CHAPTER SIX

SIMULATION RESULTS OF THE CM DETECTOR

In this chapter, implementation of a simulation platform and the results generated by this platform are discussed. In general, four linear detectors are compared, which include the single user matched filter detector, the MMSE detector, the LCCM detector and the LCDCM detector. The chapter is structured in the following way. The first section discusses the simulation platform setup for three different transmission channels which include the AWGN channel, the static multipath channel and the single- and multipath fading channels. Assumptions for each of these channels are also stipulated in this first section. In the following three sections, the simulation results for the three different types transmission channels are presented and discussed. Conclusions are summarized in the next chapter, along with proposals for further study in the relevant blind multiuser detection fields.

6.1 SIMULATION SETUP

The simulation platform was implemented in an object oriented C++ environment. The top level block diagram of the simulation setup is depicted in Figure 6.1. The transmitter was simulated by spreading random data using a seven length Gold sequence. Up to six users were simulated in this way. The channel that was simulated was either an AWGN channel, a static multipath channel, or a Rayleigh fading single- or multipath channel. Full details on the simulation of the mobile fading channel is given in Appendix B. The receiver was made to simulate either the matched filter, MMSE, LCCM and LCDCM detectors for comparative evaluation. The adaptive receivers all employed the steepest gradient descent algorithm on each of their respective cost functions.

Some general simulation assumptions need mentioning:

- A synchronous channel is assumed, i.e. all users are perfectly lined up.

- A baseband model is implemented in the simulation and perfect symbol (and chip) synchronization is assumed at the receiver.
- The system is sampled at one sample per chip. The signature waveform thus has a constant modulus taken sample by sample. The chip waveform is thus *not filtered*. The effect of interpolation and constant modulus filtering (such as root of unity (RU) filtering) is trivial, as the sequence can be seen as a "longer" constant modulus signature waveform. The processing gain introduced by this apparent increase in sequence length is negated by the correlation introduced between consecutive chips.
- Unless otherwise stated, all users have equal energy, i.e. $A_1, A_2, \ldots, A_K = 1.0$.
- Differential encoding is employed to negate the effect of phase ambiguity created by the blind detectors.
- The step size of each of the stochastic gradient algorithms is chosen such that all the adaptive detectors converge at approximately the same rate. As a result, $\mu_{MMSE} = 0.001$, $\mu_{LCCMA} = 0.00003$ and $\mu_{LCDCMA} = 0.00003$.

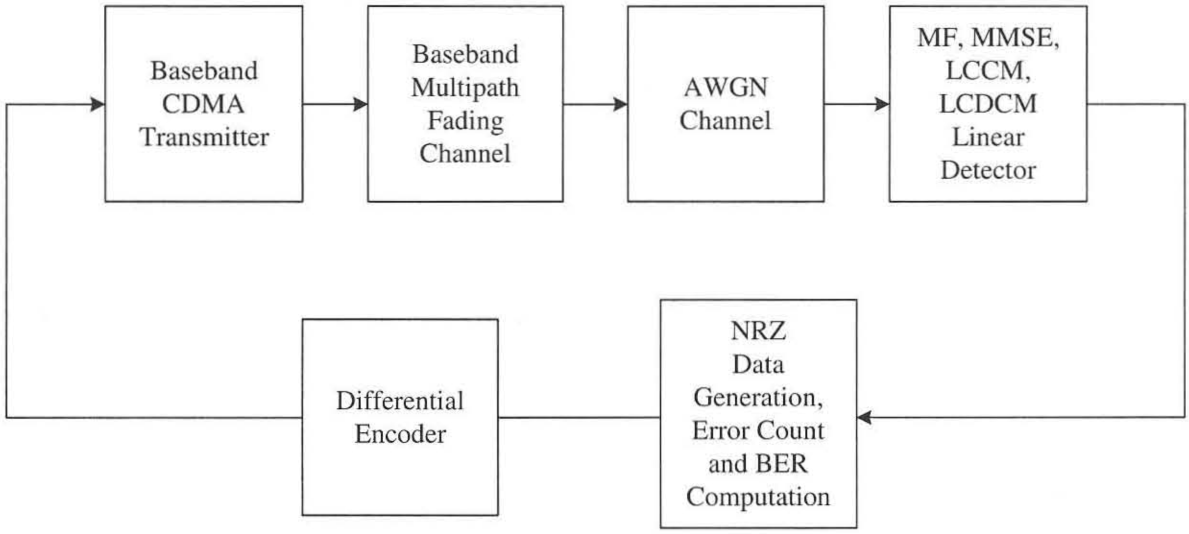

Figure 6.1: System block diagram of the simulation setup.

As we have seen in Chapter 3, the asynchronous case with K users is equivalent to the synchronous case with $2K - 2$ users. The first assumption is thus justified. To minimize simulation complexity and time duration, perfect carrier and clock synchronization is assumed.

A description of the channel types and assumptions associated with each type of channel are given in the following subsections.

6.1.1 SINGLE PATH AWGN CHANNEL

The AWGN channel was simulated by using the Marsaglia-Bray method to generate uniformly distributed samples, and subsequently using the Wichmann-Hill transformation to map the uniform distribution into a Gaussian distribution. These noise samples were then weighted with the noise standard deviation and added to the transmitted signal.

Assumptions - Single Path AWGN Channel

- The desired user sequence is assumed to be known at the receiver.
- The channel is assumed to have no channel distortion. (i.e. to be frequency flat)

6.1.2 STATIC MULTIPATH CHANNEL

The static multipath channel was simulated by a linear filter with a sampled impulse response equal to 0.86 at zero delay, 0.43 at one chip delay, and 0.26 at two chips delay. This channel is frequency selective with minimum phase. This means that the channel inverse can easily be approximated by a linear filter with finite length.

Assumptions - Static Multipath Channel

- The optimum linear inverse channel estimation in a mean square error sense is known at the receiver. This inverse channel estimation is used as a linear constraint in the case of the LCCM and LCDCM detectors.
- The channel is assumed to have minimum phase channel distortion. (i.e. to be frequency selective)

6.1.3 SINGLE- AND MULTIPATH FADING CHANNELS

The single- and multipath fading channels were simulated using Clarke's model as explained in Appendix B. The following assumptions were made regarding the simulation of the single- and multipath fading channels.

Assumptions - Single- and Multipath Fading Channel

- A three ray fading channel is assumed with a sampled multipath profile of 0.86 at zero delay, 0.43 at one chip delay, and 0.26 at two chips delay.
- All users experience the same fading channel, thereby simulating the CDMA downlink channel.
- A doppler frequency of 50Hz is assumed at a sampling frequency of 4M samples per second.
- The optimum linear instantaneous inverse channel estimation in the mean square error sense is known at the receiver. This inverse channel estimation is used as a linear constraint in the case of the LCCM and LCDCM detectors.
- The fading channel phase and amplitude is assumed to be known at the receiver.

Since the channel may have multiple paths that fade independently, the channel may readily assume a non-minimum phase form. In this case, the channel inverse may not be accurately approximated by a finite linear filter. This means that even after linear equalization at the receiver, much residual ISI may remain, thereby degrading the receiver performance. To approximate the channel inverse more accurately, a (non-linear) decision feedback structure will have to be considered.

6.2 PERFORMANCE IN AN AWGN CHANNEL

This section discusses the performance of the matched filter, MMSE, LCCM and LCDCM detectors in an AWGN channel. Even though such a channel is rarely encountered in a mobile environment, much insight may be gained on the operation of these detectors. As we have seen in the previous chapter, the optimum tap weight vector of the MMSE, LDCCM and LCDCM detectors assume the same values in the AWGN case. This notion is strongly enforced by the simulation results. The only information that is needed by the LCCM and LCDCM detectors, is the signature waveform of the desired user. In the case of the MMSE detector, a training sequence is needed.

The performance will largely be evaluated using two different, though related criteria. The first is signal to noise and interference ratio (SIR), and is the measure of how well the detector is able to cancel out interfering users. The second is bit error rate (BER), which evaluates the detector in terms of the number of bit errors made after reception. This is the most important performance measure, as it is the reliability of the transmission which most concerns digital communication engineers.

