A Multiple-Antenna-Multiple-Equalizer System for CDMA Indoor Wireless Systems

by

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ABSTRACT

A multiple-antenna-multiple-equalizer (MAME) system is proposed for overcoming cochannel interference (CCI) in code-division multiple access (CDMA) indoor wireless systems. The main advantage of the MAME system is the enhanced interference suppression capability as compared with many existing approaches. Thus, the use of the MAME system can lead to an increase in the capacity of the CDMA system. In the MAME system, a fractionally-spaced equalizer (FSE) is used to process the signal at each antenna. The number of antennas or the tap spacing of the FSEs is not fixed and inherent flexibility is available to the designer. In particular, CDMA indoor wireless systems are best suited to use the interference suppression capabilities of the MAME system.

It is shown that spectral correlation present in user signals is the reason for the interference suppression capability of the MAME system. Moreover, the MAME system is interpreted as a dual-domain diversity combiner. Spatial and bandwidth-domain diversity are used and the relative importance of the diversity domains is discussed. These discussions offer new insights into the interference suppression capabilities of the MAME system and give a clear picture of its workings.

Extensive simulation results are presented to illustrate the performance of the MAME system under various conditions. Optimal or minimum mean-squared error (MMSE) results are first presented to illustrate the superior interference suppression performance. The effects of the number of antennas, tap spacing, receive filtering, spectral correlation, diversity domains, and near-far conditions on performance are examined and results obtained support the arguments presented earlier in the thesis.

The FSEs in the MAME system are implemented as adaptive filters and the mean-squared-error (MSE) performance is investigated. A quasi-Newton (QN) algorithm is recommended over other adaptive filtering algorithms because of ill-conditioning of the autocorrelation matrix in the MAME system. Simulation results confirm the superior convergence performance of the QN algorithm. Decision-directed equalization is also investigated and bit-error rate (BER) results presented illustrate that the gains in the MMSE performance will most likely translate into gains in BER performance. The BER performance in near-far and birth of interferers conditions illustrate that the MAME system is a promising solution to counter these problems.

The thesis concludes with an indoor wireless strategy based on the MAME system which offers the following advantages:

1. More users than the processing gain of the CDMA system can share the same bandwidth.

2. No information about code sequences is needed at the receiver.

3. Simple code sequence allocation schemes can be used at the transmitter.

4. Variable numbers of users can be accommodated.

5. Simple power control and error-correction coding schemes can be used.

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It has been close to 7 years in beautiful Victoria and the many experiences will always be etched in memory. Thanks to everyone who made this Victoria experience possible.

To my parents

List of Abbreviations

AWGN : Additive white Gaussian noise

ACI : Adjacent channel interference

BER : Bit-error rate

BPSK : Binary phase-shift keying

CCI : Cochannel interference

CDMA : Code-division multiple access

DDE : Decision-directed equalization

DFE : Decision-feedback equalizer

DOA : Direction of arrival

DS-CDMA : Direct-sequence code-division multiple access

DSP : Digital signal processor

FBE : Feedback equalizer

FIR : Finite-duration impulse response

FSE : Fractionally-spaced equalizer

GHz : Gigahertz

HDSL : High bit-rate digital subscriber line

ISI : Intersymbol interference

LAN : Local area network

LPF : Lowpass filter

MAME : Multiple-antenna-multiple-equalizer

MMSE : Minimum mean-squared error

MSE : Mean-squared error

NEXT : Near-end crosstalk

NLMS : Normalized least-mean-squares

PAM : Pulse amplitude modulation

QN : Quasi-Newton

RXF : Receive filter

SRRC : Square-root raised cosine

SNR : Signal-to-noise ratio

TDMA : Time-division multiple access

WLAN : Wireless local area network

Chapter 1

Introduction

1.1 Motivation

The desire for increase in capacity, improvement in quality of service, and accommodation of diverse multirate traffic has resulted in increased research and development for wireless cellular and microcellular environments. Wireless networking is the enabling communications technology of the future and we are beginning to see the influences of portable telephones and wireless data services in our daily life [1]. Moreover, it is expected that our future will witness widespread deployment of wireless networks and that these networks will revolutionize the concept of communication and information processing for business, professional, and private applications. Several developments in the world of telecommunications have ushered in an era of "tetherless communications" based largely on wireless technology. This has resulted in a shift in the computer industry toward integration of high-performance distributed computing and portable devices in a mobile computing environment. In particular, the nascent field of indoor wireless systems is expected to grow rapidly as portable and mobile systems proliferate in office spaces, homes, and other indoor environments [2].

