/8 of the time, while the other time is considered to be the silent period[3]. This lowers the overall average interference in a CDMA system; thus enabling additional users to use the spectrum. The use of directional antennas, instead of omnidirectional antennas, also reduces the overall interference in a given area; thus improving the CDMA system's capacity.

The main advantage of CDMA over TDMA or FDMA in a cellular system is in the reuse of the frequency spectrum in each cell. Each user in a CDMA system has his own spreading sequence and all the users utilize the same spread bandwidth in a given cell. This spread bandwidth could be reused in neighboring cells since each user is identified by his spreading sequence, and the interfering signals from neighboring cells attenuate approximately with the fourth power of distance. A similar type of reuse in FDMA or TDMA is not possible since it causes severe performance degradation[1]. The implication of frequency reuse in the adjacent cells improve the spectral efficiency or system capacity.

Previous work has showed that a *Decision Feedback Equalizer (DFE)* improves the performance of a system beset by interfering users with the same

transmission rate [4, 5]. The interference thus produced is cyclostationary since the statistics of interference at the receiver vary periodically in time with a period equal to the symbol period. The DFE, having forward and feedback filters, used the *Minimum Mean-Squared Error (MMSE)* criterion to minimize the effects of interference, Intersymbol Interference (ISI) and Additive White Gaussian Noise (AWGN). The performance of the system proved to be much better than that with stationary interference. In CDMA a number of users with the same transmission rate are being serviced. This has led us to propose the use of a DFE in a CDMA system to improve its performance.

1.2 Thesis Contributions

Interference is considered to be the major impairment of a CDMA system. The work presented in this thesis shows that a fractionally-spaced DFE has better interference cancellation capabilities than other proposed systems, e.g. systems with coherent detection and conventional optimum RAKE receiver, for commercial use of spread spectrum communications. Two receiver configurations were considered, one assumes the knowledge of the spreading sequence of the desired user, while the other has no information about any spreading sequence of the CDMA users. Both receiver configurations show good interference cancellation capabilities, where the DFE works on minimizing the effects of fading, multipath, interference and AWGN.

Analysis of the DFE-receiver, assuming the MMSE criterion, is presented in this work to show the advantages of this receiver over other proposed systems. Simulation of the overall system has also been performed to study its convergence time and the practicality of implementing such a system. Power control is considered an important part in implementing a CDMA system since the transmitted

information from users close to the base station could easily overcome those of users at greater distance if no power control technique is considered. But our proposed receiver shows that accurate, fast-acting power control is not a necessity in improving the overall performance (i.e. slow-acting, rather crude, power control suffices if the receiver is an adaptive DFE).

The performance of the DFE-receiver is also examined under certain conditions, such as the sudden access and termination of calls to the system, blind equalization effects, spreading code effects and the presence of inter-cell interference. Techniques have been suggested to reduce the effects of these conditions on the performance of the proposed receiver. Finally, the Bit Error Rate (BER) performance of the receiver is presented to show the capacity gains that could be achieved for this CDMA system. It was concluded that the DFE-receiver with a number of users equal to 50% of the processing gain gives good system performance. This capacity gain is much higher than that of any other proposed CDMA system.

1.3 Thesis Structure

The first section of chapter 2 gives an overview of the research that was done in the area of CDMA for commercial applications. This presents different techniques that could lead to an improvement in the performance of a CDMA system. The last section gives our reasons for choosing the proposed DFE-receiver for a CDMA system, and provides a general description of it.

In chapter 3, the proposed *fractionally-spaced DFE (FR-SP DFE)* receiver for a CDMA system is described in more detail. Equations are derived to find the MMSE of this particular receiver, where the MMSE analysis helps in studying the potential advantages of such a receiver. Analysis of the transient behaviour

of the MSE is also given in this chapter, which will be compared later with the convergence results of the DFE-receiver.

Chapter 4 discusses the MMSE performance results for two different configurations of the proposed DFE-receiver. The performance of the system is examined under different fading and multipath channel models that are specified in this chapter. The results show the potential advantages of the proposed receiver over other CDMA systems.

Chapter 5 presents a simulation of the DFE-receiver in order to study the convergence time and compare it with the MMSE results. This provides information about the feasibility of implementing the DFE-receiver and its practical advantages over other CDMA systems.

Chapter 6 studies the convergence of the DFE-receiver under certain conditions, such as blind equalization and the sudden access and termination of users to the system. The BER performance of the proposed receiver is also presented here to verify the capabilities of the DFE-receiver in terms of capacity gains.

Finally, chapter 7 gives the conclusions of the thesis, and provides a discussion for future research.

chapter 2

Spread Spectrum System in Mobile Communications

2.1 Recent Research on Spread Spectrum

Public interest in CDMA started to grow because of its potential advantages over TDMA and FDMA with respect to spectrum efficiency and capacity. Commercially, most of the research concentrated around the use of DS/SS because it is less complex to implement than FH/SS, and the level of security provided by FH/SS is not needed for commercial implementation of spread spectrum. In the following, we will give an overview of some of the research that was done for commercial use of DS/SS. This will lead us to our proposal on a CDMA system.

An analysis was given by Pursley for an asynchronous non-multipath DS/SS system in [6]. He showed that minimizing the maximum value of the error probability is not a useful performance parameter if the period of the code sequence, N , is not much larger than the number of users, K . In this case, the average signal-to-noise ratio, SNR, performance is preferred if large cross-correlation values exist between code parameters. The SNR was derived and could be computed without the need of information about the cross-correlation functions. The approximate formula

$$SNR \approx \left[\frac{K-1}{3N} + \frac{N_0}{2E_b} \right]^{-\frac{1}{2}} \quad (2.1)$$

was also given, where E_b is bit energy and $\frac{N_0}{2}$ is the thermal power spectral noise density. This could be used to determine the code sequence period N , bit energy

E_b and noise density $\frac{N_0}{2}$ for a given SNR and number of users K . Then the exact performance could be evaluated, using the exact formula for calculating SNR, for specific code sequences.

Then Pursley et al. [7] derived upper and lower bounds on the average error probability for the DS/SS system described in [6]. The multiple access interference was considered as white Gaussian noise, and the maximum interference was restricted to be less than the desired signal component at the output of the correlation receiver. Also the multipath environment, encountered in urban and indoor communications, was not considered. It was found that a proper selection of the spreading sequences' phases could significantly improve the efficiency of the DS/SS system, where m-sequences and Gold sequences were used. Chernoff and Chebyshev upper bounds were also derived for this particular system. The Chernoff bound was not very tight, and the Chebyshev bound was even worse.

Lehnert and Pursley[8] repeated the same work in [7] but for random spreading sequences. A simplified expression for the decision statistic of a correlation receiver in a DS/SS system was obtained for randomly chosen spreading sequences. Upper and lower bounds on the average probability of error were also given. These bounds were very tight and could be used to examine a system with a large number of interfering users. The bounds were also compared with the Gaussian approximation on the multiple access interference. For a small number of users, the results showed that the Gaussian assumption is good for small values of bit energy-to-noise ratio, $\frac{E_b}{N_0}$, but bad for large values of $\frac{E_b}{N_0}$. The Gaussian approximation becomes more acceptable as the number of users increases, and the requirement on $\frac{E_b}{N_0}$ reduces as the spreading sequence's length increases for a given average probability of error. Note again that this work does not consider the

multipath environment, and each transmitter is assumed to have the same power.

The problem of multipath was considered by Lehnert and Pursley in [9] where they analyzed a multipath diversity spread spectrum multiple access (SSMA) system. This system could use QPSK, OQPSK, MSK or BPSK modulation schemes. It was assumed that each user has a number of random spreading sequences where one of them is used every few bit periods. This decreases the correlation between two successive sequences being sent. An approximation to the average probability of bit error was given where the decision statistic was modeled as a Gaussian random variable. This assumption requires a small amount of computation. It shows that better performance is achieved as the length of the spreading sequence is increased, and the approximation becomes more exact as the number of users increase. But this approximation assumes also that the variance of the number of paths received from each user is small; otherwise, the results will be inaccurate.

This approximation becomes more accurate if very long spreading sequences are used since the multiple access interference and ISI become small compared to the Gaussian noise at the receiver. Another approximation to the average probability of bit error was given and provided better results than the previous one, but at the expense of more computations. This research shows that substantial gains are possible if the channel parameters are known at the receiver; otherwise, the performance is greatly degraded in the specular multipath channel. This assumption is difficult to achieve practically in an urban mobile environment which is a fast-varying channel.

Verdu analyzed in [10] an optimum multiuser demodulator, a bank of matched filters followed by an algorithm resembling a Viterbi algorithm, and compared

it to the conventional single-user matched filter receiver using the asymptotic efficiency criterion. This criterion is defined as the ratio between the SNR needed to achieve the same uncoded BER in the absence of interfering users and the actual SNR. The asymptotic efficiency performance of the conventional detector approaches the optimum efficiency, equal to 1, for very weak interferers, but decreases monotonically until it reaches zero as the interference energy increases with respect to that of desired user. The efficiency is also dependent on the delays between the users if they had equal energy.

However, the performance of the optimum multiuser demodulator has totally different behaviour. It decreases until the interference-to-desired user energy ratio is around -10 dB, but it starts increasing until it reaches 1 and remains at this level even for very high interference. This means that the optimum demodulator is not interference-limited in contrast to the single-user detector. But those large gains achieved by the optimum system require centralized implementation, software complexity and knowledge of all users' spreading sequences.

Then Poor and Verdu studied single-user detectors for multiuser channels [11]. The single-user likelihood ratio was obtained which had a correction term that depends on the inphase and quadrature components of the input. It was assumed that the receiver has either knowledge of the interferers' waveforms or that each user had an unknown spreading sequence. The analysis shows that the correction term depends on the received waveform if very long spreading sequences were used. It was also shown that this single-user detector achieves perfect demodulation in the absence of Gaussian noise, but assuming knowledge of the chip waveform and energies of interfering users. If this assumption is acceptable then this receiver is not limited by the multiple access interference. A

locally optimum detector, a single-user correlation receiver, was also studied. It uses a replica of the desired user's signal, and could be used to provide decentralized D_k -user receiver, which would be favorable over the optimum K -user ($K > D_k$) receiver because enormous computational savings would be achieved.

Linear multiuser detectors for symbol-synchronous CDMA systems were studied by Lupas and Verdu in a near-far environment [12]. Linear transformations were applied to the outputs of the bank of matched filters in the multiuser detector. Better performance is achieved here than in the conventional single-user detector, and its near-far resistant characteristics are similar to that of optimum detector. The complexity of the detector is linear in the number of users if a fixed-energy environment is considered; otherwise, it is exponential. A decorrelating detector was also presented and shown to perform as the linear detector in a varying-energy environment, and the results were not affected by the level of multiple-access interference. The computations performed here are much easier, but it is required that the signal of the desired user does not belong to the subspace spanned by other users' signals.

Later the multiuser linear detector, analyzed in [12], was studied for asynchronous CDMA systems [13]. While the conventional receiver degraded for increasing multiple-access interference, the multiuser detector had a probability of bit error that is independent of the interfering users' energies and was near-far resistant as the optimum multiuser detector. But the receiver assumes knowledge of the spreading waveforms of the interfering users. This multiuser detector could be decentralized to be used at a mobile or portable receiver to demodulate the desired user's signal. A K -user multiuser detector could be implemented as K

separate single-input single-output filters where each uses the projection of the user's spreading waveform on the subspace orthogonal to the space spanned by the interfering signals.

Another asynchronous CDMA system was proposed by Varanasi and Aazhang where the detector uses a multistage algorithm that successively cancels out the multiple access interference and has a computational complexity that is linear in number of users [14]. The probability of error was calculated for a two-stage receiver and shown to be computationally complicated because the decision statistic depended in a non-linear form on some random variables which were dependent on each other. The probability of error showed that the multistage detector is suitable for demodulating weak signals in the presence of strong interferers. But the performance degraded for large signal cross-correlations. This multistage detector is designed to be advantageous for partial/full centralized demodulation where part or all spreading waveforms are present at the receiver. It was also assumed that users' energies are known at the receiver, which may not be practically feasible.

A decorrelating decision feedback detector for synchronous CDMA was proposed in [15] which uses the decisions of stronger users when forming decisions for the weaker ones. The complexity of the system is linear in number of users, and the performance of weaker users is better than that achieved by linear decorrelating detector. The error probability of the weakest user approaches the single-user bound as the interferers' energy become larger. Again, the major assumption in this system is the receiver's knowledge of all users' spreading sequences.

A CDMA system that combines the effects of array antenna and interference canceller was proposed in [16]. This system minimizes the cochannel interference

by performing both spatial and temporal filtering. The adaptive array portion of the system suppresses interfering signals that have arrival angles different from that of the desired user. The adaptive canceller minimizes the effects of the interfering signals with the same arrival angle as that of the desired user. But this system assumes knowledge of all spreading codes of the CDMA users and which interfering users have the same arrival angle as that of the desired user.

A receiver of suboptimum detectors for direct sequence CDMA system was considered in [17]. This receiver has a bank of matched filters, and a linear transformation is performed on those filters' outputs to minimize either the mean squared error or weighted square error performance criteria. The structure of the suboptimum receiver is much simpler than that of the optimum detector, but it performs as well as the optimum detector. However, this work assumes knowledge of all system parameters, such as signal phase, power and delay.

A CDMA system using DS/SS technique has been proposed and developed by Qualcomm Inc. of California [1]. This system could be applied to digital cellular and personal communications networks. All base stations share a pair of pseudo-random noise (PN) codes, but the stations are distinguished from each other by an assigned time offset. Transmission in the forward link (base station to mobile) is done by modulating a signal, centered on an assigned radio channel frequency, by the base station's pair of PN codes and its assigned time offset. To identify each mobile's signal, the base station uses Walsh (Hadamard) [18] codes of length 64 where it assigns one of these codes to a given mobile. So the transmitted signal is modulated again with a given Walsh code. The last stage involves encoding and scrambling the digital information signal.

In the reverse link (mobile to base station), the same pair of PN codes with a

fixed code phase offset that was used in the forward link modulate the transmitted signal which is also centered on a given radio channel frequency. To identify different mobiles' transmitted signals, a very long PN sequence with a different time offset for each mobile is used to modulate the transmitted signal for the second time. Then the transmitted information is convolutionally encoded, and the output of the encoder is taken 6 bits at a time to select one of 64 different Walsh functions. The use of Walsh functions is different here than in the forward link where it is used to identify different mobile stations.

To improve on the capacity of the CDMA system, Qualcomm takes into consideration the voice activity ratio of its users, the number of sectors in the base station's antenna and the reuse of the frequency spectrum in neighboring cells. The capacity of the system is determined by the equation:

$$N = \frac{W}{R} \cdot \frac{1}{\left(\frac{E_b}{N_0}\right)_{min}} \cdot \frac{1}{D_v} \cdot F \cdot G \quad (2.2)$$

where [1] :

W = SS bandwidth, taken to be 1.25 MHz.