Figure 6.2 shows the signal to noise interference ratios of the LMS, LCCMA and LCDCMA versus time in an AWGN channel with a bit energy to noise spectral density ratio of $E_b/N_0 = 10$ dB. There are 6 simultaneous equal energy users, each employing a Gold sequence with a spreading factor of 7. From this figure it can be seen that the different adaptive linear multiuser detection techniques

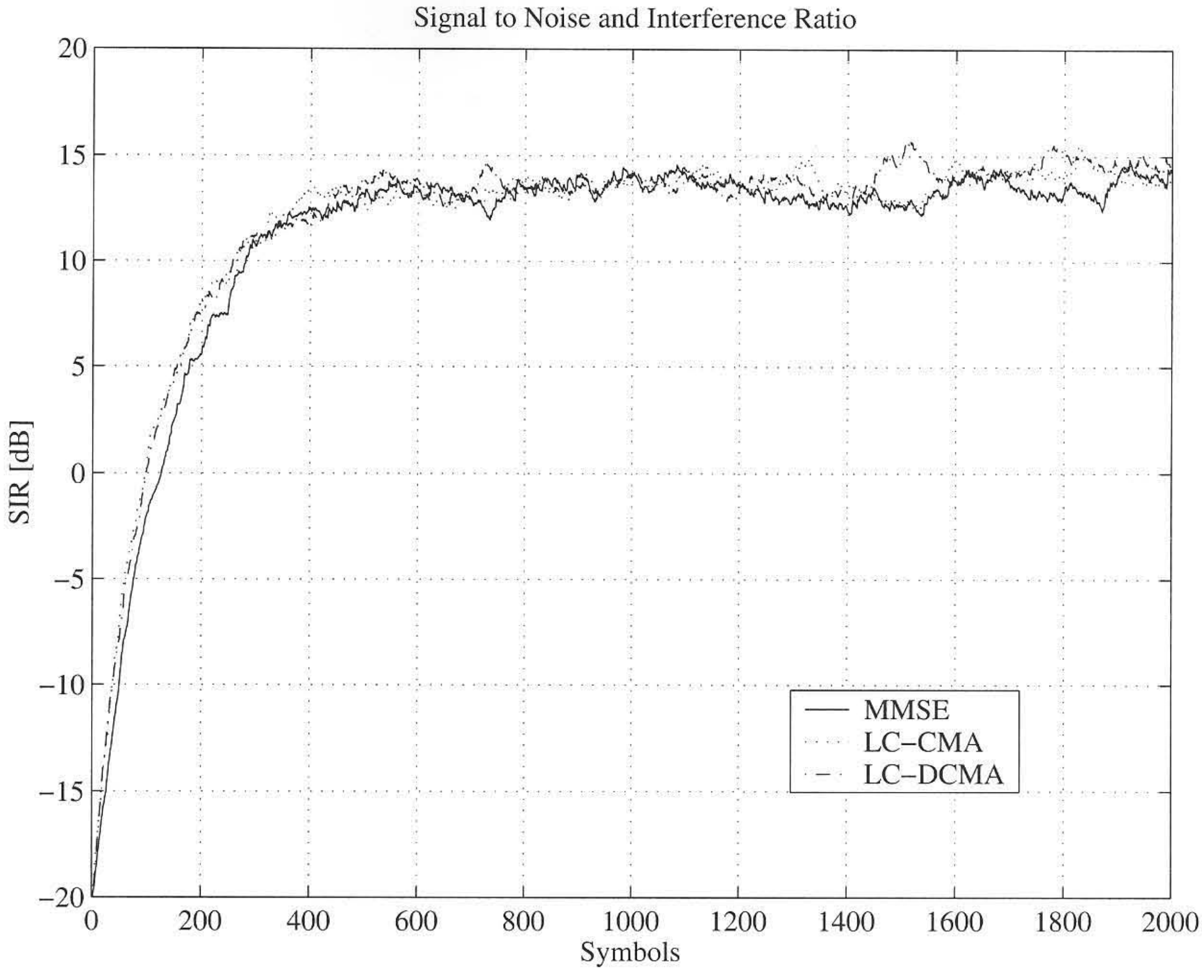

Figure 6.2: Signal to noise and interference ratios versus time of a CDMA system with 6 users and a spreading factor of 7 in an AWGN channel using the MMSE, LCCMA and LCDCMA detection techniques.

approach similar performance with similar speed of convergence. This intuitively satisfies the fact that the MMSE, LCCM and LCDMA have the same tap vector weight solutions. Note that in this case $A_1^* A_1 \geq \alpha/4$, which insures convergence of the LCCMA.

In Figure 6.3, we have that $A_1^* A_1 < \alpha/4$, which means that the LCCMA will not converge to the desired minimum. This is evident in the figure, in that the SIR in the case of the LCCMA decreases as time passes. Note that this condition may readily be encountered in a automatic gain controlled (AGC) uplink channel where all the users fade independently. If the fading on the desired user is severe, while it is not on the other users, the desired user power level may be below the threshold $\alpha/4$. In the downlink channel on the other hand, all users have the same amplitude, and the AGC will keep all the amplitudes above the threshold. From Figure 6.3, we can see that the LCDCM algorithm

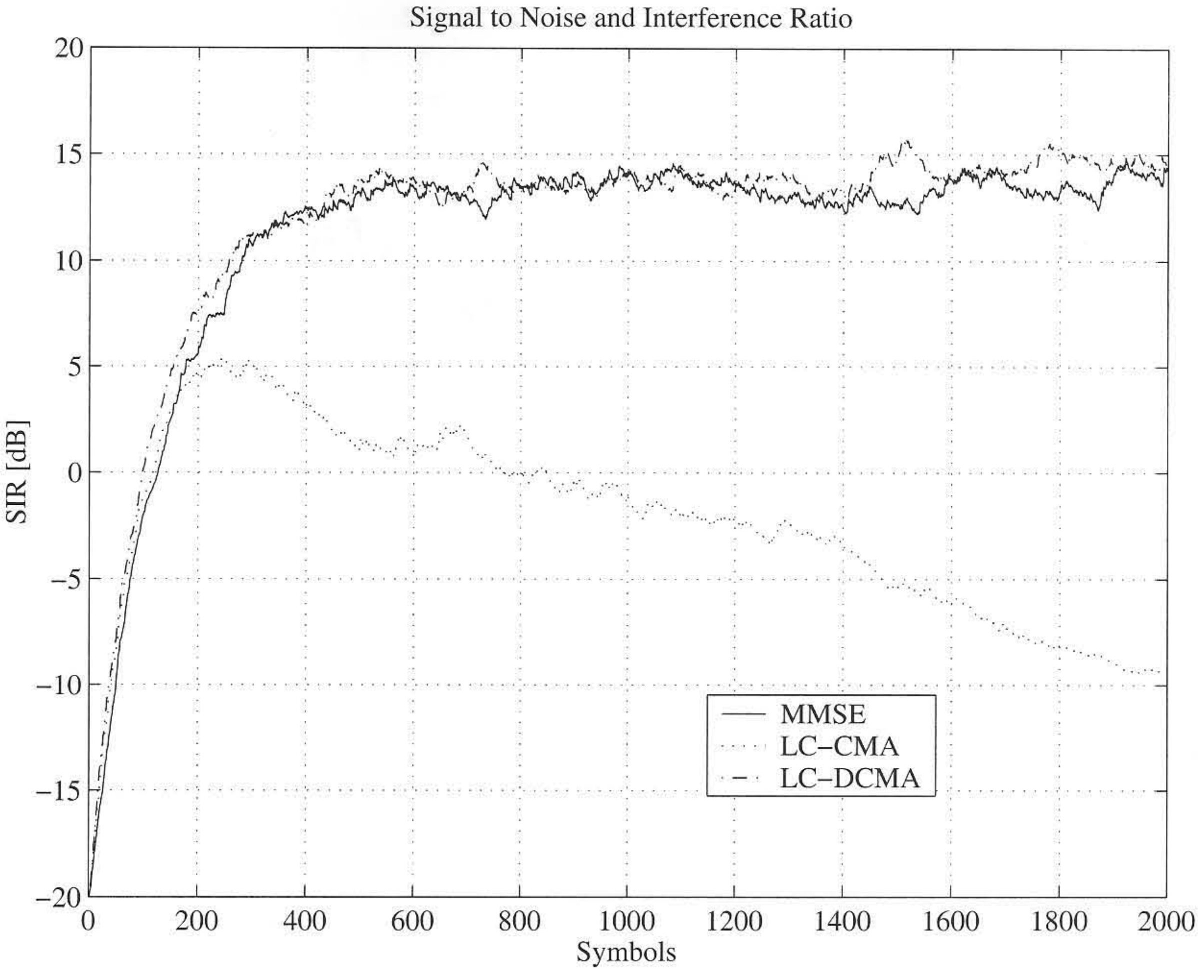

Figure 6.3: Signal to noise and interference ratios versus time of a CDMA system with 6 users and a spreading factor of 7 in an AWGN channel using the MMSE, LCCMA and LCDCMA detection techniques. In this case $A_1^* A_1 < \alpha/4$.