An important indoor wireless application is the use of wireless local area networks (WLANs) for a limited number of users [3]. Today, most office buildings are equipped with plans for wiring conventional LANs as a standard procedure during the design phase. One of the problems then comes with reconfiguring the network since it is estimated that the cabling costs can be as high as 40% of the total installation cost of the network [3]. All equipment and software can be reused in a LAN except the cabling which might need to be moved in some cases. Moreover, in many situations wiring difficulties can make the installation of conventional LANs cumbersome and expensive, for example, in manufacturing floors, stock exchanges, and warehouses [4]. Also, in historical buildings and monuments or in other situations where any construction work can damage the significance of the site, WLANs can serve as an alternative. Another application area which is very attractive for the future is the possibility of a group of portables to network in a classroom, business, or conference environments using WLANs. They have also been popular as an extension to wired LANs [4] [5].

Manufacturers offer WLANs based on conventional radio modem technology, spread-spectrum techniques, and infra-red technology [1]. Spread-spectrum based WLANs have been more successful in the market than the other technologies [4] and compared with infra-red systems they have been shown to offer higher range and data rates [6]. Spread-spectrum techniques are used in indoor wireless applications to counteract the severe multipath nature of the indoor environment [3]. The multipath is caused by walls, ceilings, and other objects close to the transmitter and the receiver and is aggravated due to the high carrier frequencies used for many indoor wireless applications. However, the low spreading gains [4] used in these systems provide little resistance to multiuser interference when conventional methods are used at the receiver [7]. Some of the other challenges with wireless LANs are data rates, frequency management, and security [3][8]. The major standards initiatives pertaining to WLANs are WINForum in North America and HIPERLAN in Europe [9].

In this work, our main concern is to counteract multiuser interference present in indoor wireless systems like WLANs, which are based on spread-spectrum technology. Traditionally, spread-spectrum based systems have been used mainly due to their inherent interference suppression properties [10]. Moreover, one of the main advantages of a code-division-multiple-access (CDMA) system, which is a type of spread-spectrum system, is that no complex frequency allocation or synchronization schemes for facilitating multiple access are necessary. This means that CDMA systems offer a tremendous advantage in the area of spectrum planning and utilization. In a world where frequency resources are becoming significantly important, this aspect of CDMA systems is crucial. Hence, there is intense research activity in this area for many wireless applications and an outdoor cellular wireless standard based on the CDMA scheme has been established [11].

Conventional interference suppression measures that use the inherent properties of the CDMA systems are dependent on the processing gain of the system. Typically, the interference suppression capability is expected to improve as the processing gain is increased. Hence, CDMA systems with low spreading or processing gains do not offer sufficient interference suppression capability when conventional interference suppression measures [7] are used at the receiver. This means that measures to counteract multiuser interference in CDMA systems with low processing gains can improve capacity while still benefiting from the simple multiple-access nature of these systems. Such systems are typically suited for indoor wireless systems like wireless LANs where there is a small number of users. Hence, measures to counteract multiuser interference could aid in the development and deployment of CDMA indoor wireless systems. Such a motivation is timely when proliferation of indoor wireless systems is expected to occur in the near future. In this work, we are concerned only with direct-sequence CDMA (DS-CDMA) systems and any reference to CDMA systems shall mean that we are addressing DS-CDMA systems unless otherwise specified.

1.2 Background

In this section, we present a literature survey of techniques where adaptive equalization and multiple antennas have been used for interference suppression in digital communications systems with particular emphasis on CDMA wireless systems. A review of adaptive techniques for interference minimization in CDMA systems is presented in [12] and includes adaptive equalization and diversity combining schemes. Several different minimum mean-squared error (MMSE) schemes for overcoming interference in CDMA systems are presented in [13]. Many interference suppression schemes presented in the literature have relied on the availability of spreading codes of all users, channel information or other data which might not be easily available in practice. However, in [13], one of the advantages of the MMSE schemes presented is that they do not need any such information. The scheme which is relevant to CDMA systems with low processing gains is an adaptive finite-duration impulse response (FIR) filter which operates at the chip rate. The number of taps is fixed and is equal to the processing gain of the system. Numerical results presented confirm the near-far resistance of the MMSE schemes presented. An adaptive receiver strategy is also investigated in [14] for interference rejection in CDMA systems. Here, a chip-rate matched filter followed by an adaptive filter is used for de-spreading the signals in a CDMA system and the main motivation is to overcome co-channel and narrowband interference. The near-far resistance of this system is also investigated. The adaptive equalizer has a fixed number of taps equal to the processing gain of the system. Numerical results are presented which show the interference suppression capability and near-far resistance of the receiver.