R = data rate, equal to 9600 bps.

$\left(\frac{E_b}{N_0}\right)_{min}$ = minimum $\frac{E_b}{N_0}$ for acceptable performance, equal to 6 dB after powerful coding/decoding techniques are applied.

D_v = voice duty cycle, assumed to be 50%.

F = frequency reuse efficiency, assumed to be 60%.

G = number of sectors in a cell, chosen to be equal to 3.

N = number of users accessing a cell.

Note that the multiple access interference has been considered to be Gaussian-noise distributed because of their use of long spreading sequences. These se-

quences contribute to the overall interference as do large number of binomial variables which approximate Gaussian random variables. Near-far problem is considered a major impairment in CDMA systems; to alleviate this problem power control is implemented. The base station and mobile exchange control information about the need of higher or lower received power in order to equalize the power of signals from the mobiles within the same cell.

2.2 Proposed System

The above review of recent research showed that many of the proposed DS/SS systems perform well if they have knowledge of the channel parameters, users' spreading sequences or the received energies of some of the interferers. Information about the channel parameters could be difficult to achieve in a fast varying channel such as the urban mobile environment. Similarly, the knowledge of the interferers' energies is not always easy to estimate because we deal most of the time with energy-varying channels. Knowledge of all users' spreading sequences is possible, but that would make the system very complex in terms of design and operation. This could be feasible in a base station but not at a mobile or portable. Another consideration is that some users might not like the idea of a receiver designed to have knowledge of all users' spreading sequences because of impending security risks.

These considerations have led us to suggest a FR-SP DFE for DS/SS system that has information about only the desired user's spreading sequence and assumes no knowledge of the channel parameters, other users' sequences or their energies- but assumes knowledge of desired user's data sequence during training, and also assumes synchronization. References [4, 5] have shown that a FR-SP DFE improves the performance in a Near-End crosstalk (NEXT) dominated

environment. The NEXT interferers had their power varying periodically with the symbol period, which meant that their interference statistics were cyclostationary. With symbol-rate sampling and appropriate sampling phase, the DFE gained on system performance by exploiting the cyclostationary nature of NEXT interferers. Better performance and no sensitivity to sampling phase was achieved when two samples were taken in a symbol period, where the interference was approximately eliminated by the forward filter of the DFE.

As mentioned in the previous chapter, SS users who share the same spectrum transmit at the same rate and each has his own spreading sequence. The proposed receiver, whose block diagram is explained in more detail in the next chapter, has knowledge of its user's spreading sequence. So a matched filter of the user's sequence is used as the input stage of the receiver to despread the transmitted signal in time. The output of the matched filter has crosscorrelation peaks at multiples of the chip-rate of the spreading sequences, which means that chip-rate or faster sampling is needed in the equalization stage that follows the matched filter. The existence of multipath signals and fading causes nulls in the spectrum of the transmitted signal. A DFE could be used at the receiver because its non-linear equalization properties handle the problem of nulls. The forward filter of the DFE not only works on minimizing the effect of interference, ISI and AWGN, but it would also behave as a RAKE receiver [19] by coherently adding the multipath components since the sampling rate of the DFE is at the chip rate.

A large PG is often chosen to spread the multiusers' signals, for example the Qualcomm system [1], [2] uses a PG equal to 128. Since no LPF will be used after the matched filter of our receiver, the DFE has to perform sampling at the chip-rate of the spread signal. The complexity of the DFE may be high for large

PG. To avoid this problem, a modest PG equal to 8 is proposed for our receiver to a combination of CDMA and FDMA, since few users are served per carrier. The use of transversal filters for linear CDMA systems, but with larger PG, was also investigated in [20] and [21]. In this case, preprocessing of the input was performed by a bank of filters that are less in number than the PG.

As given in the previous section, the Qualcomm system could provide service for 120 users in a 1.25 MHz bandwidth. If voice duty cycle, frequency reuse and sectorization are not considered in the Qualcomm system, then the maximum capacity of their system is approximately equal to

$$N = 1 + \frac{W/R}{(E_b/N_0)_{min}} \quad , \quad (2.3)$$

where the effects of background noise are ignored. This means that the number of users will drop from 120 to 33 users, which corresponds to a capacity of the system that is almost 26% of the PG. The performance results of the proposed receiver, given in future chapters, show that good MMSE and convergence are achieved for 4 users with a PG of 8, which corresponds to a capacity of 50% of the PG. Voice duty cycle and antenna sectorization might add the same benefits to the equalizer system as to the conventional Qualcomm-type system. This shows that our system has potentially almost double the capacity of the Qualcomm system.

Timing and carrier recovery are the two important synchronization blocks of any proposed receiver. Timing circuitry recovers the symbol rate of the transmitted data from the received waveform. The sampling phase, a sampling point within a symbol period, is also needed to be determined for receivers that have their performance dependent on the sampling phase. The use of timing recovery is more economical than transmitting the clock information that requires bandwidth and power. Carrier recovery provides an accurate estimate of the frequency of

the carrier and its phase offset. The variations in the channel also cause phase jitter which needs to be estimated to avoid degradation in the performance of the system.

After carrier and timing information have been accurately established at the receiver, the equalizer response needs to be estimated. The time-varying equalizer response is affected by multiple access interference, fading, ISI and other channel impairments. The receiver, using timing information, adapts to these impairments by adjusting an equalizer that equalizes the channel's response, given an initial training sequence of known data symbols. In this thesis, we consider the existence of accurate carrier and timing recovery at the receiver. The problem of adapting the proposed DFE-receiver is considered in detail. Conventional Least Mean Square (LMS) coefficient adaptation algorithm could be used to update the forward and feedback taps of the DFE.

Initially, each particular user has an assigned data-training sequence that could be used for the initial acquisition of the DFE. This sequence, affected by the different channel impairments, will be received by the DFE which already has a copy of the data-training sequence. The exact time of the start of this sequence must also be known at the receiver (to within one or two bit periods). The DFE adapts accurately to these impairments since it already knows the transmitted data bits. Then actual transmission could start, and the new decisions made by the DFE will be used to update the taps and thus reduce the error caused by multiple access users, ISI, AWGN and fading.

Filtering is performed at both the matched filter stage and the DFE. The forward filter of the DFE might be able to adapt to the previously mentioned impairments, and to the spreading sequence of his desired user. If this adaptation

is possible with no cost in terms of system performance, then the matched filter stage could be eliminated and replaced with a bandlimiting filter whose bandwidth equals to the SS bandwidth. This might lead to another configuration of the proposed receiver. One receiver has knowledge of the desired user's spreading sequence, and the other does not use this information where the DFE handles the job of the matched filter. Details of the specifications of both configurations of the receiver are given in future chapters.

chapter 3

Fractionally-Spaced DFE for CDMA

In this chapter, the fractionally-spaced DFE receiver for a CDMA system is discussed in more detail. First, the transmitter part of the CDMA system is described in section 3.1, followed by a description of the DFE-receiver in section 3.2. The calculation of the MMSE is shown in detail in section 3.3, and section 3.4 presents an analysis of the MSE transient behaviour of the proposed receiver. Finally, section 3.5 gives concluding remarks on the analysis presented in this chapter, and suggests improving the adaptation process if the performance results in chapter 4 show a need for speeding up the convergence of the DFE-receiver.

3.1 Transmitter

The block diagram of a set of CDMA transmitters is shown in figure 3.1. The transmitted signal of user k is represented as:

$$X_k(t) = \sqrt{2} \operatorname{Re} \left(\sum_{\lambda} b_{\lambda}^k a_k(t - \lambda T_b - \Omega_k) e^{j2\pi f_0 t} \right) \quad (3.1)$$

where b_{λ}^k is a real-valued transmitted symbol, $a_k(t)$ is the spreading sequence of user k , T_b is the symbol period, Ω_k is the delay of user k with respect to the desired user, and f_0 is the carrier frequency. The spreading sequence of user k is defined as

$$a_k(t) = \sum_{\alpha=0}^{p-1} a_{\alpha}^k \Psi(t - \alpha T_c) \quad (3.2)$$

where $\{a_{\alpha}^k\}$ is the spreading code of user k , p is the length of the spreading sequence, T_c is the chip period of the spreading sequence and $\Psi(t)$ is the pulse

Figure 3.1 Block diagram of $N+1$ CDMA transmitters.

shape. Note that the duration of the spreading code is equal to one symbol period, and the same code is reused in every symbol period. The block *Multipath Channel* k in figure 3.1 represents the channel variations of the transmitted signal of user k that it encounters, which produces different replicas of the transmitted signal arriving at different times at the receiver. AWGN is also added to the received signal.

3.2 Receiver

Figure 3.2 shows the block diagram of receiver "0". The received signal after demodulation is presented as

$$d(t) = \sum_{k=0}^N d_k(t) + n(t) \quad (3.3)$$

where

$$d_k(t) = \sum_{\lambda} b_{\lambda}^k \sum_{m=0}^{M_k} C_{mk} a_k(t - \lambda T_b - \Omega_k - t_{mk}) \quad (3.4)$$

M_k is the number of paths of user k , C_{mk} is the amplitude and phase variation of the m th path of user k , and t_{mk} is the delay of the m th path of user k .

Using (3.2), equation (3.4) could be written as

$$d_k(t) = \sum_{\lambda} b_{\lambda}^k h_k(t - \lambda T_b) \quad (3.5)$$

where

$$\begin{aligned} h_k(t) &= \sum_{m=0}^{M_k} C_{mk} a_k(t - \Omega_k - t_{mk}) \\ &= \sum_{m=0}^{M_k} C_{mk} \sum_{\lambda=0}^{p-1} a_{\lambda}^k \Psi(t - \tau_k) \end{aligned} \quad (3.6)$$

Figure 3.2 Block diagram of CDMA receiver for user "0".

and $\tau_k = \lambda T_c + \Omega_k + t_{mk}$.

Figure 3.2 represents a receiver that has knowledge of its user's spreading sequence, where the spreading sequence matched filter (SSMF) block provides an output of the peaks of autocorrelations with the desired user's paths and crosscorrelations with other CDMA users. This output is defined as

$$g(t) = \sum_{k=0}^N g_k(t) + \vartheta(t) \quad (3.7)$$

where

$$\begin{aligned} g_k(t) &= \int d_k(\tau) a_0(\tau - t)^* d\tau \\ &= \sum_{\lambda} b_{\lambda}^k V_k(t - \lambda T_b) \quad , \end{aligned} \quad (3.8)$$

$$\begin{aligned} V_k(t) &= \int h_k(\tau) a_0(\tau - t)^* d\tau \\ &= \sum_{m=0}^{M_k} C_{mk} \int a_k(\tau - \Omega_k - t_{mk}) a_0(\tau - t)^* d\tau \\ &= \sum_{m=0}^{M_k} C_{mk} R_{0k}(t - \Omega_k - t_{mk}) \quad , \end{aligned} \quad (3.9)$$

$$R_{0k}(t) = \int a_k(\tau) a_0(\tau - t)^* d\tau \quad (3.10)$$

and

$$\vartheta(t) = \int n(\tau) a_0(\tau - t)^* d\tau \quad . \quad (3.11)$$

The input to the fractionally-spaced DFE is given in equation (3.7). As it was explained in section 2.2, this signal will be sampled at the chip rate or multiples of it, processed by the forward filter and then added to the signal fed back by the

feedback filter to give the following input to the decision device :

$$y_n = \sum_{l=0}^{N_z} Z_l^* g(nT_b - l\Delta) + \sum_{h=1}^{N_f} f_h^* b_{n-h-D}^0 \quad (3.12)$$

where $N_z + 1$ and N_f are the numbers of forward and feedback taps respectively, Z_l is the setting of the l th tap of the forward filter, f_h the setting of the h th tap of the feedback filter, $\Delta = \frac{T_c}{M}$ where M is an integer, and D is the equalizer delay assumed in the system.

Equation (3.12) could be written as

$$y_n = \mathbf{U}^H \mathbf{X}_n \quad (3.13)$$

where

$$\mathbf{U}^H = [Z_0^*, Z_1^*, \dots, Z_{N_z}^*, f_1^*, f_2^*, \dots, f_{N_f}^*] \quad (3.14)$$

and

$$\begin{aligned} \mathbf{X}_n^H &= [g(nT_b)^*, g(nT_b - \Delta)^*, \dots, g(nT_b - N_z\Delta)^*, b_{n-1-D}^0, \dots, b_{n-N_f-D}^0] \\ &= [\mathbf{G}_n^H \quad \mathbf{b}_{n-1-D}^T] \end{aligned} \quad (3.15)$$

3.3 Calculation of the MMSE

The calculation of the optimum settings of the forward and feedback coefficients was done by finding the MMSE of the fractionally-spaced DFE. The MSE is defined as

$$\begin{aligned} MSE &= E[e(n) e(n)^*] \\ &= E[(y_n - b_{n-D}^0)(y_n^* - b_{n-D}^{0*})] \end{aligned} \quad (3.16)$$

Using (3.13) in (3.16), and assuming that $E(b_{n-D}^0)^2 = 1$,

$$MSE = \mathbf{U}^H \mathbf{A} \mathbf{U} - \mathbf{U}^H \mathbf{V} - \mathbf{V}^H \mathbf{U} + 1 \quad (3.17)$$

where

$$\mathbf{A} = E(\mathbf{X}_n \mathbf{X}_n^H) \quad (3.18)$$

and

$$\mathbf{V} = E(\mathbf{X}_n b_{n-D}^0) \quad (3.19)$$

The derivative of MSE is equated to zero and the result, which provides the optimum settings of the forward and feedback coefficients, is substituted back in equation (3.17) to give the MMSE :

$$\frac{d}{d\mathbf{U}}(MSE) = 0 \Rightarrow \mathbf{U}_{\text{optimum}} = \mathbf{A}^{-1} \mathbf{V} \quad (3.20)$$

and using (3.20) in (3.17),

$$MMSE = 1 - \mathbf{V}^H \mathbf{U}_{\text{optimum}} \quad (3.21)$$

In order to find the MMSE we need to calculate the matrix and vector given in equations (3.18) and (3.19) respectively. The calculation of these two is shown below.