is resistant to this condition. This observation reinforces the fact as derived in Chapter 5, that the LCDMA has a global minimum regardless of the value of the desired user amplitude.

Figure 6.4 shows the response of the relevant detectors to a strong user (34dB) powering on in the channel. Note that the MMSE detector is more severely affected by this event than the LCCM and LCDCM detectors. This is easily explained by the fact the the matched filter component of the LCCM and LCDCM detectors is not affected by the channel disruption. Only the adaptive part of these detectors are affected. Consequently, since the MMSE detector is purely adaptive, it is more sensitive to changes in the channel. It must be mentioned that in the multipath case where the channel is adaptively estimated and employed in the linear constraint, for the same reason as the MMSE

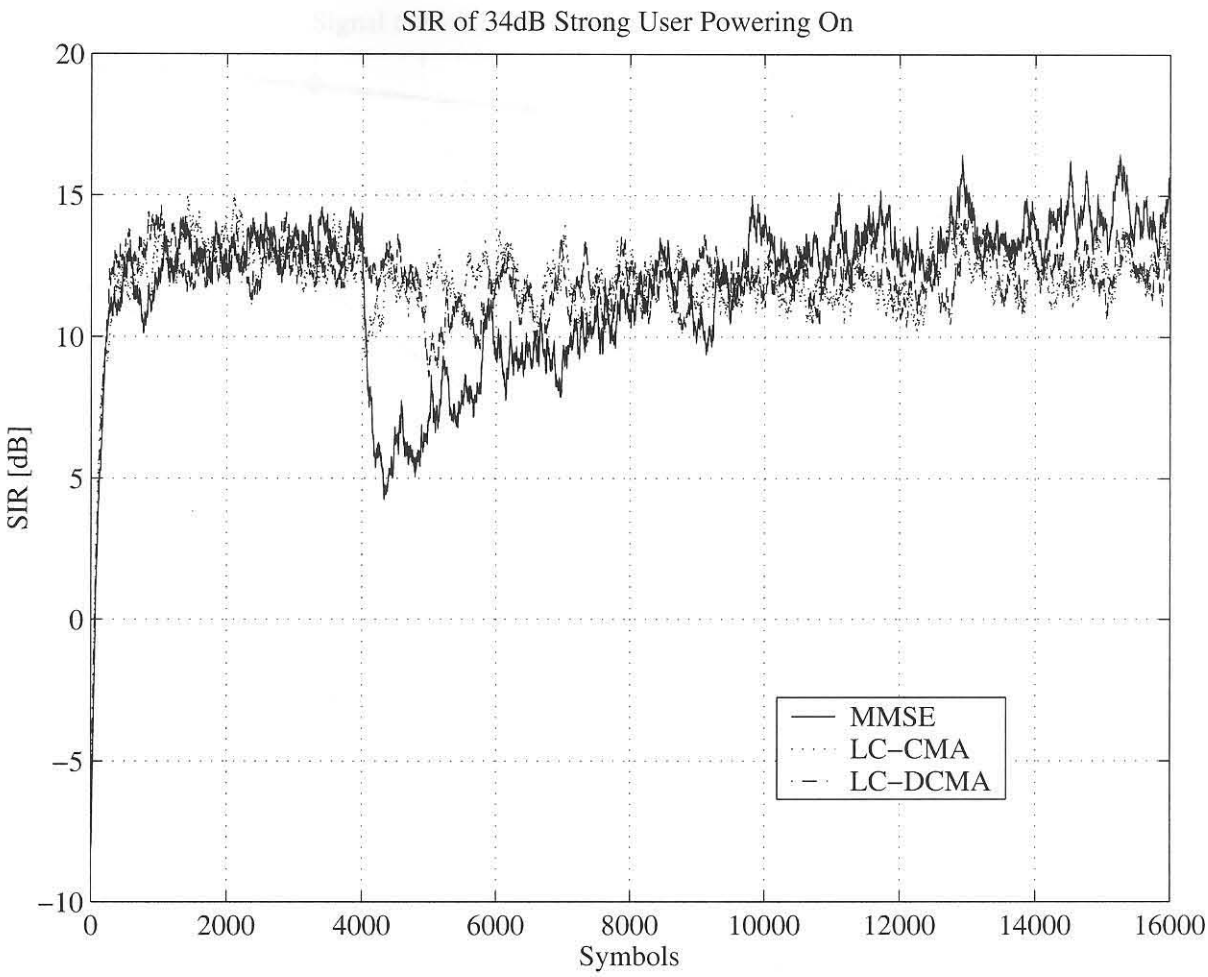

Figure 6.4: Signal to noise and interference ratios versus time of a CDMA system with 3 users, and a 34dB strong fourth user powering on at time $t = 4000$ symbols.

detector, the LCCM and LCDCM detectors' performance will also deteriorate if a strong user powers on.

Another important consideration, is how these multiuser detection techniques perform as the number of users increase. Figure 6.5 shows the SIR versus the number of interfering users. Here the matched filter, LMS algorithm, LCCMA and LCDCMA are compared in a AWGN environment with a bit energy to noise spectral density ratio of $E_b/N_0 = 10$ dB. It is evident that the matched filter ignores the contribution of the interferers, and fares rather poorly as the number of users increase. All the adaptive detector are able to cancel out the interference, only at a slight penalty in SIR as the number of users increase. Also here, the MMSE, LCCM, and LCDCM criteria exhibit comparable performance due to the fact that they have the same tap weight vector solutions.