In [15], adaptive linear receiver structures and centralized decision-feedback equalizer (DFE) structures are considered for interference suppression. The presence of cyclostationarity in the interference is pointed out by these authors whereas many studies ignore this aspect. The receiver structures are shown to achieve advantages with respect to timing recovery, interference rejection, near-far resistance, frequency selective fading, and user privacy. The centralized DFE has an enhanced interference rejection performance at the cost of increased complexity. An adaptive DFE with a fractionally-spaced equalizer (FSE) as the forward filter is proposed in [16] for effecting interference suppression in CDMA systems. The ability of the FSE to suppress cyclostationary interference which has been investigated in [17] is utilized in the proposal and results demonstrate the advantages of the FSE-based DFE receiver. An important contribution of [16] is the demonstration of the fact that the performance of the DFE is better than that of the conventional RAKE receiver used in CDMA systems. The use of a receiver which does not use any information about code sequences is also proposed and investigated in [16]. The use of spectral correlation to suppress interference in digital communications systems using FSEs is explained in [18][19][20] [21].

Many researchers have also investigated multiple-antenna systems and combinations of multiple antennas and equalizers for interference rejection in wireless systems. A combination of an adaptive array antenna and a canceler was proposed for interference rejection in CDMA systems in [22]. The adaptive array uses direction of arrival (DOA) information to suppress interference while the temporal canceler is used to suppress any residual interference which might exist after the spatial processing. Optimum diversity combining schemes are investigated in [23] for overcoming intersymbol interference (ISI) and fading in time-division multiple access (TDMA) systems. The interference is modeled as additive white Gaussian noise (AWGN) and the optimum combiner is derived to be a structure which has a filter at each antenna matched to the respective combined channel followed by a common equalizer for all the antennas. In [24], optimum combining schemes are proposed for overcoming co-channel interference (CCI) and to combat fading in a digital mobile radio environment. The antennas are spaced sufficiently far apart to obtain copies of user signals which have experienced independent fading and the signals at the different antennas are weighted before combining such that the signal-to-interference ratio is maximized. It is shown that the use of M antennas can increase capacity by a factor of M and optimum combining was proposed for indoor systems in [25]. Beamforming and detection are combined in an antenna array system for a CDMA cellular radio system in [26]. The impact of using multiple antennas on the capacity of interference-limited wireless systems is analyzed in [27] and results presented show the advantages of using antenna diversity in such systems.

The use of antenna diversity to realize the gains is made more compelling by the continued advances in digital signal processor (DSP) hardware and the reduction in the cost of DSP devices. The use of FSEs and multiple antennas to suppress mutual interference in digital communications systems is outlined in [28]. The advances in equalization and diversity for wireless systems is summarized in [29] and forms a important basis for the MAME system proposed in this work. Recent advances in signal processing for wireless systems were presented in [30] and a similar update for wireless networks was presented in [8]. An exhaustive list of techniques for interference rejection in digital wireless communication system is reviewed in [31] and signal processing schemes relevant to interference suppression in CDMA systems are discussed in [32]. Progress and misconceptions relating to multiuser interference suppression are examined in [33].

1.3 Thesis Contributions

The main contribution of this thesis is the proposal and presentation of a multiple-antenna-multiple-equalizer (MAME) system for CCI suppression in CDMA indoor wireless systems. The proposal is based on the generalized zero-forcing equalizer results for suppressing ISI and CCI presented in [28]. The MAME system has enhanced interference suppression capabilities as compared to many existing approaches and this means that more users can share the same bandwidth. In particular, CDMA indoor wireless systems are best suited to use the interference suppression capabilities of the MAME system. Hence, the use of the MAME system can lead to an increase in the capacity of CDMA indoor wireless systems.

It is shown that spectral correlation present in user signals is the reason for the interference suppression capability of the MAME system. Moreover, the MAME system is interpreted as a dual-domain diversity combiner. Spatial and bandwidth-domain diversity are used and the relative importance of the diversity domains is discussed. These discussions offer new insights into the interference suppression capabilities of the MAME system and give a clear picture of its workings.

The interference suppression capabilities of the MAME system are confirmed by extensive simulation results under various conditions. First, the optimum or MMSE performance is examined. The MMSE results presented clearly illustrate the superior interference suppression performance of the MAME system. The effects of the number of antennas, tap spacing of the FSEs, receive filtering, spectral correlation, diversity domains, and near-far conditions are investigated. Results are presented and discussed thus offering a clear idea of the properties of the MAME system.

In the MAME system, FSEs are implemented as adaptive filters. Simulation models are used to study the mean-squared-error (MSE) performance. A quasi-Newton (QN) algorithm is recommended for use since the autocorrelation matrix is ill-conditioned. Simulation results illustrate the superior convergence performance using the QN algorithm when compared with the performance using the normalized least-mean-squares (NLMS) algorithm. Moreover, the MSE performance using the QN algorithm shows excellent agreement with MMSE results.