The vector in equation (3.19) was found to be equal to

$$\mathbf{V} = E(\mathbf{X}_n b_{n-D}^0)$$

$$= \begin{bmatrix} E(g(nT_b)b_{n-D}^0) \\ E(g(nT_b - \Delta)b_{n-D}^0) \\ \vdots \\ E(g(nT_b - N_z\Delta)b_{n-D}^0) \\ E(b_{n-1-D}^0b_{n-D}^0) \\ \vdots \\ E(b_{n-N_f-D}^0b_{n-D}^0) \end{bmatrix} = \begin{bmatrix} V_0(DT_b) \\ V_0(DT_b - \Delta) \\ \vdots \\ V_0(DT_b - N_z\Delta) \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad (3.22)$$

and the matrix in equation (3.18) was calculated to be

$$\mathbf{A} = E(\mathbf{X}_n \mathbf{X}_n^H)$$

$$= \begin{bmatrix} E(\mathbf{G}_n \mathbf{G}_n^H) & E(\mathbf{G}_n \mathbf{b}_{n-1-D}^T) \\ E(\mathbf{b}_{n-1-D} \mathbf{G}_n^H) & \mathbf{I} \end{bmatrix} \quad (3.23)$$

$$= \begin{bmatrix} \mathbf{A}_1 & \mathbf{A}_2 \\ \mathbf{A}_2^H & \mathbf{I} \end{bmatrix}$$

where

$$\mathbf{A}_2 = E \left[\begin{pmatrix} g(nT_b) \\ g(nT_b - \Delta) \\ \vdots \\ g(nT_b - N_z\Delta) \end{pmatrix} \begin{pmatrix} b_{n-1-D}^0 & b_{n-2-D}^0 & \cdot & \cdot & \cdot & b_{n-N_f-D}^0 \end{pmatrix} \right] \quad (3.24)$$

$$= \begin{bmatrix} V_0((D+1)T_b) & \cdot & \cdot & \cdot & V_0((D+N_f)T_b) \\ V_0((D+1)T_b - \Delta) & \cdot & \cdot & \cdot & V_0((D+N_f)T_b - \Delta) \\ \vdots & & & & \vdots \\ \vdots & & & & \vdots \\ V_0((D+1)T_b - N_z\Delta) & \cdot & \cdot & \cdot & V_0((D+N_f)T_b - N_z\Delta) \end{bmatrix}$$

$$\mathbf{A}_1 = \begin{bmatrix} E(g(nT_b)g(nT_b)^*) & \cdot & \cdot & \cdot & E(g(nT_b)g(nT_b - N_z\Delta)^*) \\ E(g(nT_b - \Delta)g(nT_b)^*) & \cdot & \cdot & \cdot & E(g(nT_b - \Delta)g(nT_b - N_z\Delta)^*) \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ E(g(nT_b - N_z\Delta)g(nT_b)^*) & \cdot & \cdot & \cdot & E(g(nT_b - N_z\Delta)g(nT_b - N_z\Delta)^*) \end{bmatrix} \quad (3.25)$$

where

$$\begin{aligned} E(g(nT_b - i\Delta)g(nT_b - j\Delta)^*) &= \sum_{k=0}^N \sum_{\lambda} V_k(\lambda T_b - i\Delta)V_k(\lambda T_b - j\Delta)^* \\ &\quad + 2\sigma_n^2 R_{00}((j-i)\Delta) \end{aligned} \quad (3.26)$$

σ_n^2 is the variance of AWGN and $\mathbf{I}$ is a N_f -by- N_f identity matrix.

This MMSE analysis will be used in chapter 4 to calculate the MMSE of the proposed receiver. The results will determine the performance gains of this receiver over other CDMA systems. It will also help in determining the best parameter settings for simulating the DFE-receiver.

3.4 Transient Behavior of the MSE

A simulation of the proposed receiver will be presented in chapter 5. The results provide information about the convergence or transient behavior of the MSE of the DFE-receiver under different fading environments. An analytical presentation of the transient behavior of the MSE for our proposed CDMA system is presented in this section. Using the analysis given in [22] and assuming the independence theory, the MSE at time n is defined to be equal to :

$$J(n) = J_{ex}(n) + J_{min} \quad (3.27)$$

where $J_{ex}(n)$ is the excess mean-squared error which varies with time, and J_{min} is the MMSE value which is given in equation (3.21). The excess mean-squared error could also be expressed in terms of

$$J_{ex}(n) = \underline{\lambda}^T \mathbf{x}(n) \quad (3.28)$$

where

$$\underline{\lambda} = [\lambda_1, \lambda_2, \dots, \lambda_{N_z+N_f+1}]^T \quad (3.29)$$

is the vector of eigenvalues of the correlation matrix $\mathbf{A}$ defined in equation (3.18). $\mathbf{x}(n)$ is calculated using the iterative equation :

$$\mathbf{x}(n+1) = \mathbf{B}\mathbf{x}(n) + \mu^2 J_{min} \underline{\lambda} \quad (3.30)$$

where $\mathbf{B}$ is an $(N_z + N_f + 1)$ -by- $(N_z + N_f + 1)$ matrix with elements

$$b_{ij} = \begin{cases} (1 - \mu\lambda_i)^2 + \mu^2\lambda_i^2, & i = j \\ \mu^2\lambda_i\lambda_j, & otherwise \end{cases} \quad (3.31)$$

and μ is the step size of the adaptation algorithm. An initial setting is needed for the vector $\mathbf{x}(n)$ to calculate the excess mean-squared error. This was found to be equal to

$$\mathbf{x}(0) = \mathbf{Q}^H \mathbf{U}_{opt} \mathbf{U}_{opt}^H \mathbf{Q} \quad (3.32)$$

where $\mathbf{Q}$ is the matrix of eigenvectors associated with the eigenvalues $\underline{\lambda}$ [22], and $\mathbf{U}_{opt}$ is the optimum settings of the receiver's taps which are given in equation (3.20).

The MSE at time n could now be calculated to observe analytically its behavior. This will be done at the beginning of chapter 5 and compared with the results of the simulation to verify the latter's operation before performing detailed tests on the convergence of the LMS-receiver.

3.5 Remarks on MSE Analysis

The results of the MMSE analysis given in section 3.3 are used in chapter 4 to calculate the optimum performance of the DFE-receiver for different environments, such as fading, multipath and power control conditions. The optimum performance results could be good, but the eigenvalues of the correlation matrix need to be observed at the same time. If the eigenvalue spread, ratio of largest eigenvalue to the smallest eigenvalue, is large then the convergence of the LMS algorithm will be slow. The analysis of the MSE transient behavior in section 3.4 is used in chapter 5 to study the convergence of the LMS algorithm. If the results show slow convergence, then other adaptation algorithms could be used to speed up the adaptation process. The N(Normalized)LMS algorithm is one of those algorithms that could replace the LMS algorithm. The step size of the NLMS algorithm is affected by the received signal response, which could result in a faster convergence than that achieved by the LMS algorithm with a fixed step size.

chapter 4

Optimum Performance of DFE-Receiver

In this chapter, the MMSE performance of the proposed receiver is presented using the equations derived in the previous chapter. The results are used to explain the advantages of the DFE-receiver in a CDMA system. Section 4.1 defines the channel models that were used, and gives different parameter values that were chosen to calculate the MMSE. Figure 3.2 showed that an SSMF is used at the input of the DFE to match the desired user's spreading code. The results obtained for this configuration are given in section 4.2. Another configuration is considered where the SSMF is replaced by a lowpass filter. The bandwidth of the lowpass filter is the same as the transmission bandwidth of the spreading code, where Figure 4.1 shows the filter response for square-root raised-cosine transmitted pulses with 100% roll-off factor relative to the chip rate, $1/T_c$, of the spreading code.

This new configuration is considered to explore the feasibility of simplifying system architecture by omitting a fixed matched filter based on the desired user's code, without affecting overall performance. The performance results of this configuration are shown in section 4.3. Different transmitted pulses are also investigated in section 4.4 to determine their effects on the optimum MMSE of the receiver. The fading characteristics of indoor channels vary widely from one location to another. Section 4.5 studies the effects of different fading characteristics of received paths on MMSE performance of the receiver. Finally, section 4.6 compares the MMSE performances of the receiver for both average and strict power control on the CDMA users.

Figure 4.1 Frequency response of the lowpass filter for square-root raised cosine transmitted pulses, with 100% roll-off factor.

4.1 Channel Models and System Initialization

We propose the use of this receiver in a multipath, slow-fading and Rayleigh-distributed channels. Such channels are typical of indoor wireless communications. Equation (3.4) shows the multipath effect on the transmitted signal. Saleh and Valenzuela reported the results of indoor multipath propagation measurements in [23]. They found that the delay spread could extend up to 200 *nsec*, but in most cases the delay spread was around 100 *nsec*. It was also noticed that there are 3 major peaks in most of the measurements they presented in their work. Based on these measurements, we have chosen the number of paths of each user, M_k , received at the DFE-receiver to be equal to 3. The paths are distributed uniformly within the first $6T_c$ of a bit period, where T_c is the chip period. As an illustrative example, we assume that the chip period, T_c , is equal to 20 *nsec*, which means that a maximum delay spread of 120 *nsec* is allowed.

C_{mk} , amplitude and phase variation of the m th path of user k , was chosen to be a complex Gaussian variable. The real and imaginary parts of C_{mk} are then Gaussian variables with equal variance and zero mean. This meant that the fading of each sample of the impulse response was Rayleigh-distributed. Two cases are considered for the relationship between C_{mk} of the m th path and C_{nk} of the n th path of user k . In one channel model we assume all three paths have the same variance. This model, which we will call the **Constant-Variance** model, is an extreme case of a fading channel where all the received paths had the same fading characteristics. Although this model is rare in indoor channels, it constitutes a "worst case" of multipath. The use of this channel model will help in determining the effects of bad channels on the performance of the DFE-receiver. The variance of the real and imaginary parts of C_{mk} was normalized to unity.

Another model we consider, which will be called the *Exponential-Variance* model, has an exponentially decaying variance of the received paths. The variance of each path is equal to $e^{-(\frac{L-1}{3})}$, where L is the arrival time, in terms of chip periods, of the m th received path with respect to the first received path. Note also that the total average power of the received paths in the constant-variance model is higher than that of exponential-variance model. The root-mean-square (rms) delay spread of the multipath channel

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2}, \quad (4.1)$$

where

$$\overline{\tau^n} = \frac{\sum_{m=1}^{M_k} \tau_m^n |C_{mk}|^2}{\sum_{m=1}^{M_k} |C_{mk}|^2}, \quad n = 1, 2. \quad (4.2)$$

gives a measure of the temporal extent of the multipath delay profile, where τ_m is the arrival time of the m th path [23]. This parameter is important in determining the effects of ISI on the performance degradation. The rms delay spread was calculated for both channel models that we considered. The constant-variance model had a median and maximum rms delay spread of about 21 *nsec* and 56 *nsec* respectively, while those of the exponential-variance model were found to be equal to 24 *nsec* and 50 *nsec* respectively. Note that a 25 *nsec* median value and a 50 *nsec* maximum value of the rms delay spread were reported in [23].

We assume the CDMA system operates with slow average power control. All users of the CDMA system have the same ensemble-average received power. The average Signal-to-Interference ratio, *SIR*, is equal to $\frac{1}{N}$, where N is the number of users. AWGN is considered to be a major impairment in CDMA systems since the power spectral density of users can be around the same level of that

of AWGN. In practice, a chip-energy-to-noise ratio, $\frac{E_c}{N_0}$, of 6 dB is considered a typical worst case value, where E_c is the energy transmitted in a given chip period and $\frac{N_0}{2}$ is the two-sided power spectral density of AWGN. As was explained in section 2.2, we decided to choose a modest PG, where the length of the spreading sequence, p , has been chosen to be $8T_c$, which gives the DFE-receiver a bit rate of 6.25 *Mbps*. This also means that the transmitted bit-energy-to-noise ratio, $\frac{E_b}{N_0}$, is equal to $\frac{E_b}{N_0} = \frac{E_c}{N_0} + 10\log_{10}8 = 15$ dB.

The choice of spreading codes for CDMA users is very crucial in minimizing interference between subscribers. For a sequence length of 8, we made the arbitrary choice of Hadamard, or Walsh codes. In our proposed system, BPSK modulation is considered where each user has one of the eight available Hadamard codes for a sequence length of eight. Note that QPSK modulation was used in presenting the preliminary results of our proposed system in [24, 25]. Both modulation techniques had good performance at $\frac{E_b}{N_0}$ of around 40 dB, but we preferred BPSK since each user needs one spreading sequence while QPSK requires two spreading sequences. Equation (3.1) shows that the transmission of user k is delayed with respect to that of desired user "0" by the value Ω_k . This value is chosen randomly between 0 and T_c for each user.

The DFE equalizer needs to operate at a given sampling phase, decision delay, and a number of forward and feedback taps. We have chosen for the case of optimum performance of the proposed DFE-receiver to calculate the MMSE performance for a varying number of forward filter taps. The MMSE was determined for the best sampling phase and equalizer delay, and the DFE-receiver had a fixed number of feedback filter taps. The feedback taps were chosen to be two since further tests showed that performance of this CDMA system is not

sensitive to the number of feedback taps beyond two; furthermore, the feedback taps cannot affect cochannel interference suppression.

Any MMSE value shown in the following sections is calculated by averaging the MMSE values of 200 different sets of fading channels, where these MMSE values were calculated for the best sampling phase and equalizer delay, two feedback taps and the corresponding number of forward taps shown in a particular figure. Note that each of the 200 sets of channels has Rayleigh faded responses of 8 possible users. For example, when we calculate the MMSE of 4 users for the 200 channel sets then 4 different independent impulse responses are used from each channel set. If the MMSE of 5 users is determined, then these four impulse responses and the fifth one in each channel set are used. Each channel set has a maximum of eight impulse responses since we studied the operation of this receiver for up to eight users.

4.2 Matched Filter DFE-Receiver

Most of the previously proposed receivers for interference cancellation in CDMA assume knowledge of the spreading sequences of all users, which makes these systems more complex and less secure [13, 17, 16]. One version of our proposed receiver (with an input low pass filter) for CDMA does not need information about even the desired user's spreading code. Another version does use this information by providing a DFE-receiver with a spread spectrum matched filter (SSMF) at its input. This filter is a matched filter to the spreading code and transmitted pulse shape of the desired user. The output of SSMF is sampled at the chip-rate or multiples of it before being fed into the forward filter of the DFE. In this thesis, we use both chip-rate DFE and FSE_2 DFE, where FSE_2 means

that the DFE is a fractionally-spaced equalizer which samples the input at twice the chip-rate of the spreading code.

The performance of the proposed receiver needs to be compared with that of other systems to determine the gains that could be achieved. So an acceptable level of MMSE needs to be defined for this system in order to compare with other CDMA systems. This DFE receiver has an $MSE_{dB} \approx -SNR_{dB}$, where SNR_{dB} is measured at the input to the decision-making detector, and $SNR_{dB} = \left(\frac{E_b}{N_0}\right)_{dB} + 3$. Since an $\frac{E_b}{N_0}$ of about 3 dB at the receiver's output is considered adequate for good performance of a coded coherent system [18], then a MSE_{dB} of about -6 dB is needed for good performance of the proposed DFE-receiver.