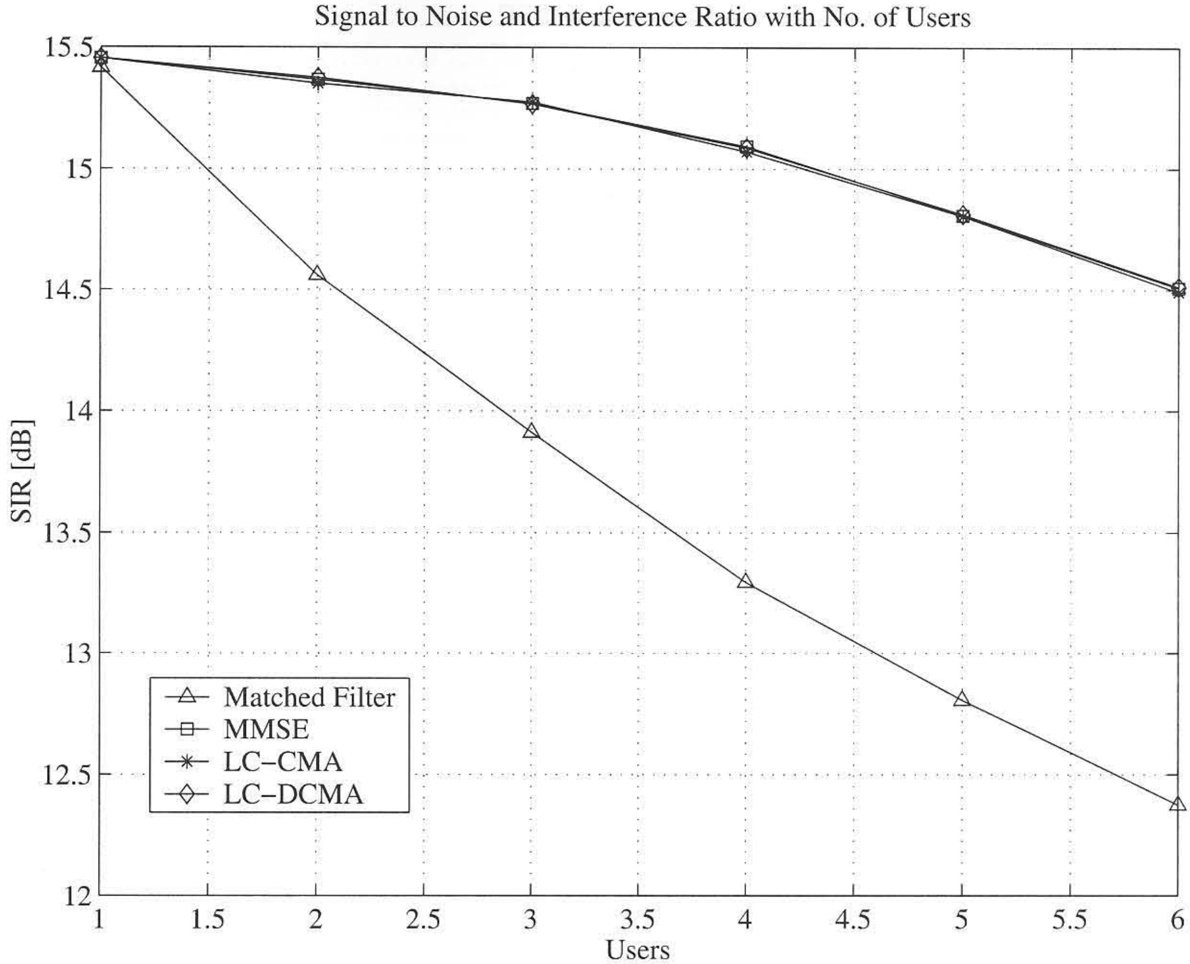

Figure 6.5: Signal to noise and interference ratios versus no. of users of a CDMA system with a spreading factor of 7 and $E_b/N_0 = 10$ dB in an AWGN channel.

Figure 6.6 shows that due to the increased number of uncancelled interferers, the matched filter detector exhibits a significant increase in BER as the number of users increase. Concerning the adaptive detectors, due to only a slight drop in SIR as the number of interferers grow in Figure 6.5, we can expect a slight increase in BER in Figure 6.6. This is readily verified by comparing the two figures. This once again supports the notion that there exists a strong relation between SIR and BER.

Since we are using the desired user's signature waveform as the linear constraint for the LCCM and LCDCM detectors, it might be informative to see how inaccuracies in the constraint affect the performance of these detectors. This will be of interest in multipath channels, as inaccuracies in channel estimation adversely affects the operation of the LCCM and LCDCM detector. Note that it is well documented [20] [60], that the LCCM detector is much more robust to these inaccuracies that the

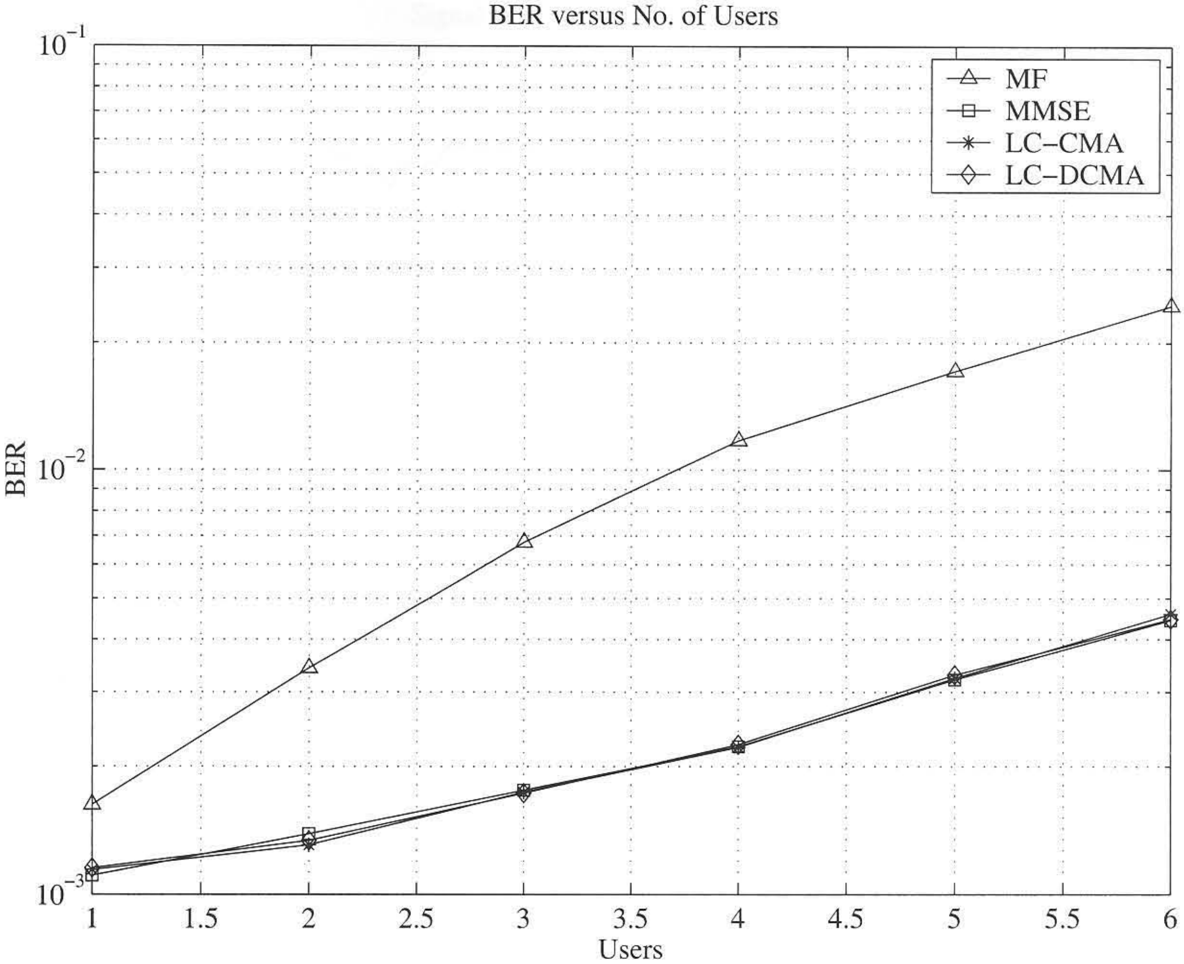

Figure 6.6: Bit error rate versus no. of users of a CDMA system with a spreading factor of 7 and $E_b/N_0 = 10$ dB in an AWGN channel.

LCMV detector of Honig [3]. In Figure 6.7 it can be seen that the LCCM and the LCDCM detectors appear to achieve the same robustness to signature waveform mismatch with a variance of 0.1, though some loss in SIR is inevitable. This may be due to two factors: the fact that the receiver is not a perfect matched filter with respect to the transmitter and that the desired component is not sufficiently protected from being cancelled out due to an imperfect constraint.