Decision-directed equalization was also investigated and BER and outage results are presented for a representative MAME system under different conditions. The BER results demonstrate that gains in MMSE performance will most likely be translated into gains in BER performance. This means that the MAME system can be used in indoor wireless networks to achieve very low BERs that are required in many applications without the need for complex error-correction coding schemes.

The near-far performance of the MAME system was also investigated. Based on the generalized zero-forcing equalizer conditions, it is predicted that the interference suppression capability of the MAME system will not be affected by near-far conditions. Optimum performance results illustrate a very slight degradation in performance due to near-far conditions. The MSE performance under near-far conditions illustrates the adaptive nature of the system which quickly adjusts to these conditions. The BER performance highlights the practical advantages of using the MAME system because of its superior capability to deal with near-far conditions. All these results demonstrate the excellent potential of the MAME system as a solution to countering the near-far problem present in many CDMA systems.

An indoor wireless system strategy based on the MAME system is discussed. This strategy is developed to use the many advantages of the MAME system. The main advantages of this strategy are as follows:

1. The number of cochannel users can exceed the processing gain of the CDMA system.

2. No information about code sequences is needed at the receiver.

3. Simple code sequence allocation schemes can be used at the transmitter.

4. Flexibility in the number of users that can be accommodated is available.

5. Simple power control and error-correction coding schemes can be used.

1.4 Thesis Organization

In this chapter, we have discussed the motivation for the work and the contributions which have come about in the pursuit of the motivation. The necessary background was also presented through a literature survey of relevant material. In Chapter 2, we discuss the use of adaptive equalization and multiple antennas to overcome interference in CDMA systems. This discussion forms the basis for the proposal of the MAME system. In Chapter 3, we propose the MAME system for suppressing CCI in CDMA indoor wireless systems. The effects of spectral correlation, diversity domains, and the near-far condition are discussed. A mathematical model of the MAME system, which is used to calculate the MMSE, is also presented. The MMSE performance is studied in Chapter 4 under various conditions. Several properties of the MAME system are discussed. The MSE performance under various conditions is investigated in Chapter 5. Results on BER performance are also presented. An indoor wireless system strategy based on the MAME system is discussed in Chapter 6. Simulation results are presented to illustrate some of the unique advantages due to the use of the MAME system. Conclusions and a discussion of further work, which could ensue from the ideas dealt with in this thesis, are outlined in Chapter 7.

Chapter 2

Interference Suppression Using Adaptive Equalizers and Multiple Antennas

2.1 Introduction

Our focus in this chapter is on concepts concerning adaptive equalization and multiple antennas for multiuser interference suppression in digital communication systems. We shall first discuss the general model for signal and interference which are relevant to interference suppression concepts discussed in this thesis. The generalized zero-forcing conditions for complete ISI and CCI suppression will be studied and this forms the basis for the proposal of the MAME system. The applicability of these ideas to CDMA systems will then be examined.

2.2 Adaptive Equalization for Interference Suppression

Traditionally, adaptive equalizers have been successfully used for overcoming ISI in digital communication systems [34][35]. However, adaptive equalizers can also be used for interference suppression under certain conditions which shall be made clear in this chapter. Let us consider Fig. 2.1 where the baseband model of a multi-user system sharing the same communications resource is shown. In this model, it is assumed that the desired user's signal and the interferer's signal as seen by the receiver is nothing but the respective data sequence pulse-shaped by a linear channel or cochannel as