Figures 4.2 and 4.3 give the MMSE performance for both chip-rate and FSE_2 of the DFE-receiver, respectively, with an SSMF at the input of the receiver¹. The constant-variance model was used as the channel model, and a square pulse was chosen as the pulse shape for transmitting data information. Figure 4.2 shows that an acceptable MSE of -6 dB is easily achieved for the case of 4 users with Hadamard spreading codes. As expected, the system's performance degrades with more users. The results also show that for the "8 Users" case a MSE of -6 dB could be achieved for only 6 forward filter taps. Note that this result is calculated for the best sampling phase and equalizer delay, and the results are averaged over 200 channel sets. In a practical implementation of any communication system, a certain margin of error is inevitable, so a larger number of forward taps should be used to get an optimum MSE better than the sum of acceptable MSE and its standard deviation.

Figure 4.2 also shows the MMSE results of a conventional coherent RAKE receiver with different numbers of users. Note that the RAKE receiver operates

¹ Standard deviations are shown later (in section 4.6).

Figure 4.2 Chip-rate DFE using SSMF, constant-variance model and square transmitted pulses.

Figure 4.3 FSE_2 DFE using SSMF, constant-variance model and square transmitted pulses.

on collecting the desired user's energy which is received through the multipath channel model [19]. The results show the advantages of the DFE-receiver over RAKE receiver, where "RAKE_Us" means that the RAKE receiver has u users transmitting at the same time. The reason for the large improvement in performance of the DFE-receiver over the RAKE receiver is that the forward filter of the DFE, whose structure is similar to that of a RAKE receiver, works on maximizing desired user's energy and minimizing the effects of cochannel interference, ISI and AWGN.

As figure 4.3 shows, FSE_2 DFE-receiver behaves similar to a chip-rate DFE-receiver in terms of performance or degradation as the number of users are increased in the system. For a number of users less than 7, the chip-rate performance is better than that of FSE_2. But the time span of the forward filter of FSE_2 DFE-receiver is half that of the chip-rate DFE-receiver. For the case of 7 and 8 users, FSE_2 gives somewhat better performance than the chip-rate receiver. In other words, both types of receivers give more or less the same MMSE variation between 4 and 8 users.

It is also noticed in the results of both chip-rate and FSE_2 DFE-receiver that the performance drop between 4 and 5 users is more than that between 5 and 6 users. The same relationship is observed for the performance drop between 6 and 7 users, and that between 7 and 8 users. This relationship could be related to the crosscorrelation properties of the Hadamard codes of these users. Note that the k th Hadamard code of the Hadamard matrix was assigned to user k . To investigate the effects of the crosscorrelation properties on performance, the spreading sequences were reassigned to the CDMA users, where the first four users were given the odd Hadamard codes. The other four users were assigned

the even Hadamard codes. Note that each user still goes through the same fading channel model of the previous results.

Figure 4.4 shows the MMSE results of chip-rate DFE-receiver with the new spreading codes assignment to all users. Comparing these results to those of Figure 4.2, we find that performance in Figure 4.2 is better, on a given user basis, than that of Figure 4.4. However, the drop in performance between 4 and 8 users in the new code assignment method is less than that of Figure 4.2. The relationship observed previously of the drop in performance between user i and user $i + 1$ has also changed as could be seen in Figure 4.4. This shows the effects of different spreading codes on overall performance of DFE-receiver. Note that the new assignment of codes to all users, as was done for the results of Figure 4.4, will not be used for calculating the MMSE of other configurations of the DFE-receiver, which will be presented in the following sections.

4.3 Lowpass Filter DFE-Receiver

A simpler DFE-receiver presented here, uses no *a priori* information about the spreading sequence of the desired user. This reduces the complexity of the CDMA system by replacing the SSMF with a lowpass filter (LPF) that has a bandwidth equal to the spread spectrum bandwidth. The optimized forward filter of the DFE works on minimizing interference, ISI, and AWGN. It could also act as the matched filter of the desired user, because the structure of the matched filter is similar to that of the forward filter of the DFE. Figures 4.5 and 4.6 show the MMSE performance for both chip-rate and FSE_2 DFE-receivers when using constant-variance channel model and square pulses for data transmission.

Figure 4.5 shows that an acceptable MMSE value could be achieved for a number of forward filter taps greater than 10. The variation in performance

Figure 4.4 Chip-rate DFE using SSMF and new spreading code assignment.

Figure 4.5 Chip-rate DFE using LPF, constant-variance model and square transmitted pulses.

Figure 4.6 FSE_2 DFE using LPF, constant-variance model and square transmitted pulses.

between 4 and 8 users is less for a large number of taps than that for a small number of taps. Ten forward taps is thought to be a good length for the forward filter of the chip-rate DFE since it gives acceptable MSE performance. Figure 4.6 shows an acceptable performance for the FSE_2 DFE, but it is in general worse than that of chip-rate receiver for equal number of forward taps. FSE_2 performance drops faster for a higher number of users, and it has more MMSE variation between 4 and 8 users than that noticed for the chip-rate DFE. Note again that the length of FSE_2 DFE, in terms of chip periods, is half that of chip-rate DFE for the same number of forward filter taps.

Comparing the SSMF case with the LPF case of the DFE-receiver, we find that a LPF at the input of the DFE gives better MMSE. Since all users have Hadamard codes as their spreading sequences, the desired user and any other interferer have a zero crosscorrelation, with equal delays for each user, for the case of one received path. This orthogonality is lost when multipath channels or different delays are considered. The SSMF will work on minimizing the crosscorrelation between the desired and interfering users in such channels. But bad channels might result in high interfering peaks generated from the SSMF. However, the LPF DFE-receiver is unbiased to any CDMA user, and the DFE will try to minimize the effect of interference through the adaptation algorithm. The results could be better for the case of bad channels since no SSMF was used at the input of the DFE. This could explain the reason for the LPF case to have better MMSE performance than the SSMF DFE-receiver. Note that a long FSE_2 DFE-receiver with a LPF at the input should theoretically be equivalent to a bank of matched filters followed by FIRs.

Even though the optimum performance of the DFE-receiver shows better

MMSE results for the LPF case of the CDMA system than that of the SSMF case, these gains might be achieved at a higher cost when implementing the LPF system practically. For example, as we will see in the simulation of the DFE-receiver in chapter 5 the convergence time of the SSMF system might be somewhat shorter than that of the LPF system. Then the choice of either system is affected by the system design requirements, or whether it is feasible to have the longer convergence time to gain the extra dBs provided by the LPF DFE-receiver.

4.4 Transmitted Pulses Effects on Performance

The results in the previous two sections assumed a square pulse shape for the transmission of data by different users of the CDMA system. To study the effect of band-limiting the transmitted pulses on performance, square-root raised-cosine ($\sqrt{\text{RC}}$) pulses with 100% excess bandwidth were used for filtering purposes, and the results were compared with that of square pulses. Figures 4.7 and 4.8 show the optimum MSE for both SSMF and LPF cases of chip-rate DFE-receiver, respectively. The constant-variance channel model was also used to simplify the comparison of results with that of square transmitted pulses.

Figure 4.7 shows that a good MMSE could be reached for the case of $\sqrt{\text{RC}}$ pulses when 10 or more forward filter taps are used for the chip-rate SSMF receiver. The drop in performance is around 6 dB between 4 and 8 users for the case of 16 forward taps. Comparing this degradation with the 4.5 dB drop in performance of square transmitted pulses in Figure 4.2, we find that $\sqrt{\text{RC}}$ pulses give worse MMSE for the same number of users and more variation as more users are added to the system. Figure 4.8 shows the MMSE performance for LPF case of DFE-receiver when $\sqrt{\text{RC}}$ pulses are used for filtering. Similar to a previous conclusion earlier in this chapter, the performance in the LPF case

Figure 4.7 Chip-rate DFE using SSMF, constant-variance model and square-root raised-cosine pulses.

Figure 4.8 Chip-rate DFE using LPF, constant-variance model and square-root raised-cosine pulses.

is better than that of the SSMF case in Figure 4.7. For the case of 4 users, the LPF case gives a MSE around -23 dB at 14 taps, which is almost 7 dB better than that of its counterpart for the SSMF case. However, more variations in MSE are observed here when more users are added to the system. For 16 forward filter taps, the performance drops almost 10 dB between 4 and 8 users cases in comparison with the 6 dB degradation for the SSMF case.

Comparing the LPF system of sqrt(RC) pulses in Figure 4.8 with the LPF system of square transmitted pulses in Figure 4.5, the former has more variations in performance, with respect to the number of users, than the latter system. The performance of the LPF receiver with sqrt(RC) improves as more forward taps are used. This is noticed for the case of 16 taps, where the MMSE is better than that of the LPF system with square transmitted pulses for a small number of users. The LPF receiver with square transmitted pulses is better for the cases of 7 and 8 users. The reason could be that the LPF receiver with sqrt(RC) pulses is more effective in filtering the white noise and the small number of interferers than the LPF receiver with square pulses. But as more users are added, the LPF receiver with square pulses filters the new interference better than its counterpart, which results in better performance for the cases of 7 and 8 users.

4.5 Multipath Profile Effects

The constant-variance channel model was used in the previous sections to calculate the MMSE for different receiver's configurations or parameters. In this channel model, different received paths with Rayleigh-fading characteristics had the same average power. Since this model is an extreme case of a fading channel, another model has been considered which we call the exponential-variance model. This more realistic model has the variance of the next received path less than that

of the previous path. This represents less severe multipath, but less potential implicit diversity gain. The MMSE results of the exponential model is compared with that of constant-variance model to gain more insight into the effects of multipath profile characteristics on the performance of the DFE-receiver. Figure 4.9 shows the MMSE for chip-rate DFE-receiver with LPF and square transmitted pulses. Good results were achieved when the forward filter had 10 or more taps. The drop in performance is less than 4 dB between 4 and 8 users for the case of 16 forward taps.

Comparing these results with their counterpart of the constant-variance model in Figure 4.5 for the same number of users, the exponential-variance model gives an MMSE which is at most 2 dB below that given by the constant-variance model. Furthermore, the overall variation between the MMSE performances of 4 and 8 users for the exponential-variance model is lower than that of the constant model. This means that an expected reduction in the diversity gain is more than compensated. This could be explained by the fact that the first path of the exponential-variance model has the same variance or average power as each of the three received paths of the constant-variance model, but the last two paths of the exponential-variance model have lower average power than the corresponding paths of the other model. This means that the constant-variance channel has an overall average power larger than that of exponential-variance model. The exponential-variance model also tends to mean a less severely-distorted channel than in the constant-variance model. This also explains the larger variations of MMSE, with respect to the number of users, in the case of the constant-variance channel model.

Figure 4.10 gives the results of the exponential-variance model for a LPF and FSE_2 DFE-receiver with square pulse for data transmission. The MMSE

Figure 4.9 Chip-rate DFE using LPF, exponential-variance model and square pulses.

Figure 4.10 FSE_2 DFE using LPF, exponential-variance model and square pulses.

performance is acceptable, but as the number of users is increased the MMSE drops faster than that observed in Figure 4.9 for the case of chip-rate DFE-receiver. Comparing FSE_2 results of the exponential-variance channel model with that of the constant-variance model in Figure 4.6, the same conclusion is observed as was found for the case of chip-rate comparison of both channel models; the MMSE for any given user and the overall MMSE increase with respect to the number of users of the exponential-variance model is less than that of the constant-variance model.

To study the effects of pulse shaping on the performance of the exponential-variance channel model, $\text{sqr}(RC)$ pulses were used for the case of SSMF and chip-rate DFE-receiver, and the results are given in Figure 4.11. The performance is acceptable for 10 or more forward filter taps. Comparing these results with those in Figure 4.7 of constant-variance model, we find the performance is slightly worse in the exponential model for 4, 5 and 6 users, and is almost the same for 7 and 8 users. The overall variation in MMSE is also lower in the case of the exponential-variance model.

The gains of the constant-variance over the exponential-variance channel model shows the ability of the DFE to provide good performance in the presence of bad channels of slowly-fading environments. Not only the DFE is working on minimizing the interferers' multipath effects, but it is also acting as a RAKE receiver to combine the energies of its desired user's paths. These energies are, on average, higher in the case of constant-variance model than that in the exponential-variance channel model, which translates into better performance for the former channel model. This would be advantageous in a multipath-dominated environment with few users, where the constant-variance model has more implicit diversity than the exponential-variance case.

Figure 4.11 Chip-rate DFE using SSMF, exponential-variance model and square-root raised-cosine pulses.

4.6 Strict Power Control

As it was explained previously, all users had paths with the same average power for the case of the constant-variance model. In the case of the exponential-variance channel model, two different users had paths with equal average power if they happen to be received at the same chip period. But looking at different channel sets of the two hundred that were used for calculating the MMSE, we find that the instantaneous power of the received paths of each channel set is different from that of other channel sets. We will call this type of power control an *average-power-control* of the fading channels; i.e. the power of all users is the same only in a long-term average sense.

A more strict control on the transmitted power of individual users is used in most CDMA systems where the base station transmits or asks the mobile/portable user to transmit at a given power so that all power-controlled users are received with exactly the same power at the base station. This type of control will be called the *strict-power-control* technique and will be represented here by normalizing the power of each user's path to the sum of powers of the three received paths. In practice, it is difficult to implement perfect (strict) power control, and different users' powers will differ slightly (resulting in performance degradation of CDMA systems [26, 27]). We ignore such imperfections in considering ideal strict power controlled systems. This means that for any one of the 200 channel sets used for studying the MMSE of the DFE-receiver, the instantaneous total power of all paths for any particular user will be exactly the same. The results of strict-power-control will be presented here and compared with that of average-power-control.

Figure 4.12 presents the MSE results of chip-rate DFE with LPF when strict-power-control is used. The constant-variance channel model and square pulses

Figure 4.12 Chip-rate DFE using LPF, constant-variance model, square pulses and strict-power-control.

were also used. The results are acceptable where the system operation could be achieved for 10 or more forward filter taps. A small drop in performance is observed when more users are added to the system, where the difference in performance between 4 and 8 users is less than 4 dB. Comparing these results with their counterpart of average-power-control in figure 4.5, the strict-power-control technique surprisingly gives more than 4 dB *worse* MMSE for the same number of users. But the overall MMSE variation between 4 and 8 users of strict-power control is almost 1.5 dB lower than that in the average power technique.

The strict-power-control technique causes less variation among the MMSEs of individual channel sets, since the total power of any user in a given channel set is the same as that in another channel set. Less variation in MMSE of individual channel sets in the strict-power-control technique means that the standard deviation of the average MMSE is smaller than that of the average-power-control technique. This explanation is supported by the results shown in Figure 4.13. The standard deviation of 200 MMSE values at a given number of forward filter taps was calculated for both average and strict-power-control schemes. The results show that an average-power-control technique provides higher standard deviation of MMSE than that of strict-power-control, for any number of forward filter taps.