The final figure in this section (Figure 6.8) depicts the simulation BER of an AWGN channel with 6 users and Gold sequences of length 7. The high channel load clearly renders the matched filter ineffective. The MMSE, LCCM and LCDCM detectors are effective at mitigating the multiuser interference problem to a large extent, but still does not approach the single user bound. The only detector that is able to approach the single user bound is the ML sequence detector, but is disqualified due to

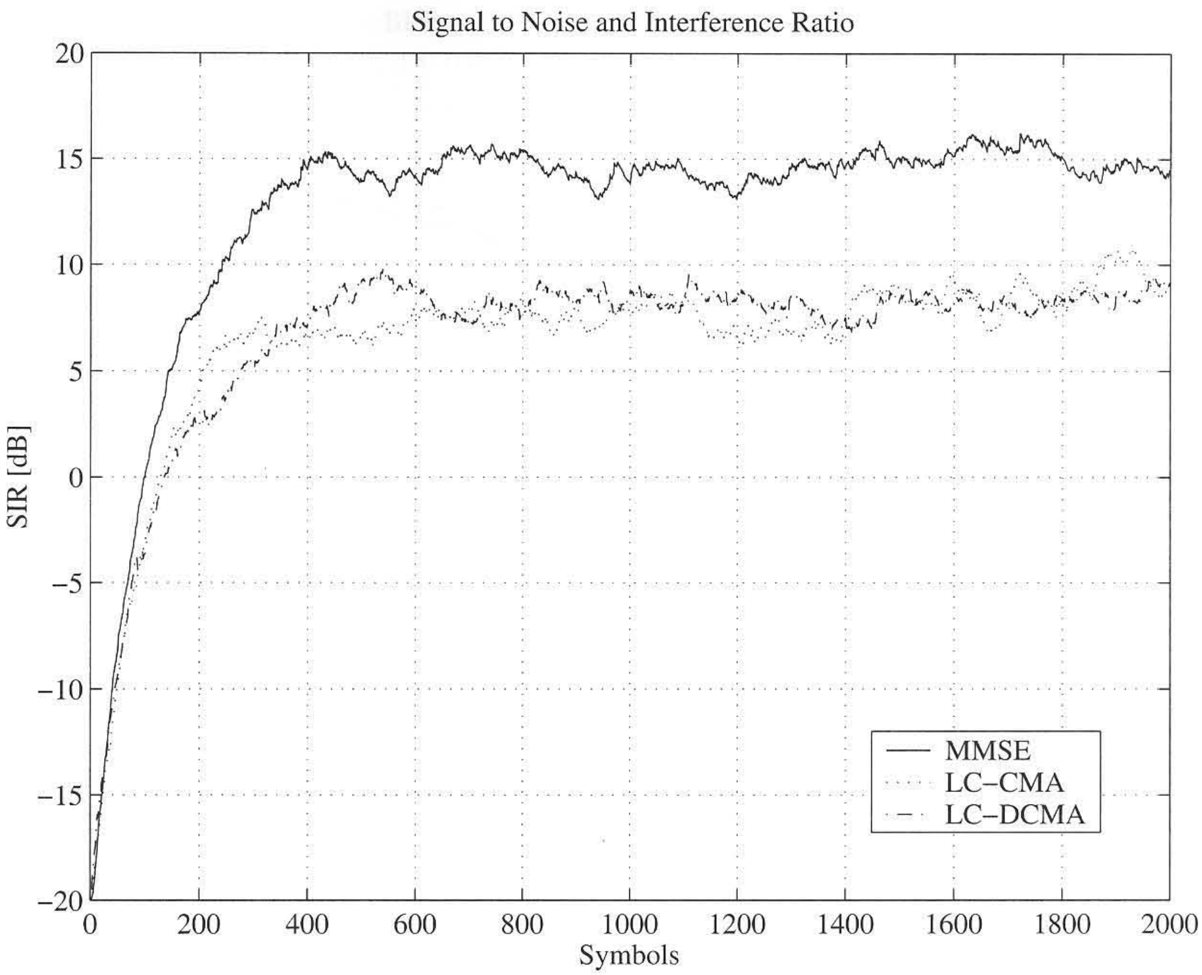

Figure 6.7: Signal to noise and interference ratios versus time of a CDMA system with K = 6 users and a SF = 7 in an AWGN channel. The plot shows the performance for a code mismatch with mismatch variance of 0.1.

its complexity, which exponentially increases with the number of users.

6.3 PERFORMANCE IN A STATIC MULTIPATH CHANNEL

We will now consider the performance of the matched filter, MMSE, LCCM and LCDCM detector in a static multipath channel. Here we choose a minimum phase channel, of which the inverse can be accurately approximated by a finite length linear filter. This means that the inverse channel impulse response rapidly decays to zero within the length of the receiver filter. The channel is chosen such that the linear receiver will be able to adaptively combine the multiple paths of the frequency selective channel. Channels with this type of impulse response are known as channels with *mild intersymbol*

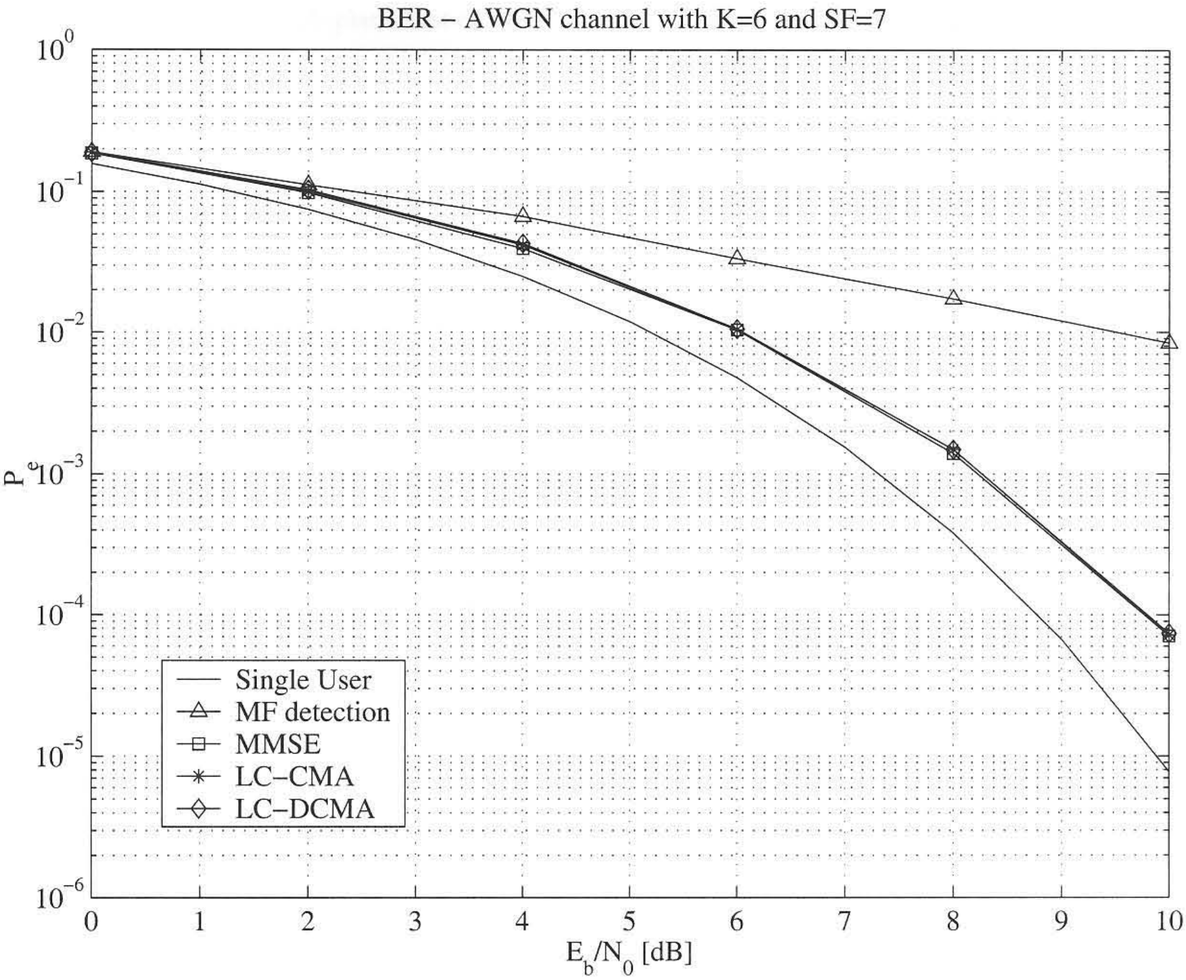

Figure 6.8: BER of a CDMA system with 6 users and a spreading factor of 7 in an AWGN channel using the matched filter, MMSE, LCCMA and LCDCMA detection techniques.

interference. We have seen in Chapter 5 that the LCCM and LCDCM detectors will attempt to suppress the multiple paths, instead of combining them. For these detectors to be able to combine the paths, accurate channel estimation is needed to find the optimum channel plus noise inverse, and use it (convolved with the desired signal waveform) as the linear adaptation constraint. In this way the effect of the multipath channel is negated, and the multiple paths are optimally combined. The multiuser interference is then cancelled out on the subspace orthogonal to this modified constraint. Once again it must be stated that it is only possible if the channel (plus noise) inverse can be accurately approximated by a finite linear filter. The MMSE detector on the other hand, will automatically find the best linear inverse channel plus noise in the mean square error sense that is also able to cancel out the multiuser interference.