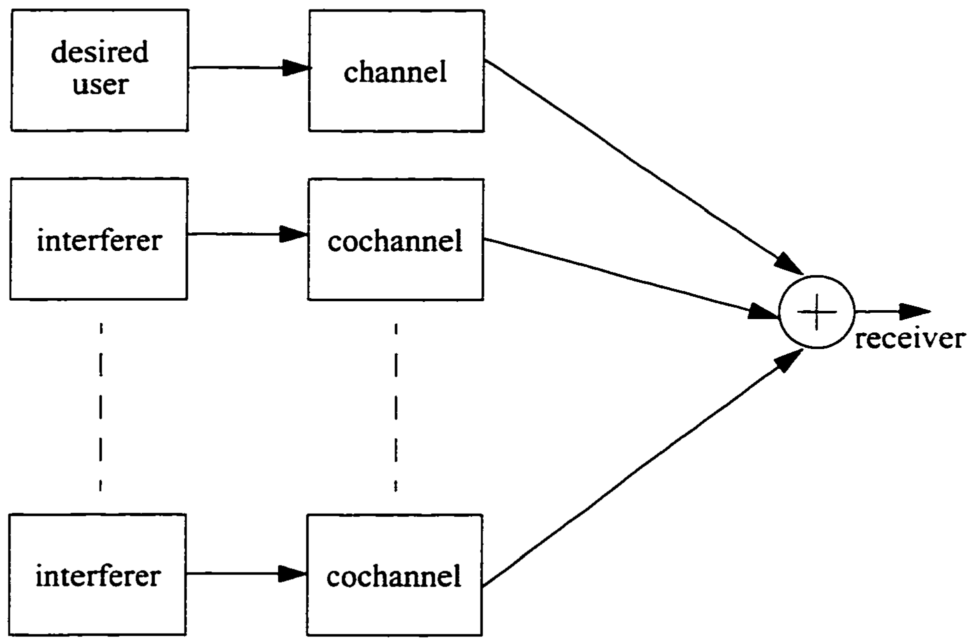

Figure 2.1 Model of a multi-user digital communications system.

appropriate. An impulse response model can then be considered for the channel and cochannels shown in Fig. 2.1. In this work, we are mainly concerned with interference from users of the same service who are transmitting on the same carrier frequency i.e., CCI from users of the same service. Interference can also occur from users on adjacent channels and from other services which might completely or partially overlap with the spectrum of the desired user's signal. The type of interference considered can have the most impact on the capacity of a system among different types of interference.

In the model shown in Fig. 2.1, ISI and CCI can be considered equivalent since both are linear combinations of undesired symbols [29]. It is well known that ISI can be completely suppressed using zero-forcing equalizers provided that the Nyquist bandwidth criterion is met [34]. The *net* channel or cochannel impulse response is used to denote the cascade of the transmitter pulse-shaping filter, physical transmission channel, and the receiver as illustrated in Fig. 2.2. Hence, for zero ISI, the net channel impulse response has to have nulls spaced at the symbol interval except at the origin as illustrated in Fig. 2.3. Similarly, for zero CCI, the net cochannel impulse response has

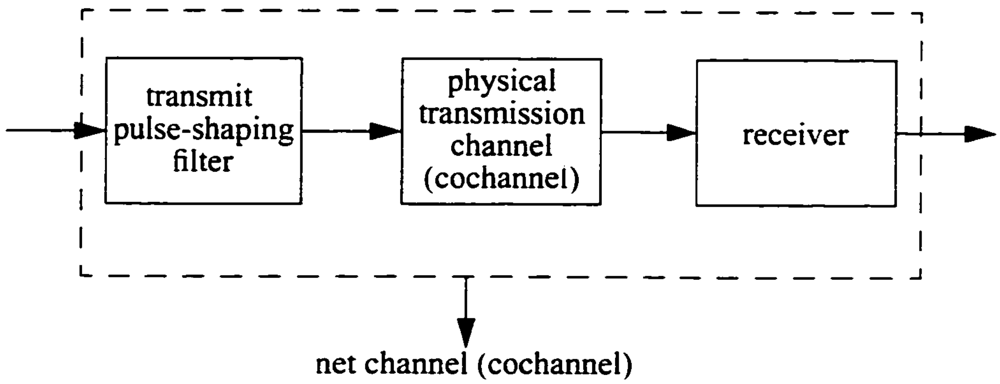

Figure 2.2 Components in the *net* channel.

to have nulls spaced at symbol intervals including at the origin as illustrated in Fig. 2.4. These two conditions have been combined into a single criterion called the generalized zero-forcing equalizer criterion and have been used for predicting the interference suppression capability of a combination of FSEs and antennas [28]. These results were used in [17] to propose a system for suppressing near-end crosstalk (NEXT) in high bit-rate digital subscriber line (HDSL) systems. There are certain conditions under