Figure 4.14 shows the results of chip-rate DFE with SSMF, constant-variance channel model and sqrt(RC) pulses for the strict-power-control technique. Similar to the previous case, the results are on average 3.5 dB worse than that in Figure 4.7 of average-power-control. The difference in MSE is almost 4.5 dB for 4 users, but it becomes lower as the number of users is increased where the difference reaches 2 dB for 8 users. The variation in MSE between 4 and 8 users is also lower in the case of strict-power-control. The standard deviation of MSE of both power control techniques, given in Figure 4.15, also shows higher standard deviation for

Figure 4.13 Standard deviation of MMSE for chip-rate DFE using LPF, constant-variance and square pulses.

Figure 4.14 Chip-rate DFE using SSMF, constant-variance model, sqrt(RC) pulses and strict-power-control.

the average-power-control technique, which is almost 1 dB higher than that of strict-power-control for forward filter taps higher than three.

For the case of the exponential-variance model, Figure 4.16 shows the MSE results of chip-rate DFE with LPF and square pulses for the case of strict-power-control. Comparing these results to those in Figure 4.9 of average-power-control, we again have worse MSE in the strict-power-control technique. The only difference from previous observations is that this drop in performance for a given number of users is about 1.5 dB, which is smaller than the 4 dB drop observed between average and strict-power-control techniques in the constant-variance model.

This could be explained by the fact that the overall average power of paths in the constant-variance model is higher than that in the exponential-variance case. Adding strict-power-control to the exponential-variance channel model will raise the average value of MMSE by a smaller amount than that of constant-variance. Figure 4.17 gives the standard deviation of the present receiver configuration for both average and strict-power-control techniques. The results show again strict-power-control has lower standard deviation, which means there are less variation between the MMSE results of all channel sets.

Looking at the exponential-variance model with SSMF, Figure 4.18 shows the results of chip-rate DFE with $\sqrt{\text{RC}}$ pulses and strict-power-control. Comparing these results with those in Figure 4.11 of average-power-control, there is a drop in performance of around 1.5 dB for the same number of users in the case of strict-power-control. The same comparison of both power techniques in the constant-variance model had a drop of almost 3.5 dB. Figure 4.19 shows the standard deviation of MMSE for this system configuration of exponential-variance model, where the strict-power-control technique has smaller standard deviation than that

Figure 4.15 Standard deviation for chip-rate DFE using SSMF, constant-variance and sqrt(RC) pulses.

Figure 4.16 Chip-rate DFE using LPF, exponential-variance model, square pulses and strict-power-control.

Figure 4.17 Standard deviation for chip-rate DFE using LPF, exponential-variance and square pulses.

of average-power-control, or less MMSE variations, as it was observed in the previous cases.

4.7 Remarks on MMSE results

The MMSE results of the proposed system showed that the DFE-receiver had good performance in the presence of either a SSMF or LPF at its input. Effects of pulse shaping on the performance were considered where both square and sqrt(RC) pulses were used for data transmission. Two channel models were also presented, where the constant-variance model had better MMSE performance than the exponential-variance since the former channel model had more implicit diversity gain. The effects of strict-power-control on performance were also considered, and it was seen that average-power-control gives better results than the strict control technique when using adaptive equalization for the CDMA system that we proposed.

The finding that the average performance for average-power-control is better than that of strict-power-control is very significant. It implies that the use of adaptive equalization in CDMA systems can greatly relax the systems' power control requirements, or in other words it is more resistant to near-far interference. The difficulty of ensuring strict power control in conventional multiple access direct sequence CDMA systems has been cited as one of their major disadvantages [26, 27].

The MMSE results present the potential gains in capacity when using the DFE-receiver in a CDMA system. Many of the channel sets considered in calculating the MMSE had large eigenvalue spread. This means that many of these channel sets could result in poor convergence when using the LMS algorithm for adapting the DFE coefficients. A study of the convergence of the receiver is needed to

Figure 4.18 Chip-rate DFE using SSMF, exponential-variance model, sqrt(RC) pulses and strict-power-control.

Figure 4.19 Standard deviation for chip-rate DFE using SSMF, exponential-variance and sqrt(RC) pulses.

determine whether it is practical to implement such a system in the presence of these badly fading channels. This study is presented in chapter 5, which will be also compared with the MMSE results obtained in this chapter.

chapter 5

Convergence of the Adaptive DFE-Receiver

In this chapter, a simulation of the DFE-receiver is presented and the convergence time is compared with the calculated MMSE in chapter 4. The convergence time will help in determining the feasibility of implementing the proposed DFE-receiver, and the advantages of one receiver configuration, SSMF or LPF, over the other. Section 5.1 presents the values of parameters needed for simulating the receiver, and the adaptation algorithm used to update the DFE coefficients. Section 5.2 shows the convergence time of the DFE-receiver with a SSMF at its input. These results will be compared with the calculated MMSE values for the same receiver configuration. Section 5.3 presents the simulation results for a LPF DFE-receiver to determine its performance in the absence of information about the spreading code of the desired user. Section 5.4 studies the effects of pulse shaping on the convergence time of the proposed receiver. The convergence time of the multipath profile is presented in section 5.5. Finally, section 5.6 presents the effects of strict power control on the convergence time of the DFE-receiver.

5.1 The Simulation

To simulate the DFE-receiver, a number of parameters need to be chosen. For example, the length of the forward and feedback filters, the equalizer delay, and perhaps the sampling phase should be determined to provide adequate performance over a wide selection of channel sets. An adaptation algorithm needs to be specified for updating the DFE coefficients. We have decided to simplify the

simulation by choosing one specified value for each of these parameters, even though they may be suboptimal for some channel sets.

It is evident from the MMSE results of chapter 4 that a different minimum number of forward taps is needed for each receiver configuration, pulse shaping, multipath profile or strict power control cases considered in calculating the optimum performance. So we decided to use 14 forward taps since it provides good performance in all cases presented in chapter 4. The feedback filter is fixed at two taps since we have found that the MMSE does not improve for larger numbers of feedback taps. The equalizer delay was chosen to be equal to two, and the sampling phase was also fixed to simplify the process of simulating the proposed receiver.

Before starting an extensive study on the convergence of the DFE-receiver for the different cases presented in chapter 4, a comparison is needed between the analytical and simulated MSE of the receiver. This should prove the functionality of the simulation under the chosen parameters. Figure 5.1 shows a comparison between the simulated and analytical steady state MSE of a particular channel set. The analytical MSE was calculated using the equations derived in section 3.4. The Least-Mean-Squared (LMS) algorithm was used to update the coefficients of the DFE-receiver. As the results show, the simulation gives a MSE that is comparable to the analytical one, which means that the simulation is working well under the chosen parameters. Similar results were obtained for other channel sets, but the step size of the LMS algorithm needs to be adjusted for many channel sets.

The MMSE value is also given in Figure 5.1 to study the speed of the LMS algorithm in approaching the optimum result. It is seen that the convergence is slow for this channel set, and similar results were observed for other channel sets. The reason is that many of the 200 channel sets used in the simulation were badly

Figure 5.1 Analytical and simulated convergence of chip-rate DFE with SSMF.

distorted and/or faded. These channel sets required an adaptation algorithm that is related to the impulse response of the received signal. So we decided to use the Normalized Least-Mean-Squared (NLMS) adaptation algorithm to update the coefficients of the forward and feedback taps of the DFE [28], since it is related to the response of the received signal. The NLMS adaptation equations are :

$$\begin{aligned}\mathbf{f}_f[n+1] &= \mathbf{f}_f[n] + \frac{\mu}{\|\mathbf{m}_f[n]\|^2} e[n] \mathbf{m}_f[n] \\ \mathbf{f}_b[n+1] &= \mathbf{f}_b[n] - \frac{\mu}{\|\mathbf{m}_f[n]\|^2} e[n] \mathbf{m}_b[n]\end{aligned}\tag{5.1}$$

where $\mathbf{f}_f[n]$ and $\mathbf{f}_b[n]$ are the forward and feedback coefficients vectors at time n , $\mathbf{m}_f[n]$ is the vector of received signals at time n , $\mathbf{m}_b[n]$ is the vector of decision bits used in the feedback filter, $e[n]$ is the error, μ is the step size which ranges between zero and 2, and $\|\cdot\|$ is the norm of a given vector.

Finally, the convergence times of all cases that are shown in the following sections are averaged over 200 channel sets. Furthermore, the MMSE result of each channel set was averaged over 5 trials where each trial represents a simulation of the DFE-receiver with the same fading channel set but using a different data sequence. So an average MSE convergence versus the number of transmitted data bits is obtained from the 1000 instantaneous convergences obtained through the simulation. A training sequence was also used to study the convergence time of all cases presented in the following sections.

5.2 Convergence of DFE-Receiver with SSMF

A simulation of the DFE-receiver with a SSMF at its input was done to study the convergence time of the receiver. The best step size μ of the NLMS adaptation algorithm was found to be equal to 1. Figure 5.2 gives the convergence time of

this receiver configuration with chip-rate sampling and constant-variance model. Comparing these results to the calculated MMSE results of the same receiver in Figure 4.2, we find that the convergence of 4 users in the simulation is almost the same as the calculated MSE. But for a larger number of users, the simulation provides a MSE which, after 3000 transmitted bits, is worse by at least 3 dB than the calculated MSE. One reason for the slow convergence is that the equalizer delay and sampling phase were not optimized for each particular channel set. The simulation results for any number of users show that at least 2000 bits are needed to approach its calculated MSE value.

To decrease the time needed to reach an acceptable MSE, a gear-shifting of the step size of the NLMS algorithm was considered. Figure 5.3 represents the results of simulating the DFE-receiver using gear-shifting of the NLMS where the step size μ changes from 1 to 0.1 after 300 bits. The results show faster convergence, especially for higher numbers of users where the MSE improved by 1 to 2 dB. Therefore, this gear-shifting of the step size will be used when simulating the DFE-receiver. As was explained in chapter 4, a MSE of -6 dB is acceptable for good system performance which is easily achieved for up to 8 users as seen in Figure 5.3. However the information provided by the average MSE of the 200 channel sets is not enough to determine the number of users that could be handled by the DFE-receiver, because some of the channel sets could have very bad MSE.

As was explained previously, the MSE convergence was calculated by taking the average of 1000 simulations of the DFE-receiver for 200 channel sets. More understanding of the capability of the proposed receiver could be obtained by simulating the outage probability. We define here the outage probability, at a given number of transmitted bits, as the probability of the number of channel

Figure 5.2 Convergence of chip-rate DFE with SSMF, constant-variance model and square pulses.

Figure 5.3 Gear-shifting NLMS for chip-rate DFE with SSMF, constant-variance model and square pulses.

sets that have MSE values greater than the acceptable MSE of -6 dB. Figure 5.4 presents the outage probability of a chip-rate DFE with a SSMF, constant-variance model and square pulses. We find that the outage probability of 4 users is approximately 2×10^{-2} , which means that the MSE of all channel sets is 98% of the time better than -6 dB. But the outage probability is much worse for higher number of users. This shows that this configuration of the DFE-receiver could handle easily 4 users.

Figures 5.3 and 5.4 also show the MSE and outage probability of 1 user. It is seen that the outage probabilities of 1 and 4 users are around an acceptable outage of 10^{-2} . This means that the outage probability is mainly due to fading, multipath and ISI for small number of users. But it becomes affected more by interference as the number of users is increased. It is also noticed that the MSE value of 1 user in Figure 5.3 is almost equal to $-((E_b/N_0)_{dB} + 10 * \log_{10}(3)) = -19.77$ dB, where the transmitted E_b/N_0 is 15 dB and 3 is equal to the number of received paths. This means that the DFE-receiver acts as a RAKE receiver for the case of 1 user, then adapts itself to the effects of interference caused by the CDMA users.

The advantages of an equalizer over RAKE receiver is confirmed in the results given in Figure 5.5. Since no feedback section was used in the equalizer, both the RAKE and equalizer have the same structure. The system starts with one user, so both receivers have the same MSE. When the second user starts transmitting, the RAKE receiver stops adjusting its taps since its job is to equalize for the desired user's response. So the performance of the RAKE drops with respect to the power of the new interferers who start accessing the system at 750, 1500 and 2250 bits. But the linear equalizer adjusts its taps always, so the effects of interference are minimized as the results show. This clearly shows the advantages of linear or decision feedback equalizers over RAKE receivers.

Figure 5.4 Outage probability of chip-rate DFE with SSMF, constant-variance model and square pulses.

Figure 5.5 Convergence of linear equalizer and RAKE with SSMF, constant-variance model and square pulses.

Figure 5.6 shows the convergence of FSE_2 DFE-receiver with a SSMF at the input. Comparing these results to those in Figure 5.3, we see that the chip-rate DFE has better MSE. The reason is that the forward filter of both equalizers has the same length, which is a disadvantage for the FSE_2 receiver. When the forward taps of the FSE_2 receiver were increased, as seen in Figure 5.7, the average MSE improved. This means a FSE_2 DFE-receiver needs more taps than a chip-rate receiver in order to have better performance, as expected. The simulation results for both chip-rate and FSE_2 receivers show that the performance drop between 4 and 5 users is more than that between 5 and 6 users, which was also noticed for the optimum MMSE in chapter 4. The same relationship is also seen between 6 and 7 users, and that between 7 and 8 users. This relationship was shown in chapter 4 to be related to the type of codes assigned to the CDMA users.

5.3 Convergence of DFE-Receiver with LPF

A simulation of the proposed receiver with a LPF at its input was performed to study the effects of having no information about the spreading code of the desired user. Figure 5.8 shows the convergence for this receiver with constant-variance model and square transmitted pulses. Comparing these results to the optimum MSE in Figure 4.5, we see that the convergence of 4 users is worse by about 2 dB. However, the difference in performance is at least 6 dB for a number of users higher than 4. The reason is again related to the simulation parameters that were not optimized for each particular channel set, which means that the equalizer requires longer time to converge. The outage probability of this receiver configuration could also be seen in Figure 5.9, which shows good performance only in the case of 4 users being serviced by the DFE-receiver.

**Figure 5.6 Convergence of FSE_2 DFE with SSMF,
constant-variance model and square pulses.**

Figure 5.7 Convergence of FSE_2 DFE-receiver with SSMF and 16 forward taps.

Figure 5.8 Convergence of chip-rate DFE with LPF, constant-variance model and square pulses.

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Figure 5.9 Outage probability of chip-rate DFE with LPF, constant-variance model and square pulses.