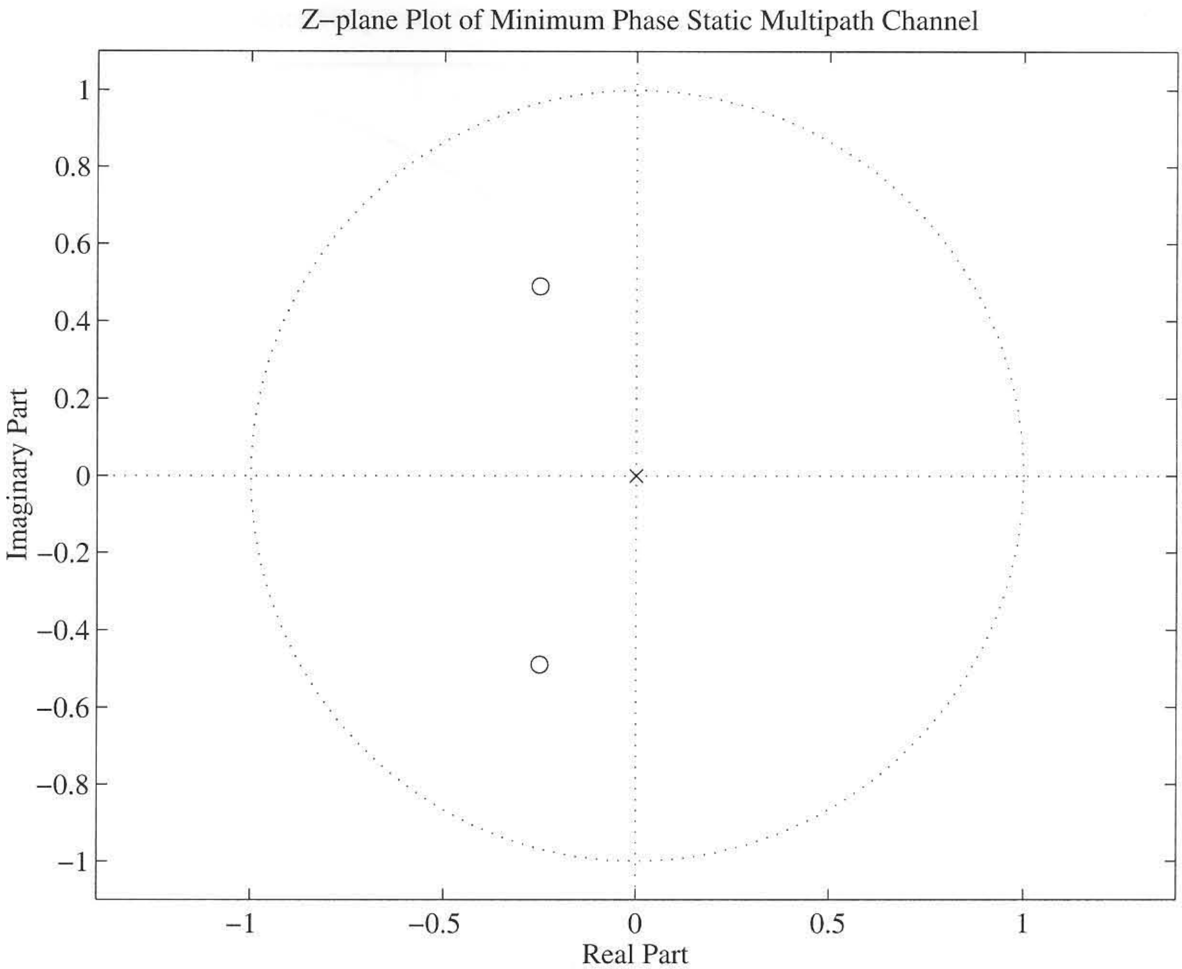

Figure 6.9: Z-plane plot of a minimum phase static 3-ray multipath channel. The multipath profile consists of 0.86 at zero delay, 0.43 at 1 chip delay and 0.26 at 2 chips delay.

In the simulation, perfect channel knowledge is assumed. Many authors propose methods to achieve accurate channel estimation ([60], [15], [68]), but it is beyond the scope of this dissertation.

The z-plane plot of the simulated channel with impulse response $\{0.86, 0.43, 0.26\}$ is given in Figure 6.9. The channel only has two singularities (zeros) within the unit circle, clearly indicating that it is minimum phase. The frequency response of the multipath channel is depicted in Figure 6.10, from which it can be readily seen that there exists no zero in the spectrum. The inverse of the channel can thus easily be obtained without needing a pole with infinite gain. Once again this supports the fact that a linear (feed forward) filter is sufficient to negate the effect of the channel, by forming the inverse frequency response of the channel.

The simulated BER is depicted in Figure 6.11. From this figure it can be seen that the LCCM and