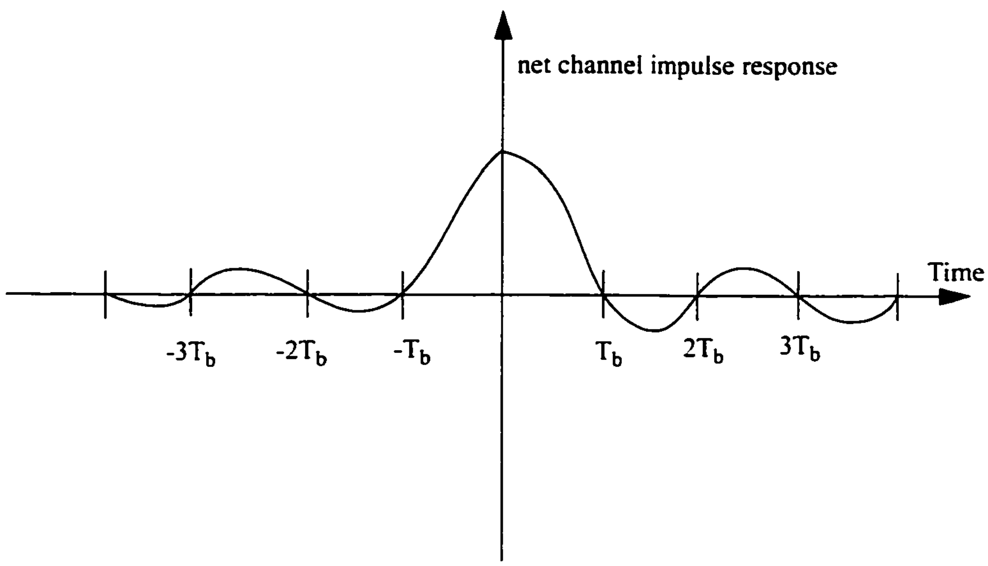

Figure 2.3 Zero ISI condition.

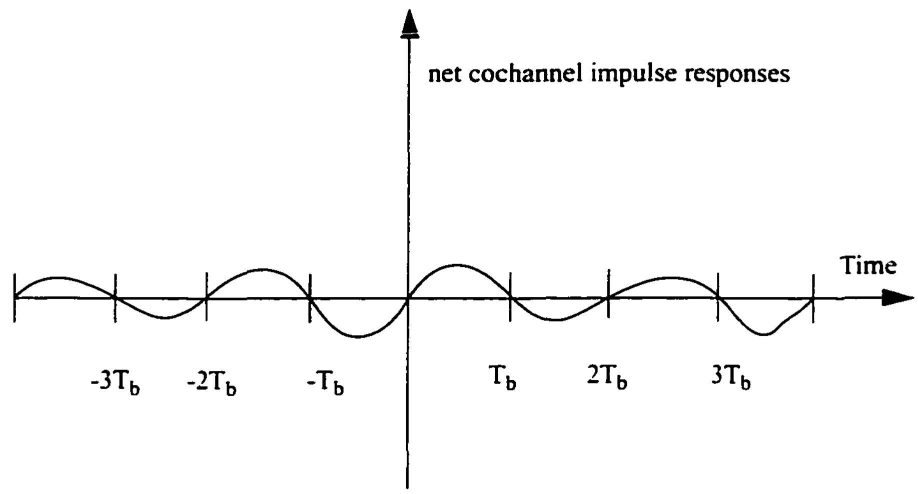

Figure 2.4 Zero CCI condition.

which multiuser interference, which can be modeled as in Fig. 2.1, can be suppressed and these are clearly outlined in [28].

An FSE of appropriate tap spacing can be used to suppress interference provided that the transmitted signal and, consequently, the received signal has sufficient bandwidth. The relevant result with respect to a single FSE can be expressed as follows [28]:

- Every $k/2T_b$ increase in the bandwidth of the transmitted signal, where T_b is the data symbol period, can enable the suppression of CCI from k-1 *distinct* interferers by an FSE with a tap spacing of T_b/k.

Hence, if the transmitted and, consequently, the received signal in a digital communications system as modeled as in Fig. 2.1 have a larger bandwidth as compared with the Nyquist rate, then FSEs can be used to achieve interference suppression. The exact number of interferers which can be completely suppressed will depend on the bandwidth of the received signal and the tap spacing of the FSE. This method will be successful provided that the combined channel impulse response (which denotes the impulse response that includes all effects before equalization) is distinct from the combined cochannel impulse responses. Moreover, the success of this method is expected to increase as the differences between the combined channel and combined cochannel impulse responses are enhanced [36]. It should be noted that all discussion is based on the complex baseband signal model.

There is a basic limitation in using just FSEs to suppress interference since it is crucially dependent on the bandwidth of the transmitted signal. This means that one cannot achieve gains just by decreasing the tap spacing of the FSEs if there was no commensurate increase in the bandwidth of the transmitted signal. Moreover, bandwidth is becoming an important resource especially in wireless applications. Hence, to enhance the interference suppression capability under these limitations, multiple antennas can be combined with FSEs. A relevant result is as follows [28]:

- If L interferers can be suppressed by an FSE of a certain tap spacing, then under *certain conditions*, if A_r antennas are used, where *each* antenna's output signal is processed by a separate FSE, then one can, in theory, suppress $A_r L$ interferers.