The slow convergence of 5 or more users is probably caused by the absence of a SSMF at the input of the receiver. Initializing the forward filter coefficients of the DFE with the spreading code of desired user does not improve the convergence, as seen in Figure 5.10. The forward filter is not only trying to maximize its desired user's energies, but is also working on minimizing the effects of interference, multipath, fading and AWGN. The final settings of the forward taps are different for each of the 200 channel sets, and not necessary close to the particular values of the spreading code of the desired user. A better way to approach the calculated MSE is to use more forward taps. The results with the selected receiver parameters show that at least 4 users could be handled by the receiver, without initializing the forward filter to the spreading code of the desired user.

Comparing the convergence of the LPF system with its counterpart of the SSMF in Figure 5.3, the LPF system gives better convergence for a number of users less than 7. Looking at the convergence of FSE_2 DFE-receiver with LPF, Figure 5.11 shows unacceptable convergence when using 16 forward taps. This is expected since the length of the forward filter is small and a SSMF is not used at the input of the receiver which could help in improving the peaks of the desired user's paths. To offset the loss of the SSMF, Figure 5.12 shows much better convergence than that in Figure 5.11 when 22 forward taps are used at the receiver. The outage probability is given in Figure 5.13 which shows acceptable performance for the LPF receiver with 4 users. Comparing the convergence of Figures 5.12 and 5.7, the performance of the LPF receiver is better than that of SSMF. However, 6 additional forward taps are needed when a LPF is used at the input of FSE_2 DFE-receiver.

Figure 5.10 Initialization of forward filter with spreading code of desired user for LPF DFE-receiver .

Figure 5.11 Convergence of FSE_2 DFE with LPF, constant-variance model and square pulses.

Figure 5.12 Convergence of FSE_2 DFE with LPF and 22 forward taps.

Figure 5.13 Outage probability of FSE_2 DFE with LPF, constant-variance model and square pulses.

5.4 Pulse Shaping Effects on Convergence

In the convergence characteristics of both SSMF and LPF receivers shown in the previous two sections, both receiver configurations assumed square transmitted pulses. To study the effect of pulse shaping on the convergence of the DFE-receiver, $\sqrt{\text{RC}}$ pulses were used in this section. Figure 5.14 shows the convergence of chip-rate DFE-receiver with SSMF, constant-variance model and $\sqrt{\text{RC}}$ pulses. Comparing these results to the calculated MSE of the same receiver configuration in Figure 4.7, we find that the convergence of 4 users provide almost the expected MSE in a short period of time. However, the convergence of a number of users higher than 4 is worse by at least 3 dB than the calculated MSE.

Figure 5.15 confirms the ability of this receiver configuration to handle 4 users, where the outage probability of 4 users is about 2×10^{-2} . The outage probability for higher number of users is shown to be above this value. To study the effects of $\sqrt{\text{RC}}$ pulses on the convergence of the DFE-receiver with a LPF at its input, Figure 5.16 shows the outage probability of this receiver configuration. We could see clearly that 4 users have better outage probability than that seen for the SSMF case in Figure 5.15. As was explained in chapter 4, the use of LPF at the input of the receiver allows the receiver to be unbiased to any user. The presence of badly distorted channels results in larger crosscorrelation peaks of the Hadamard spreading codes which would result in higher multipath peaks of the interferers at the output of the SSMF. The use of a LPF avoids this problem, and thus improves overall performance.

Figure 5.14 Convergence of chip-rate DFE with SSMF, constant-variance model and sqrt(RC) pulses.

Figure 5.15 Outage probability of chip-rate DFE with SSMF, constant-variance model and sqrt(RC) pulses.

Figure 5.16 Outage probability of chip-rate DFE with LPF, constant-variance model and sqrt(RC) pulses.

5.5 Multipath Profile Effects on Convergence

In studying the convergence of the DFE-receiver in the previous three sections we used the constant-variance channel model that we described previously in chapter 4 to be an extreme case of a fading channel. We have also introduced an exponential-variance channel model which is considered to be a more realistic representation of a multipath Rayleigh-fading channel. In this section, the convergence of the DFE-receiver with exponential-variance model will be shown and compared to the calculated MMSE, given in chapter 4, for the same receiver configuration.

Figure 5.17 shows the convergence of the DFE-receiver with LPF and square transmitted pulses in the presence of an exponential-variance channel model. Comparing these results to the calculated MSE of the same receiver setup in Figure 4.9, we find that the convergence of 4 users is almost equal to the calculated MSE. However, the convergence for higher number of users is at least 5 dBs worse than the calculated MSE. The outage probability curves given in Figure 5.18 also confirm that the receiver is capable of handling 4 users.

Comparing the convergence of the exponential-variance model with that of the constant-variance model in Figure 5.8, the constant-variance model has the convergence of 4 users better by almost 1 dB. But the steady state MSE of the exponential-variance does not degrade as rapidly as more users are added to the system, and it becomes better than that of the other channel model when 8 users are accessing the DFE-receiver. As was explained in chapter 4, the desired user's energy in the constant-variance model is higher than that in the exponential model. This meant that the exponential-variance channel model had less severe multipath channel sets, which also corresponds to less potential implicit diversity gain than

Figure 5.17 Convergence of chip-rate DFE with LPF, exponential-variance model and square pulses.

Figure 5.18 Outage probability of chip-rate DFE with LPF, exponential-variance model and square pulses.

the constant-variance model. This characteristic gives better performance for the constant-variance model for a small number of users.

To study the effects of pulse shaping on the convergence of the DFE-receiver with exponential-variance channel, Figure 5.19 presents the outage probability of the proposed receiver with a SSMF and sqrt(RC) transmitted pulses. The results again show good performance for 4 users case, but unacceptable outage probability for higher number of users. Comparing these results to those in Figure 5.15 for the constant-variance model, we find that the results are similar. Looking at Figure 5.18, we find that the outage probability is slightly better when square pulses are used for the exponential-variance model.

5.6 Convergence of DFE-Receiver with Strict Power Control

As was explained in chapter 4, strict-power-control technique means that the instantaneous total power of all paths for any CDMA user is exactly the same as that of any other user in a given fading channel set. We will look here at the convergence of the DFE-receiver when using such power control technique, compare the results with the optimum calculations obtained in chapter 4 and compare it also with the convergence of a DFE-receiver that uses average-power-control technique. Figure 5.20 shows the convergence for chip-rate DFE with LPF at its input, square transmitted pulses and strict power control. Comparing these results to the calculated MSE in Figure 4.12, the converged MSE of 4 users is worse by 1 dB than the calculated MSE. As more users are added in the system the difference between the converged MSE and the calculated MSE increases, and the converged MSE is worse by 4 dB for the case of 8 users. This difference is better than that observed for average power control where we have seen it reaches 6 dB as more users are accessing the system.

Figure 5.19 Outage probability of chip-rate DFE with SSMF, exponential-variance model and sqrt(RC) pulses.

Figure 5.20 Convergence of chip-rate DFE with constant-variance model and strict power control.

This result is expected since all users in the strict power control technique have the same total instantaneous power, while in the average power control technique the instantaneous power of some interferers could be much higher than that of the desired user, which causes a larger difference between its steady state MSE and the calculated MSE than that difference obtained for the strict power control technique. Using the exponential-variance model, Figure 5.21 shows the convergence of chip-rate DFE with LPF, square pulses and strict power control. Comparing these results to the calculated MSE of the same receiver configuration in Figure 4.16, the steady state MSE of 4 users is almost the same as the calculated MSE, but the difference increases as more users are added to the system. The steady state MSE becomes worse by 5.5 dB when 8 users are being serviced by the DFE-receiver.

A similar conclusion was also observed for the same receiver configuration but using the average power control technique. The reason could be related to the variation in the exponential-variance model where the average power of a given path decreases proportionally to the exponent of the received time of the path. The strict power control technique is less effective on the exponential-variance model since the instantaneous total power of a given user is less than that of the same user in the constant-variance model. Therefore, the difference between the steady state MSE and calculated MSE of both power control techniques is almost the same when exponential-variance model is used.

Looking at the outage probability of strict power control technique, Figure 5.22 shows the outage of chip-rate DFE with SSMF, sqrt(RC) pulses and constant-variance channel model. As the results show, the receiver could handle 4 users whose outage probability is in the order of 10^{-2} , but does not have good performance for a higher number of users. The outage probability of this receiver

Figure 5.21 Convergence of chip-rate DFE with exponential variance model and strict power control.

Figure 5.22 Outage probability of chip-rate DFE with constant-variance model and strict power control.

is also similar to that in Figure 5.15 where we assumed an average power control technique. The outage probability of the exponential-variance model is given in Figure 5.23 which again shows a good outage probability for the case of 4 users accessing the proposed DFE-receiver. The results are also similar to those obtained for the average power control technique given in Figure 5.19.

5.7 Remarks on Convergence Results

A detailed study on the convergence of the DFE-receiver was presented. In general, the convergence of 4 users was comparable to its MMSE results that were given in chapter 4. But the MSE convergence for higher number of users is at least worse by 3 dB than the optimum results. The parameters that were used to start the simulation were suboptimal for many of the 200 Rayleigh-fading channel sets. The sampling phase and equalizer delay were always fixed for any number of users. Better results could have been achieved if those parameters were adjusted for each channel set and number of users. But because of simulation complexity, we decided to ignore that issue. Even though the convergence gives worse results than expected, it has been proven that at least 4 users could be serviced by the DFE-receiver. This is a major performance gain because the DFE-receiver shows that the user capacity is equal to 50% of the processing gain in a single cell system. The capacity gains of a multi cell system will be considered in the next chapter.

It was stated in chapter 4 that many of the 200 Rayleigh-fading channel sets had large eigenvalue spread which corresponds to slower receiver convergence. Using the NLMS algorithm, the results have given an acceptable convergence time for most of the simulations. Previous work showed that the convergence time for narrowband transmission is very slow in comparison to the convergence time of our CDMA system [29, 30]. This shows that the spreading bandwidth

Figure 5.23 Outage probability of chip-rate DFE with exponential variance model and strict power control.

of the CDMA system speeds the adaptation process of the DFE-receiver in the presence of many badly-fading channels, because the receiver acts as a RAKE receiver and interference canceller.

chapter 6

DFE-receiver for Cellular Systems

The previous two chapters have demonstrated some of the advantages of using our proposed DFE-receiver for a CDMA system in a frequency-selective Rayleigh-fading environment. The optimum performance and convergence of the DFE-receiver gave an insight into the potential improvement in capacity of the CDMA system. But other practical issues, such as sudden entry of users to the system and inter-cell interference, need to be considered to observe their effects on the performance of the proposed receiver. Section 6.1 represents the effect of using random spreading codes, instead of Hadamard codes, on the performance of the DFE-receiver. The issue of blind equalization for the DFE-receiver was also considered, and the results are given in section 6.2.

Section 6.3 presents the effects of sudden birth or entry of users in the system and proposes a technique that could be used to reduce the sudden drop in performance. Sudden death or termination of access is also considered, and the results are also given in section 6.3. Inter-cell interference is a major consideration in determining the capacity of the overall system, and section 6.4 gives the performance of the DFE-receiver in such an environment. The bit error rate (BER) performance of the DFE-receiver is presented in section 6.5 which provides with the previous issues given in this chapter an understanding of the capacity limitations of the proposed receiver. Finally, section 6.6 gives an overall design of a cellular system that uses a fractionally spaced DFE as its receiver and the advantages in terms of capacity over other practical implementations of CDMA receivers.

6.1 Effects of Spreading Codes on Performance

We have assumed previously that Hadamard codes were used as the spreading sequences of the CDMA users. In this section we study the effects of using randomly picked spreading codes on the performance of the DFE-receiver. Figure 6.1 represents a comparison between the performances of Hadamard and randomly generated set of spreading codes for a chip-rate DFE with a SSMF, square transmitted pulses, constant-variance channel model and 4 CDMA users. The performance of the DFE-receiver with Hadamard spreading sequences is seen to be better by more than 2 dB, which shows the effects of spreading codes on the overall performance of the proposed DFE-receiver. To determine the effects of the random spreading codes on the performance of the DFE-receiver with a LPF at its input, Figure 6.2 shows again that Hadamard spreading codes give almost the same gain as that achieved when we used a SSMF at the input of the receiver. This shows again the effects of spreading codes on the performance of the proposed receiver.

Determining the best spreading sequences for our DFE-receiver was not an issue in this thesis, but it could be a topic for future research. We have used Hadamard sequences for spreading the CDMA users even though there might be other spreading codes that give better performance for our proposed receiver. Hadamard codes are optimum in channel environments where each CDMA user has one received path, and all these signals are received synchronized within a chip period at the input of the DFE-receiver. But we have considered environments where each user had three paths, and users' signals were not necessarily synchronized.

Figure 6.1 Performance of chip-rate DFE with SSMF and random spreading codes.

Figure 6.2 Performance of chip-rate DFE with LPF and random spreading codes.

6.2 Performance of DFE-receiver with Blind Equalization

In studying the performance of the DFE-receiver, we have always assumed that the receiver uses a training sequence to improve its convergence. It is also interesting to see the effects of blind equalization, or no training sequence, on the performance of the DFE-receiver. This helps in determining whether the receiver is able to recover the desired user's data without the overhead of a training sequence at the receiver. Figure 6.3 shows the convergence of two receivers, one with blind equalization and the other using a training sequence. Each receiver has a chip-rate DFE with a SSMF, sqrt(RC) transmitted pulses, constant-variance model and 4 users.

The "blind equalization" curve in Figure 6.3 shows that the DFE-receiver with no training sequence gives a good MSE of -14 dB for 4 users. The MSE is evaluated in the case of blind equalization by calculating the error between the input of the detector and the DFE decisions that were made without using any training sequence. The convergence of the receiver with blind equalization is seen to be almost 1 dB worse than the convergence of a receiver that uses a training sequence. But a large difference is observed in the BER of both receiver configurations.

The receiver with blind equalization had a BER of 15.07%, which is not acceptable for either voice or data transmissions. However, a BER of 0.07% was achieved for the receiver with a training sequence, which is much better than that for blind equalization. This shows that blind equalization is not acceptable for our receiver, and the MSE criterion is not a good measure for the performance of the proposed system with blind equalization. The DFE-receiver with a SSMF needs a short training sequence to achieve a good BER. When the receiver used a training

Figure 6.3 Performance of blind equalization for chip-rate DFE with SSMF.

sequence, the MSE criterion provided similar information about the performance of the receiver as that provided by the BER criteria. But it is preferred to observe both performances to assure the functionality of the receiver in both cases.

The effects of blind equalization on the performance of the DFE-receiver with a LPF at its input is shown in Figure 6.4. The results show that blind equalization gives 5 dB better MSE convergence than a DFE-receiver with a training sequence. But the BER criterion gives a totally different conclusion. A BER of 4.67×10^{-4} was achieved for the DFE-receiver with a training sequence, while the receiver had a very high BER of 34.27% with blind equalization. It has been shown again that the MSE convergence of blind equalization is not a good indicator of system performance.