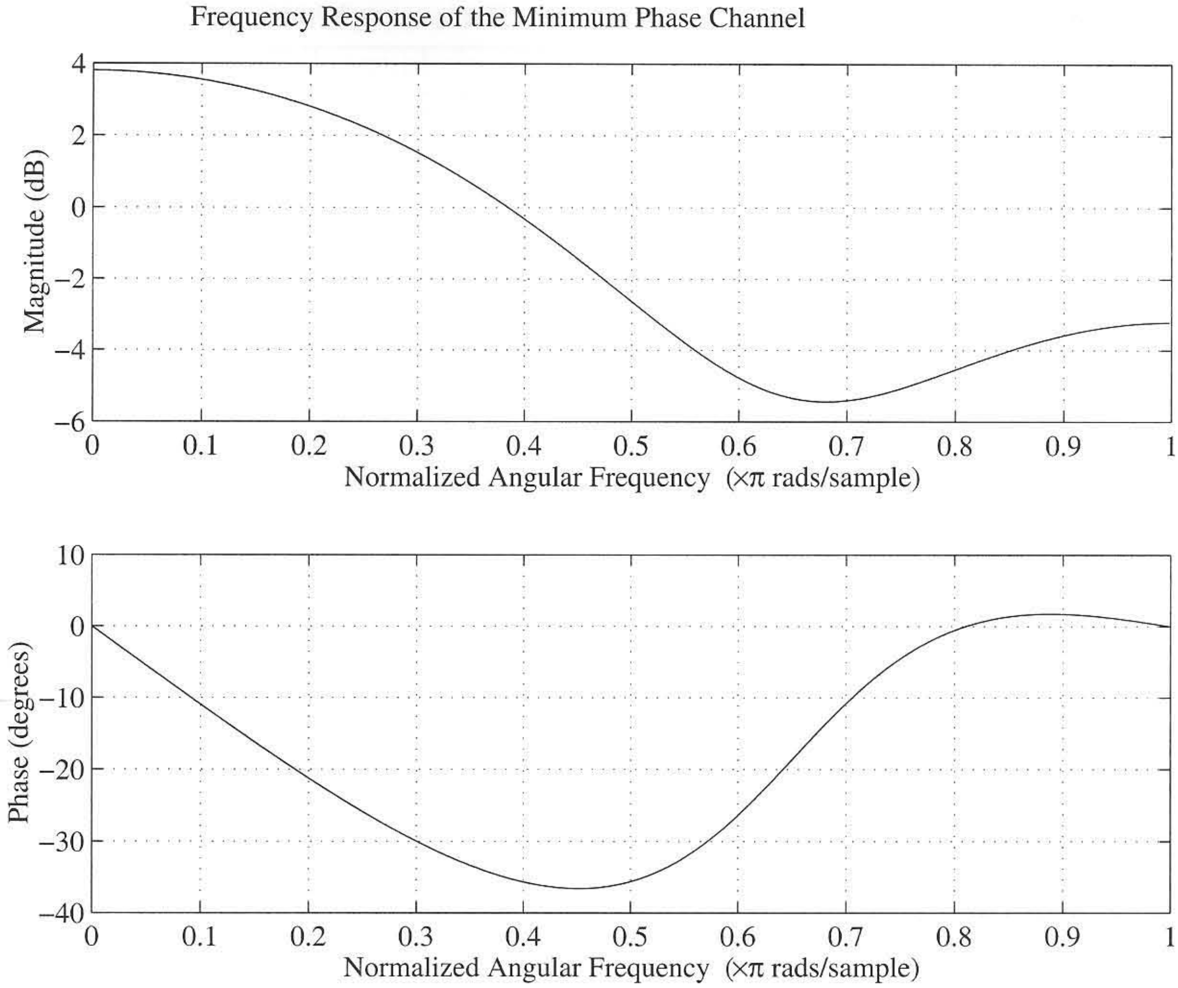

Figure 6.10: Frequency response of the static three-ray multipath channel of which the z-plane representation is shown in Figure 6.9.

LCDCM detectors with optimum linear channel estimation are just as effective as the MMSE detector in simultaneously combating multipath and multiuser interference. As can be expected, the matched filter has no chance in effectively demodulating a signal that has multipath in addition to being saturated with users.

6.4 PERFORMANCE IN RAYLEIGH FADING SINGLE- AND MULTIPATH CHANNELS

Before we consider the multipath fading case, we will first consider the single path fading channel. In this case, the fading is frequency flat, i.e. no channel distortion is introduced. As explained in

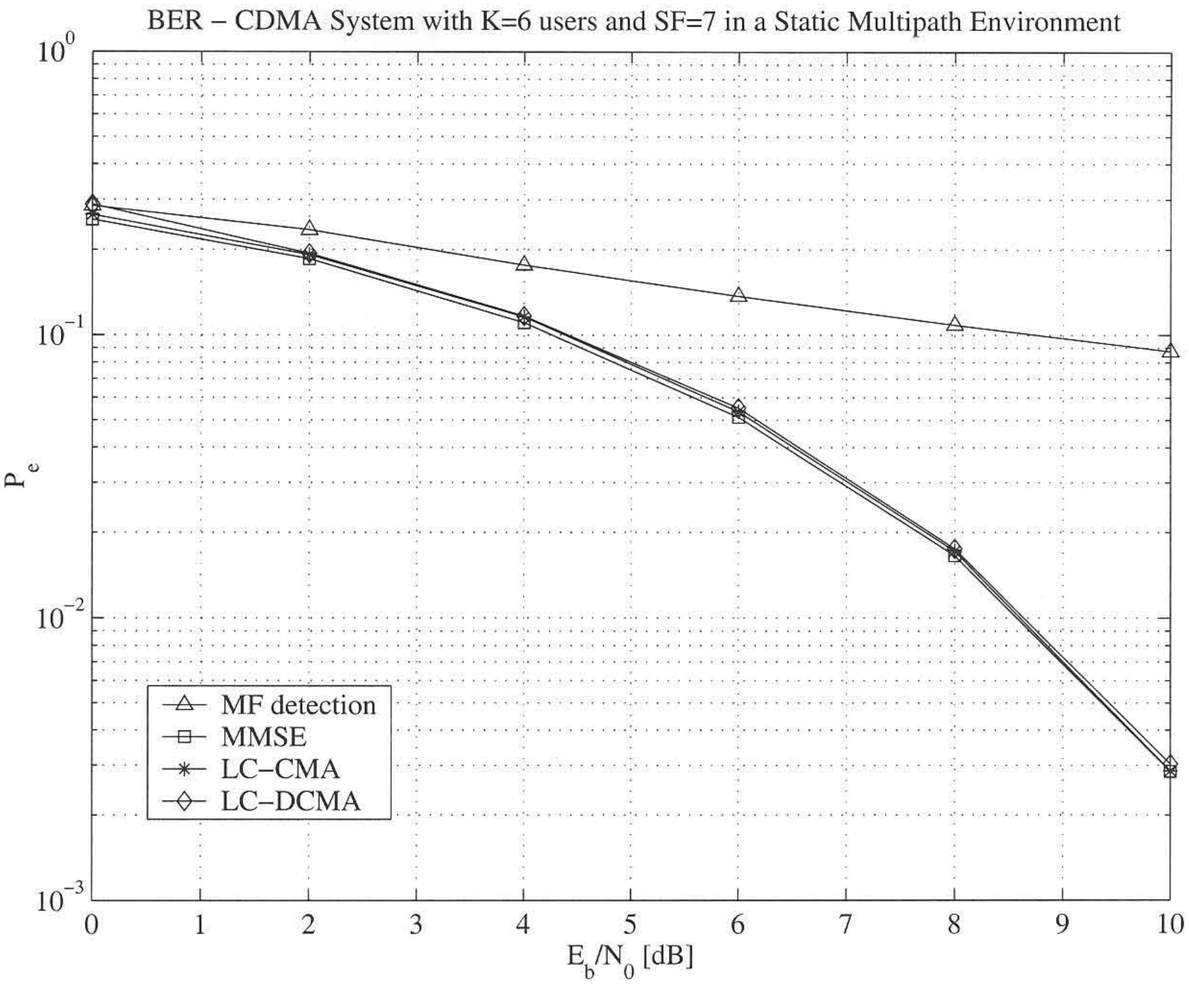

Figure 6.11: BER of a CDMA system with 6 users and a spreading factor of 7 in a static 3-ray multipath channel using the matched filter, MMSE, LCCMA and LCDCMA detection techniques. The multipath profile consists of 0.86 at zero delay, 0.43 at 1 chip delay and 0.26 at 2 chips delay.

Appendix B, the amplitude envelope of the fading channel assumes a Rayleigh distribution. The doppler frequency of the fading channel is chosen to be 50Hz in a system sampled at 4M samples per second. At this sampling rate, the fading is rather slow, and can easily be followed by an adaptive receiver employing a stochastic gradient descent algorithm. We assume that all users experience the same amount of fading, thereby simulating the CDMA downlink channel. The deep fades introduced by such a channel introduces a large burst of errors, severely degrading the effective SNR and consequently the average BER. It is for this reason that Figure 6.12 shows a modest improvement in BER compared to the matched filter receiver. The periods of deep fades tend to make the AWGN dominant over the multiuser interference, thereby reducing the margin of performance increase that can be achieved by cancelling out the multiuser interference.