This result means that the bandwidth limitation which can restrict the interference suppression capability of a single FSE can be overcome by combining multiple antennas and FSEs. The predicted increase in interference suppression capability due to this strategy is only possible when each user's combined channel (cochannel) impulse responses as seen at different antennas are independent. These two results suggest that multiuser interference suppression is possible in some situations and forms the basis of the proposal of the MAME system in this thesis.

An FSE with a tap spacing of $T_b/2$ to suppress NEXT from 49 interferers in an HDSL system was proposed in [36]. In this work, the transmitted pulse was assumed to have 100% excess bandwidth and all the transmitter clock pulses at the central office were assumed to be synchronized. This proposal was based on measured cochannel impulse responses which were nearly identical when the user clock pulses were synchronized. Hence, the 49 interferers appeared to the FSE as a single interferer and thus, an FSE with a tap spacing of $T_b/2$ was successful in suppressing the interference. The limited bandwidth capability of the local telephone loop plant means that interference suppression using FSEs will not be viable in such an environment. This is because of the fact that the number of distinct interferers which can be suppressed using FSEs is directly proportional to the bandwidth of the transmitted signal. The multiple-antenna system is also not relevant to the wireline medium.

An FSE with a tap spacing of $T_b/2$ was also proposed to overcome the CCI from a dominant interferer in a TDMA digital mobile radio system [37]. The effects of using a combination of multiple-antennas and FSEs were investigated for reducing the carrier spacing between adjacent channels in [28]. However, the combination of multiple antennas and FSEs are suited to interference suppression in systems where the transmitted signal is inherently wideband in nature and our focus is on these types of systems.

2.3 Interference suppression in CDMA systems

As mentioned earlier, a CDMA system is a type of spread-spectrum system. The characteristic of any spread-spectrum system is that the bandwidth of the transmitted signal is much larger than the data symbol rate. The amount of spreading is quantified by the processing gain of the system which is the ratio of the spread bandwidth to the symbol rate. In a DS-CDMA system, which is the main focus in this work, the spreading is achieved by multiplying the signal by a periodic pseudonoise code sequence. Different cochannel users are assigned different code sequences. At the receiver, the received signal is multiplied by the desired user's code sequence to despread the desired user's signal back to within the symbol-rate bandwidth. However, the interferer's signals are respread since they were spread using different code sequences. Thus, the desired user's signal energy is concentrated in the symbol-rate bandwidth while the interferer's signal energy is spread across a larger bandwidth. This means that after suitable filtering, there is an enhancement in the signal-to-interference power ratio in the CDMA system. This is one of the important reasons for the interest in CDMA systems for multiuser communications. In indoor wireless applications, CDMA systems have been mainly used to counteract the effects of the severe multipath.

The spreading operation is equivalent to pulse shaping the symbol sequence [16] using a filter whose impulse response samples are equal to the values of the samples of a single period of the appropriate pulse-shaped code sequence. Hence, a baseband model of the CDMA system can be illustrated as in Fig. 2.5. Note that we are consider-