To explain the reason for having good MSE convergence and poor BER in the case of a LPF at the input of the receiver and blind equalization, we investigated the individual MSE convergences of the 200 channel sets used in the simulation. We compared the decisions of the DFE-receiver in each channel set with the transmitted data bits of all users. The BER of each user in a given channel set was calculated, and it was found that one of these BERs was very small while the others were too high. This low BER was not necessarily that of the desired user, but may have been that of one of the interferers. This meant that the adaptive DFE-receiver was "captured" by one of the interferers, probably the one with largest power.

The BER performance of each user in a given channel set was also investigated for the case of a SSMF at the DFE-receiver and blind equalization. It was again found that one of these BERs was small in comparison with the other BERs, but this small BER was always that of the desired user. This is expected since the SSMF works on maximizing the paths' energies of the desired user with respect to

Figure 6.4 Performance of blind equalization for chip-rate DFE with LPF.

that of the interferers at the input of the DFE-receiver. Thus, the SSMF provides some help to the receiver to lock on to the desired user, in the absence of a training sequence.

To summarize, the MSE criterion is not a good performance measure for the DFE-receiver when using blind equalization, especially with a LPF at the input of the receiver. A short training sequence is necessary to identify the desired user and make steady state MSE more meaningful. Another simulation was performed where the DFE-receiver with a LPF filter used a short training sequence of 50 bits. The BER of this simulation was 5.3% which is much better than the BER of 34.27% of blind equalization, but higher than the BER of a training sequence with 500 bits. But this BER of 5.3% was largely affected by the errors in a number of channel sets, where 166 channel sets out of 200 had no errors. This means that many channel sets require a short training sequence for the adaptation process.

The steady state MSE for this short training sequence was -22 dB, which is almost 2 dB better than the MSE of the same receiver configuration that used a training sequence of 500 bits. This shows that the MSE criterion still does not reflect a true picture of the system performance, because few channel sets require a training sequence longer than 50 bits. It has been also noticed that the convergence speeds of the receiver with training sequence and blind equalization are similar. This is attributed to the fact that the receiver in blind equalization was captured in many cases by a stronger interferer and was working on minimizing the MSE of that interferer which caused the convergence to be as fast as that of the desired user for a receiver with a training sequence.

6.3 Effects of Sudden Birth/Death of Users on Performance

It was assumed previously when studying the convergence of the DFE-receiver that all users start transmitting at the same time and within one bit period. But practically all users start and terminate their transmission to the CDMA receiver at different times. In this section we will study the effects of sudden birth and death of new users on the performance of the DFE-receiver. It was also concluded from section 6.2 that the DFE-receiver does not perform adequately with blind equalization, which requires the receiver to have a short training sequence. So a training sequence of 500 bits will be used in studying the convergence of the DFE-receiver in this and future sections of chapter 6.

Figure 6.5 shows the convergence of chip-rate DFE with sudden birth of users or interferers in the system. Constant-variance channel model, square transmitted pulses and a SSMF were assumed for this receiver configuration. The system starts with one user, the desired user, then a new user starts transmitting after 500 data bits. After the birth of the first interferer, a new user is added every 1000 bits until the receiver has a total number of users equal to 6. There are two curves shown in Figure 6.5, the dashed curve is called the “full power” access technique and the other is the “ramp power” access technique.

The “full power” technique represents the case when the new user starts transmitting his data sequence using full transmission power. In case of no power control, this technique could cause the performance of the overall system to drop below acceptable levels. This is seen in Figure 6.5 where the performance becomes below the acceptable -6 dB performance when the fifth user starts accessing the CDMA system. So it is necessary to find a technique that reduces

Figure 6.5 Birth of interferers for chip-rate DFE with SSMF and constant-variance model.

the sudden drop in performance when a strong interferer is given access to the system.

To reduce the effects of sudden birth of users on the convergence of the DFE-receiver, we proposed the use of the “ramp power” access technique. Here the new user does not start transmission with full power. The transmitted power is increased linearly over a span of 250 bits which, as seen in Figure 6.5, improves the convergence of the receiver over that of the “full power” technique. In the case of sudden birth of the 3rd and 5th users, the peak MSE reached by the “ramp power” technique is better by 2 dB than that reached by the “full power” technique. The improvement is barely noticeable for the 2nd and 6th user. This shows that the new technique helps in reducing the effects of strong interferers on the convergence of the DFE-receiver. The reason for the strong presence of the 3rd and 5th user is attributed to the crosscorrelation properties of the Hadamard codes, where both users have the strongest peaks generated from convolving their spreading codes with that of the desired user.

The results shown in Figure 6.5 give the convergence of the desired user when new users are entering the CDMA system, but it is also interesting to see the convergence of the new user in the system. Figure 6.6 shows the convergence of interferer 2 of Figure 6.5 for the “ramp power” access technique. When interferer 2 started accessing the system, the desired user and interferer 1 had full power. Two curves of convergence for interferer 2 are given in Figure 6.6. “MSE_W” represents the convergence of interferer 2 when the DFE starts adjusting its taps after the user has achieved full power.

“MSE_S” represents the case where the DFE starts updating its taps from the moment the user starts transmitting. But the DFE decisions, used to calculate the MSE, are multiplied by the same coefficient that increases the desired user’s

Figure 6.6 Convergence of interferer 2 for chip-rate DFE with SSMF and constant-variance model.

power. The results show that the convergence of “MSE_S” is better than that of the “MSE_W” technique for the first 500 transmitted bits. But both convergences behave the same way after that initial period. Note that a training sequence of 500 bits is used in both cases.

The advantages of the “ramp power” technique become more obvious when a LPF replaces the SSMF at the input of the DFE-receiver, as seen in Figure 6.7. The results show that the “ramp power” technique gives a peak MSE which is 2 to 7 dB better than the peak MSE of the “full power” technique. The reason for the overwhelming advantage of the “ramp power” technique in the LPF case is that the receiver has no knowledge of the spreading sequence of the desired user. When new users were added to the system in the “full power” technique, the DFE received the full power of the interferer. The DFE dropped to a very low convergence until the DFE had some time to adapt its coefficients to reduce this effect. The “ramp power” technique increases the transmitted power of a given user slowly over a time period; thus, allowing the DFE to adapt to the presence of the new interferer even before establishing full power transmission.

The large drop in performance of the “full power” technique in the LPF case was not seen in the receiver with a SSMF at its input. The receiver in the SSMF case had knowledge of the spreading code of the desired user which helped in reducing the effects of sudden birth of an interferer in the “full power” technique. To summarize the above, it is preferred to use the “ramp power” access scheme to reduce the peak MSE in the convergence of the receiver when new users are added to the system, especially when the receiver uses a LPF at its input.

To study the effects of sudden birth of interferers with strict power control, Figure 6.8 shows the convergence of chip-rate DFE with SSMF, square transmitted pulses and constant-variance model. Using the “ramp power” access technique,

Figure 6.7 Birth of interferers for chip-rate DFE with LPF and constant-variance model.

Figure 6.8 Birth of interferers for chip-rate DFE with constant-variance model and strict power control.

the performance of both average (av_pc) and strict (st_pc) power control cases is almost the same when a new user is added to the system. However, the DFE converges better for average power control for a low number of users. This is expected since the desired user has more energy in the average power control scheme. But the convergence of strict power control improves as more users are added to the system and becomes better when 6 users are accessing the system. The reason is that the average energy of 5 interferers in the average power control case is higher than that in the strict power control scheme. So a better convergence is expected for the strict power control case as more users are added in the system.

Using the exponential-variance channel model, Figure 6.9 shows the convergence of chip-rate DFE with strict power control and sqrt(RC) transmitted pulses. It is seen again that the “ramp power” access technique gives almost the same drop in performance for both average and strict power control cases. As we found for the constant-variance model, the average power control scheme has better convergence for a small number of users, but the strict power control converges faster when the number of users is higher than 4.

After considering the effects of sudden birth of users on the convergence of the DFE-receiver, it is also interesting to see the effects of sudden death or termination of calls on the performance of the CDMA system. Figure 6.10 shows the convergence of the DFE-receiver when users 2 and 3 terminate their access at 3000 and 4000 bits respectively. The system had a chip-rate DFE with a SSF, square transmitted pulses and constant-variance channel model. In comparison with the results of sudden birth of users, the convergence for sudden death of users improves as users terminate their access to the system. This is expected since less interference is present at the receiver, and the DFE converges to a better MSE. This is noticed when the 3rd user terminates his transmission where

Figure 6.9 Birth of interferers for chip-rate DFE with exponential-variance model and strict power control.

Figure 6.10 Death of interferers for chip-rate DFE with SSMF and constant-variance model.

the MSE performance improves by 1 dB with respect to that of the birth curve. The case of sudden termination of calls was repeated, but using $\text{sqrt}(\text{RC})$ pulses and exponential-variance model. Results given in Figure 6.11 show again that the convergence of the DFE-receiver improves when an interferer terminates his connection to the CDMA system.

6.4 Inter-Cell Interference Considerations

Since we have proposed this receiver for a cellular CDMA communication system, it is important to see the effect of neighboring cells on the performance of the DFE-receiver. Two types of inter-cell interference could be considered here, interference caused by a user that has a spreading sequence different from that of the desired user, and interference caused by another user who is assigned the same spreading code as that of the desired user. The first type of interference could be considered similar to the case of an interferer in the same cell of the desired user. The effect of this type of interference was considered in many different cases in chapter 5. In each case, each user arrives at the receiver through a different, statistically independent, channel.

It is important to study the effects of inter-cell interference from users, in the cell(s) adjacent to the one with the desired user, with the same spreading codes as the desired user. This helps in determining the possibility of using the same spreading sequences in the neighboring cells, i.e. in all the cells. One important advantage of using CDMA is that the same spread bandwidth could be reused in neighboring cells. Since we use a small PG, it is important to find enough spreading codes for potential large number of users that will use the CDMA system. Good codes with a length of 8 are rare, so it becomes important to

Figure 6.11 Death of interferers for chip-rate DFE with SSMF and exponential-variance model.

explore the possibility of reusing the spreading sequences in the neighboring cells in a same way as to reuse the spreading bandwidth.

Figure 6.12 shows a cellular layout with users allocated to different cells. Let a desired user $d_{f_i}^{c_1}$ be located in the centre cell, where c_1 corresponds to its spreading code and f_i is the carrier frequency used for data transmission. An interferer in the same cell is represented by $I_{f_i}^{c_2}$ and uses a different spreading code. An inter-cell interferer represented by $I_{f_i}^{c_1}$ has the same spreading code and carrier frequency of the desired user. Note that each user has a different, statistically independent, channel impulse response. Figure 6.13 shows the convergence of the desired user when his receiver uses a chip-rate DFE for the constant-variance channel model.

Both SSMF and LPF DFE-receiver cases are shown in Figure 6.13. The base station of the desired user is assumed to start transmission to all users (4 in this case) in its cell. After 1000 transmitted bits, the base station in the neighboring cell starts transmitting to the interferer that has the same spreading sequence as the desired user. The power of this interferer's signal is assumed to be received at the desired user's receiver 20 dB below the desired user's average signal power. The desired user is then assumed to move toward the cell of the interferer with the assumption that the interferer's signal amplitude increases by 0.1 every 1000 bits. Note again that the DFE-receiver uses a training sequence of 500 bits.

Considering the SSMF case, the steady state MSE of the DFE-receiver is almost -13 dB when the inter-cell interference is 20 dB below the average power of the desired user. This is better than the converged MSE for 5 users presented in Figure 5.3. But as the power of the inter-cell interference increases, the steady state MSE of the receiver increases to unacceptable level. The same conclusion is drawn when comparing the results of the LPF case of inter-cell interference and that of Figure 5.8. This shows that the receiver could handle an interferer that

Figure 6.12 Hexagonal Cellular structure

Figure 6.13 Performance of chip-rate DFE with inter-cell interference and constant-variance model.

has the spreading sequence of the desired user with an average received power of around 20 dB below that of the desired user.

We conclude from these results that neighboring cells should not assign the same spreading codes over the same carrier frequency. The same spreading codes could be assigned over the same transmission bandwidth in cells that are further apart, since the receiver could handle a small inter-cell interference. Section 6.6 will give a clearer picture of the overall cellular receiver design and a plan for the spreading bandwidth and spreading codes assignments of neighboring cells.

It is also noticed in Figure 6.13 that the MSE convergence of the receiver with LPF is better than that of SSMF receiver. This is expected since the LPF case is unbiased to any user in the system, but the SSMF maximizes the multipath peaks of the desired user and the inter-cell interferer that has the same spreading code as the desired user. This results in worse performance for the DFE-receiver that uses a SSMF. Figure 6.14 shows the effect of inter-cell interference on the convergence of chip-rate DFE with SSMF, $\sqrt{\text{RC}}$ transmitted pulses and exponential-variance channel model. The results for square transmitted pulses and constant-variance model are also shown for the purpose of comparison. The results again show that the DFE-receiver could handle a small inter-cell interference. The convergence of both exponential and constant-variance model is also seen to be very similar where they differ at maximum by almost 1 dB.

6.5 Bit Error Rate Performance

The results given in the previous sections of this chapter and those of chapter 5 have shown good performance with respect to the MSE criteria if the DFE-receiver uses a short training sequence. Most of the convergence simulations were done over a transmission period of 3000 bits. In this section we will present the results

Figure 6.14 Performance of chip-rate DFE with inter-cell interference and exponential-variance model.

of BER simulations over a much longer transmission period, and compare the results with those of the convergence to determine the capacity constraints of this receiver. In these simulations each user in a given channel set transmits 50,000 data bits. The first 500 data bits of the desired user's sequence were used as a training sequence. The sampling phase and equalizer delay were fixed, unless mentioned otherwise, to simplify the process of simulating the DFE-receiver.

Figure 6.15 shows the outage probabilities of the BER for chip-rate DFE with SSMF and constant-variance model. An outage probability of "X" is defined here to be the fraction of channel sets (out of 200 channel sets) that have BER greater than the value "X". Figure 6.15a shows the outage probability for $X = 10^{-2}$, while Figure 6.15b shows the outage for $X = 10^{-4}$. The outage probability of the simulation in Figure 6.15 is also compared with that obtained from a Gaussian approximation where it is assumed that the overall interference is Gaussian.

An effort was made to derive an exact error probability for our proposed DFE-receiver. But the analysis turned out to be very complicated for multipath channels. Many assumptions were needed and calculation of the probability of error required extensive computer processing. A simple and accurate method based on Gaussian model for interference to calculate the error probability was proposed in [31], but it does not consider the case of multipath channels. We decided to compare our simulation results with those of a Gaussian approximation. The error probability of the DFE-receiver with coherent BPSK modulation for a single channel set, assuming the interference is Gaussian, is equal to

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = Q(\sqrt{SNR}) = Q\left(\frac{1}{\sqrt{MSE}}\right) \quad (6.1)$$

(a)

(b)

Figure 6.15 Outage probability of BER for chip-rate DFE with SSMF and constant-variance model.

where $\frac{N_0}{2}$ is the equivalent two-sided white noise power spectral density arising from interference and noise, the bit rate is equal to the transmission bandwidth and SNR is the signal-to-noise ratio at the input to the decision device.