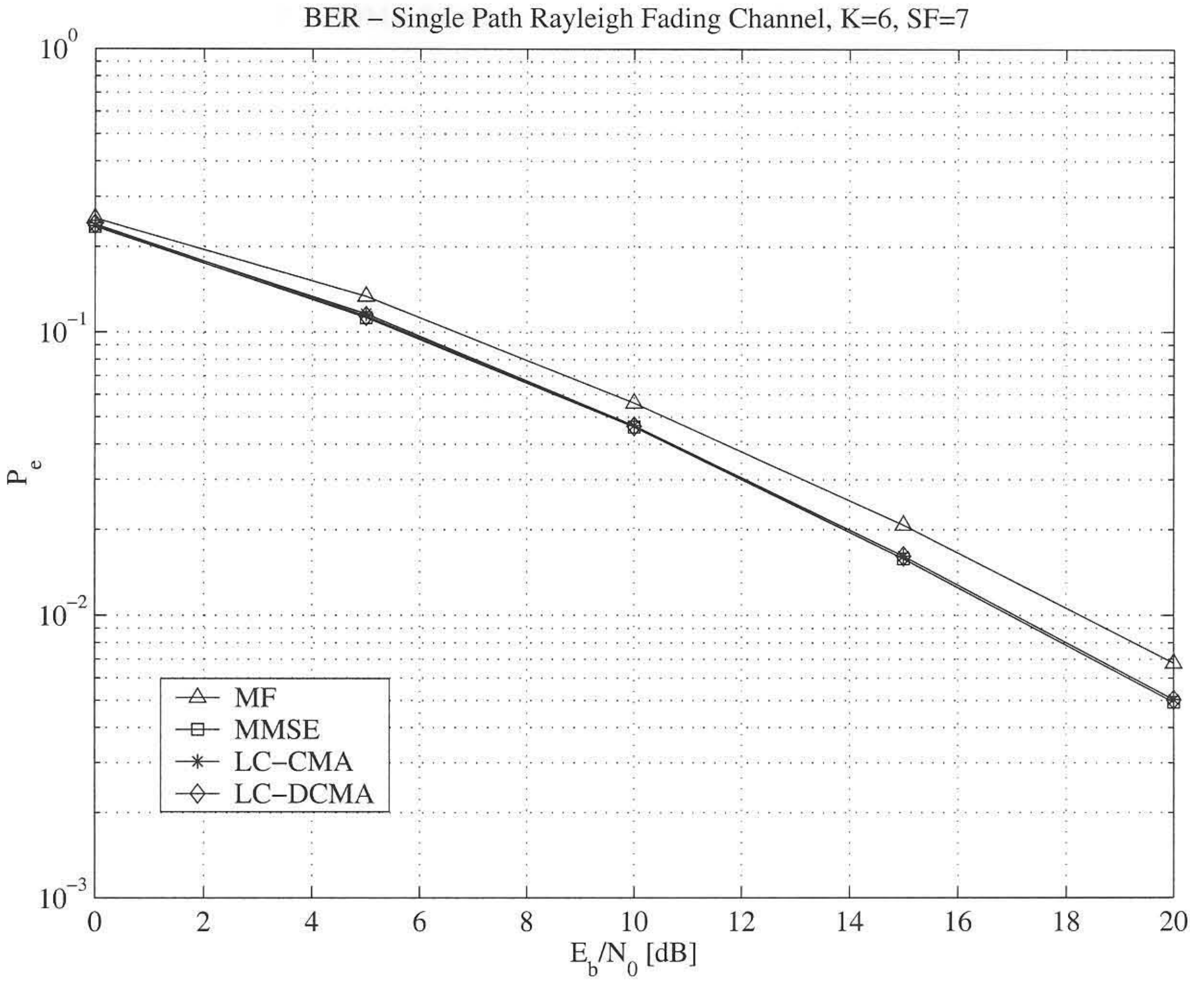

Figure 6.12: BER of a CDMA system with 6 users and a spreading factor of 7 in a Rayleigh fading single-path channel using the matched filter, MMSE, LCCMA and LCDCMA detection techniques.

As mentioned in the previous section, it is possible to effectively combine multiple paths of channels with *mild* ISI by using a linear filter. In a mobile multipath fading channel, the amount of ISI may vary between mild and severe. In the case of severe ISI (a non minimum phase channel), *no* finite length linear filter is able to effectively combine the multiple paths and negate the effect of ISI. In this case we will need to employ a non-linear or *decision feedback* structure to estimate the channel inverse (zero forcing criterion) or to estimate the channel plus noise inverse (MMSE criterion). This implementation, however, is beyond the scope of this dissertation, but warrants some further investigation.

The effect of a multipath fading channel on the relevant linear multiuser structures with linear channel

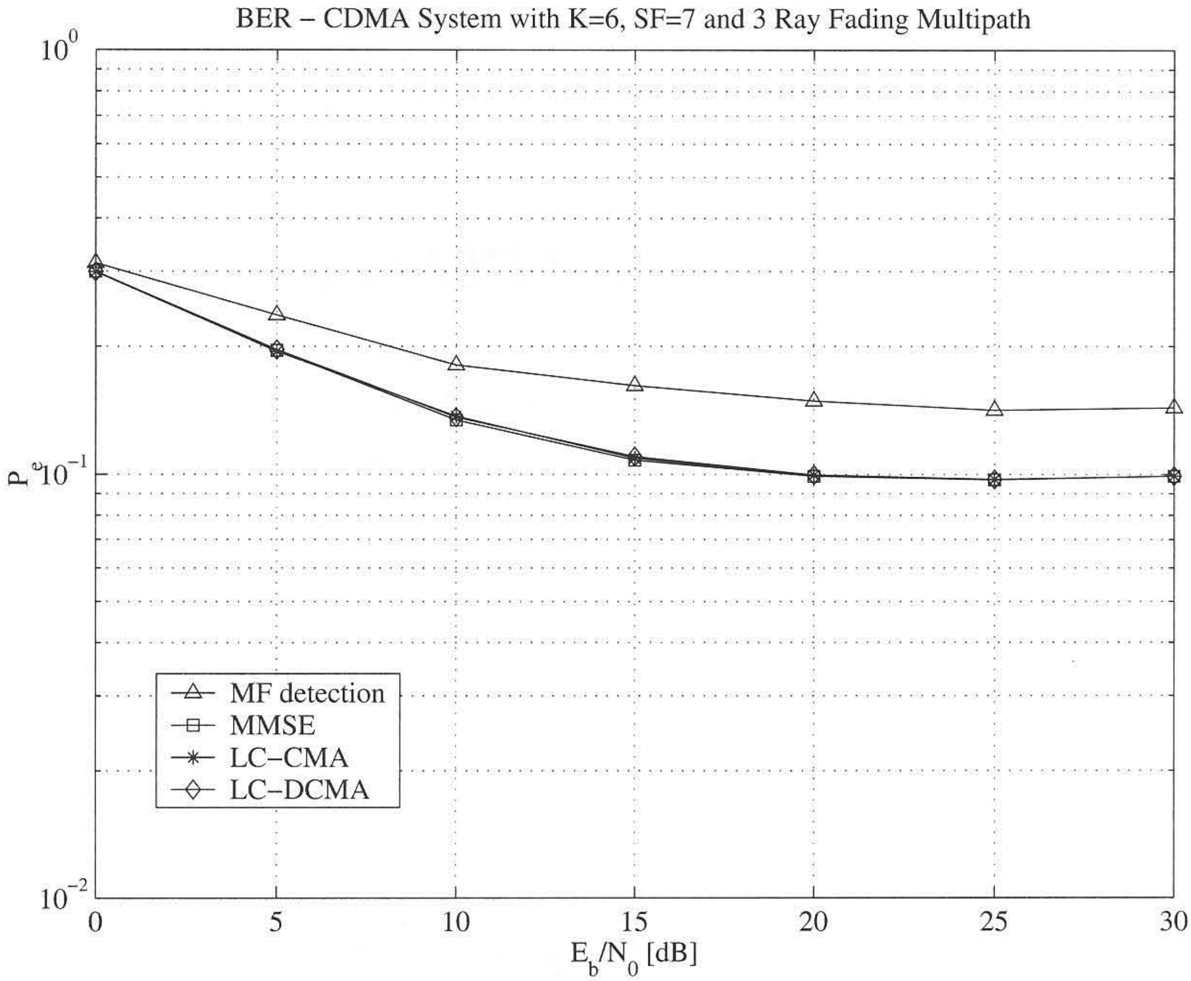

Figure 6.13: BER of a CDMA system with 6 users and a spreading factor of 7 in a 3-ray Rayleigh fading multipath channel using the matched filter, MMSE, LCCMA and LCDCMA detection techniques.

estimation is depicted in Figure 6.13. Due to the fact that a finite linear filter is unable to accurately model the mobile channel inverse, some residual ISI remains uncancelled. Looking at the BER curve beyond 25dB, the BER seems to increase. This strongly resembles the closed eye condition as depicted in Figure 3.13. The ISI causes the signal to move to the wrong side of the decision boundary. In this case, the addition of noise benefits the BER, as it may move the signal back to the correct side of the decision threshold.