Figure 6.15 shows that the outage probability of the DFE-receiver is low and relatively insensitive to the number of users for a number of users less than 5. Note that one channel set in the 1 user case needed an adjustment in its equalizer delay, because its DFE decisions were off by one bit from the correct sequence. Comparing the results of the simulation with those of the Gaussian approximation, both methods give almost the same performance for a number of users up to 4. However, the results differ for higher number of users, especially for an outage probability of 10^{-4} . The reason for the similarities and differences between the two methods is that the DFE is able to suppress most of the interference caused by a number of users up to 4. The remaining part of this interference and the Gaussian noise could be represented as another Gaussian noise variable, which resulted in similar performance between the simulation results and the Gaussian assumption.

For a number of users higher than 4, the DFE has a reduced ability to handle more users in the system. The results in [4, 5] have shown that users with the same bit rate generate interference with cyclostationary statistics. This means that the interference, caused by the new users, which greatly affects the MSE value can not be represented by a Gaussian random variable. This explains the reason for having inaccurate results when using the Gaussian approximation for a number of users higher than 4, especially for an outage probability of 10^{-4} .

The outage probability of an FSE_2 DFE-receiver, with SSMF, was also obtained and the results are compared with those of chip-rate receiver in Figure 6.16. Note that the FSE_2 equalizer uses 16 forward filter taps, while the chip-

(a)

(b)

Figure 6.16 Outage probability of BER for chip-rate and FSE_2 DFE.

rate DFE uses 14. It was also found that one channel set in the 1 and 2 users cases in the FSE_2 receiver required an adjustment of its equalizer delay, similar to the case in the chip-rate receiver. As the results show, the FSE_2 receiver could handle up to 4 users, but its performance is not as good as that of chip-rate receiver. The FSE_2 receiver could have better results if more forward taps were used. Comparing these results of the outage probability with those obtained from the convergence study of the proposed receiver, we again find that the system is able to handle 4 users.

Replacing the SSMF with a LPF, Figure 6.17 shows the outage probability of the DFE-receiver for both the simulation and Gaussian assumption on the multiple access interference. Similar to the SSMF case, both the simulation and the Gaussian approximation provide similar results for a number of users less than 5, and they differ for higher numbers of users. The results also show that a DFE-receiver with a LPF has a good outage probability when the system services 4 users. Note that one channel set in the 1 user case required two more forward taps, because the forward filter was not long enough and the DFE was giving a decision of -1 all the time. Comparing the outage of the LPF case to those in Figure 6.15 for the SSMF receiver, the SSMF case provides slightly better outage for a number of users less than 5. The difference in their performance increases for higher number of users, but it is not important to consider since both provide unacceptable outage probability in this case.

Considering the issue of power control, Figure 6.18 presents a comparison between strict and average power control techniques for a chip-rate DFE with SSMF, square transmitted pulses and constant-variance channel model. For a number of users less than 5, both techniques have the same performance for an outage probability of 10^{-2} , and almost the same for an outage probability of

(a)

(b)

Figure 6.17 Outage probability of BER for chip-rate DFE with LPF and constant-variance model.

(a)

(b)

Figure 6.18 Outage of BER for chip-rate DFE with SSF, power control and constant-variance model.

10^{-4} . For higher numbers of users, the strict power control technique provides somewhat better results than the other technique. But this is not beneficial for the DFE-receiver since the outage probability is not acceptable for a number of users higher than 4. Similar to the conclusions drawn from the results of the MMSE calculations and convergence time in the previous chapters, it is seen again that strict power control would not be necessary. Rather, the implicit diversity in the multipath channels could be used to improve the system's performance without imposing power control requirements on the CDMA system.

Using the exponential-variance channel model and sqrt(RC) pulses, Figure 6.19 shows a comparison between the outage probabilities of strict and average power control techniques. For a number of users less than 5, the outage performance of the average power control technique is always better or equal to that of the other technique. The opposite is true for higher number of users. But we again find that the performance is not acceptable for a number of users higher than 4, which means that strict power control requirements could be omitted for our proposed DFE-receiver.

To summarize, the BER simulation of the DFE-receiver has shown consistency with previous results obtained for the MMSE calculations and convergence time study of the receiver. The overall conclusion is that the receiver could provide good service for 4 users when using a PG of 8. Good performance is achieved with or without knowledge of the desired user's code at the receiver. Strict power control is not necessary for the implementation of the proposed receiver; rather, the implicit diversity of the multipath channels could be beneficial in improving the overall performance.

(a)

(b)

Figure 6.19 Outage of BER for chip-rate DFE with SSF, power control and exponential-variance model.

6.6 Design of Cellular System using a DFE-receiver

After calculating the optimum performance of the DFE-receiver, studying its convergence time and BER performance under different channel and system parameters, it has been concluded that the receiver is able to handle 4 users within the cell of the desired user. In a cellular system, however, users in neighboring cells, as seen in Figure 6.12, are being serviced by their corresponding base stations. This means that the neighboring cells will be contributing to the overall interference of the desired user. It has been shown that interference from neighboring cells could contribute up to 35% of the total interference on the desired user's signal [2]. This multiple cell interference was considered to be a Gaussian random variable.

The effects of multiple cell interference could be seen in Figure 6.20, where the outage probability is presented for different chip energy-to-Gaussian noise ratio, E_c/N_0 . It is assumed that the receiver has a chip-rate DFE with SSMF and 4 active users in the desired cell. This means that each cell has three in-cell interferers. For E_c/N_0 of 0 dB, the multiple cell interference is equal to 35% of the total interference in a given cell. Note again that an acceptable receiver outage, prob. (BER>X), of .02 corresponds to 4 channel sets (out of 200) that have their BER>X. For an outage probability of 10^{-2} , the receiver outage is almost insensitive to a drop in E_c/N_0 from 6 to 1 dB. Good outage probability of 1.5% is also seen for an E_c/N_0 of 0 dB. The outage probability of 10^{-4} is affected more by changes in the power of the multiple cell interference, where an E_c/N_0 of 0 dB provides a 4% outage probability of the DFE-receiver. This shows the ability of the DFE-receiver to perform well in the presence of inter-cell interference.

Figure 6.20 Outage probability of DFE-receiver versus the chip energy-to-noise ratio.

It was seen in section 6.4 that an active user in a neighboring cell, whose spreading sequence is the same as that of the desired user, could result in a bad convergence of the DFE-receiver if this interferer's received signal was noticeably strong. Note that the DFE-receiver used here had an SSMF at its input to minimize the energies of other interferences' signals, and there were 4 users in the desired user's cell. For comparison purposes, the BER performance for the same situation was obtained where Figure 6.21 shows the outage probability for different interferer-to-desired user average power, P_5/P_1 . It is seen that a P_5/P_1 of up to -20 dB could provide an outage probability of 0.01 at the 10^{-2} level. The performance degrades very rapidly when the average power of the interferer approaches that of the desired user.

The performance of the DFE-receiver in this situation is expected to be bad since it uses a matched filter to the spreading code of the desired user, which is also a matched filter to the other cell user. The results could be better if the DFE uses a LPF at its input. In this case, the DFE-receiver is not biased toward any spreading code, but it is not expected to perform as well as another DFE-receiver with an outer cell interferer that has a different spreading code from that of the desired user. This observation is confirmed in Figure 6.22 with the MMSE performance of the DFE-receiver for both SSMF and LPF cases.

Figure 6.22a compares the MMSE performance of the DFE-receiver with a SSMF when the first and fifth user have the same and different spreading codes. There is at least 4 dB improvement when both users have different spreading codes. For the LPF case, shown in Figure 6.22b, there is over 2 dB drop in performance if the neighboring cell's user has the same spreading code as the desired user. But the performance drop in the LPF case is less than that in the SSMF case. This suggests that a neighboring cell should avoid using the

Figure 6.21 Outage of DFE-receiver when desired and 5th user have the same code.

(a)

(b)

Figure 6.22 MMSE performance of DFE-receiver when desired and 5th user have the same code.

same spreading code of the desired user to its subscribers over the same carrier frequency, especially when the DFE-receiver uses a SSMF at its input.

Using the results and conclusions drawn from this and other sections of this thesis, an overall description of the proposed CDMA system could be given. A given cell could handle up to 4 users in its cell, with multiple access interference from neighboring cells. This multiple access interference is considered to be Gaussian. The processing gain of the CDMA users was chosen to be 8, but the total available transmission bandwidth, call it B_{ss} , in any cell is expected to be many orders higher than the spreading bandwidth of the proposed CDMA system, since each cell should provide service for a lot more users than 4. By using different carrier frequencies, B_{ss} could be divided to a number of smaller transmission bandwidths where each is used by a DFE-receiver to handle 4 CDMA users.

This division of the spread spectrum bandwidth is similar to that of FDMA systems. So each cell could handle up to $\left(\frac{B_{ss}}{(2 \cdot \frac{1}{T_c})} * 4 \right)$ users. The other important issue in the design of this CDMA system is the spreading codes assignment to different cells. Figure 6.23 gives an example of code/frequency assignment to neighboring cells. It is assumed here that the overall available bandwidth is equal to three times the spreading bandwidth of the proposed CDMA system. For the same carrier frequency, each cell uses a different set of spreading codes from that used by other cells, where "Ci" is a set of 4 spreading codes different than that of set "Cj". This means that all cells could use these sets of spreading codes, but no two neighboring cells should use the same set over the same carrier frequency. Cells at a greater distance from the desired user could use the same set of codes over the same carrier frequency since their received signal is not

expected significantly to interfere with that of the desired user. Note also that set “Ci” could be reused in the same cell at different carrier frequencies, but it is preferred that these frequencies are not next to each other in order to avoid adjacent channel interference.

Figure 6.23 Example of code/frequency allocation in cells for a CDMA/FDMA system with DFE-receiver.

chapter 7 Conclusions

A fractionally-spaced decision feedback equalizer (DFE) has been proposed for a CDMA system in indoor cellular environments. The results show that the receiver is capable of minimizing the effects of interference, fading, multipath and AWGN. A literature survey is given in chapter 2 of many systems proposed for improving the performance of CDMA systems. But most of these systems assume knowledge of the channel parameters, users' energies or spreading codes of all users. We have proposed two configurations of the DFE-receiver, one of which has knowledge of the spreading code of the desired user (SSMF case), while the other assumes no information about any spreading code used in the CDMA system (LPF case).

Chapter 3 gave an overall description of the DFE-receiver. Then the optimum performance, or MMSE analysis, was derived for this system. An analytical presentation of the convergence for the DFE-receiver was also given in this chapter. In chapter 4, the MMSE performance was calculated for different fading channel sets, transmitted pulse shapes and strict power control technique for both SSMF and LPF receivers. The results showed the potential advantages of using such a receiver, whether it has knowledge of the spreading code of the desired user or not. It was also seen that strict power control need not be enforced on the CDMA users since the DFE used the implicit diversity of the multipath channels to its advantage in combining the desired user's paths, as a RAKE receiver, and at the same time minimized the effects of other interfering users.

Even though the optimum performance showed potential gains in using the proposed DFE-receiver, a study of the eigenvalues of the correlation matrices concluded that slow convergence of the receiver is expected if the LMS algorithm

is used for adapting the DFE tap coefficients. A study of the receiver's convergence was done, whose results are given in chapter 5. A comparison between the calculated and simulated convergence was performed which concluded that the N(Normalized)LMS algorithm is needed for faster convergence of the receiver. Then a detailed presentation of the simulation results was given, which showed comparable performance to that of the optimum performance. Good convergence was achieved always for a number of users less than 5.

The effects of spreading codes, blind equalization, sudden access and termination of calls, and inter-cell interference were considered in chapter 6 to examine the performance of the receiver under such conditions. The results showed that the type of spreading codes used in the system could affect its overall performance, which shows the importance of choosing good codes for our CDMA system. The use of blind equalization could result in the receiver locking to an interferer if a LPF is used at the input of the DFE. The results showed that at least a short training sequence is needed before using the DFE decisions to update the tap coefficients.

The sudden access to the system by new users could result in sudden drop of performance to unacceptable level if this user uses his full transmission power at the start of the connection. A technique was suggested where this new user increases his power linearly over a short period of time. This showed better performance for the receiver and had no effect on the new user since he is expected to use this short period for training his equalizer. The effect of inter-cell interference was also considered, and it showed that bad performance could occur if an inter-cell interferer uses the same spreading code of the desired user over the same transmission bandwidth.

The BER performance of the DFE-receiver was also considered in chapter 6, and the results showed consistency with those of MMSE and convergence. It was concluded that the DFE-receiver could handle 4 users within the desired user's cell in the presence of inter-cell interference, fading, multipath and AWGN. Finally, an FDMA/CDMA system was suggested for cellular indoor environments, where the DFE-receiver is used in each FDMA channel whose bandwidth is equal to the CDMA bandwidth. The CDMA bandwidth has a processing gain of 8 which is needed to service 4 users at a time. It was also suggested that no two neighboring cells should use the same spreading code over the same FDMA channel since it could degrade the overall performance of the DFE-receiver.

7.1 Future Research

This work has shown that the strict power control technique, mandatory for the implementation of many CDMA systems, is not a necessity in the design of the proposed CDMA system. The DFE-receiver gave better performance when using the implicit diversity of the received multipath signals. But it was assumed that all users' multipath signals are at the receiver with the same average power. More research could be done on studying the DFE performance when these received signals have different average powers. A technique for reducing the strong user's power is needed to avoid overwhelming other users' signals.

A study was also made of the effects of spreading codes on the performance of the DFE-receiver. Since the CDMA system uses a processing gain of 8, then some work is needed to find a family of codes with a sequence length of 8 that provide good crosscorrelation properties in multipath and fading channels. The proposed receiver could handle 4 users over a given carrier frequency, but each cell should have different spreading codes over the same carrier. This means that

a large number of codes are needed to be distributed between these cells. The performance of the receiver could also be studied for larger processing gains, like 16 or 32.

The sudden access of users to the CDMA system was also examined, and techniques were suggested to decrease its effects on the overall performance. This suggests that a wireless network traffic capacity study could be done for users appearing at random times in random locations.

An attempt was made to derive analytically the probability of error for the proposed DFE-receiver. The analysis was not completed since we dealt with multipath and fading channels. More work needs to be done here, and approximation to the probability of error might be necessary. The BER performance has shown that the multiple access interference could be of cyclostationary nature, so an underestimation of the performance is obtained if the overall interference is considered to be Gaussian.

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