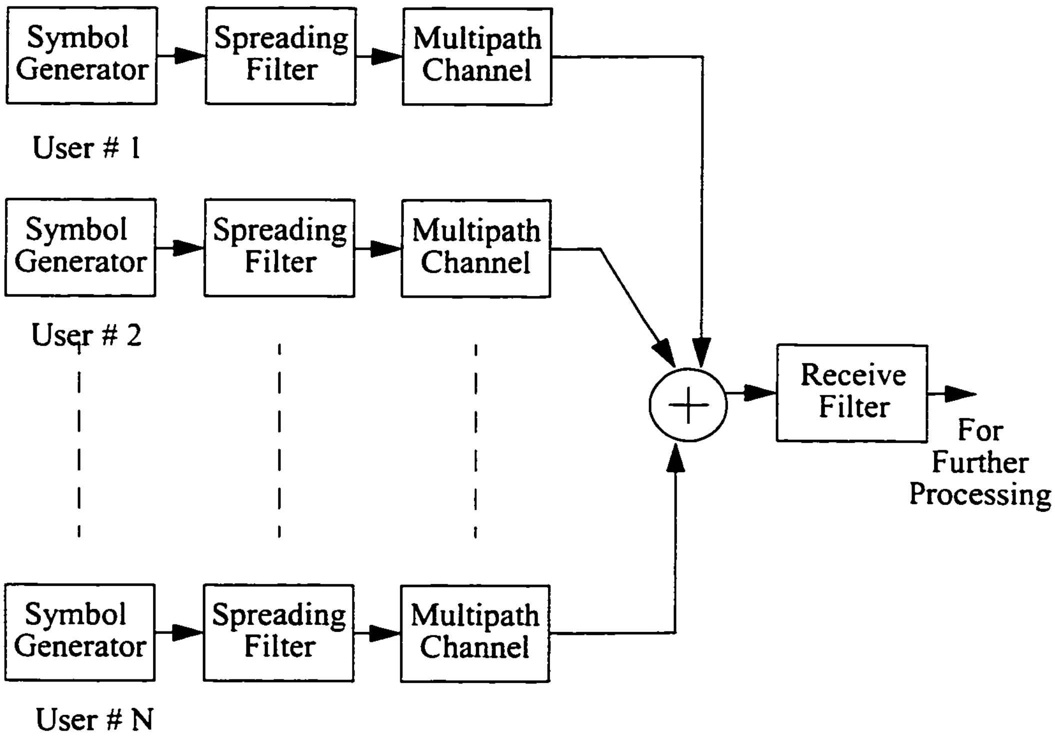

Figure 2.5 Block diagram model of the CDMA system.

ing a CDMA system where the code sequences only span a symbol period. In this model, the symbol sequences are pulse shaped by *individual* spreading filters whose impulse responses depend on the code sequences associated with the different users. The receive filter (RXF) is used to bandlimit the noise present at the input of the receiver and to filter out-of-band components before further processing can take place. It can be seen from this model that each user's signal as seen after receive filtering is nothing but a pulse amplitude modulated (PAM) signal. The *net pulse* of each user as seen after receive filtering is a convolution of the spreading filter, multipath channel, and the receive filter impulse responses. The bandwidth of the net pulse is much higher than the symbol rate. Typically, in a CDMA system whose processing gain is equal to N, the bandwidth of the transmitted signal is greater than or equal to $N/2T_b$. Hence, in theory, an FSE with a tap spacing of T_b/N can be used in a CDMA system to suppress N-1 interferers, and such a solution has been investigated in [16]. Multiple antennas can be combined with FSEs to further enhance the interference suppression capability when compared with that of a single FSE. We discuss this in the next chapter.

2.4 Conclusions

We have reviewed ideas relevant to interference suppression using a combination of FSEs and multiple antennas. The generalized zero-forcing condition for complete ISI and CCI suppression in CDMA systems was discussed. The relevance of this concept to interference suppression in CDMA systems was then examined. This sets the stage for the proposal of the MAME system for interference suppression in CDMA indoor wireless systems.

Chapter 3

The MAME System

3.1 Introduction

In the previous chapter, we have summarized relevant results which indicate the potential for a combination of FSEs and multiple antennas to suppress multiuser interference under certain conditions. It is clear that FSEs can be used to suppress CCI in CDMA systems. However, the combination of multiple antennas and FSEs, which can offer enhanced capabilities, have not been investigated for CDMA systems and forms the focus of this thesis. We concentrate on indoor wireless applications and though the results might be extended to outdoor environments, there are several other conditions which are not considered in this work that need to be addressed when dealing with outdoor wireless systems.

Many new and existing indoor wireless applications are designed to operate at very high carrier frequencies (GHz range) [1] and at these frequencies, numerous objects, even of small dimensions, can affect signal transmission. This means that in an indoor environment, several objects can influence the physical multipath transmission channel [38]. It is well established that in a multipath fading environment, one can expect each user's signal to fade independently at the different antennas when the antenna spacing is greater than half a wavelength (1.5 cms at 10 GHz). This implies that the impulse responses associated with a user at different antennas can be modeled to be independent for antenna spacings greater than half a wavelength. In practice, the spacing might need to be greater than the minimum distance of separation [39]. The physical dimensions of the antenna arrays at such high frequencies are unobtrusive because of the small physical spacing needed between the antennas to achieve independent fading. Therefore, physical implementation of the multiple antennas should not be a major concern even with portability taken into account [40]. Hence, the conditions are suitable for a combination of multiple antennas and FSEs to provide enhanced interference suppression capabilities. An important advantage of CDMA system over TDMA and FDMA systems is that user signals can share the same frequency band without the need for complex frequency allocation or synchronization schemes. Hence, CCI is the most important impediment towards achieving higher capacities and efficiencies in CDMA systems. Therefore, strategies to alleviate the influence of CCI are crucial in the development and deployment of CDMA systems. These are the reasons for proposing the MAME system for CDMA indoor wireless systems.

3.2 The MAME System

A block diagram representation of the MAME system is shown in Fig. 3.1 where each antenna's output signal is receive filtered and then individually processed by an FSE. An FBE is used to suppress ISI without noise enhancement making the overall MAME system a DFE. The feedforward FSEs are used to attenuate ISI and CCI. The FSEs and the FBE are adaptive filters and the same error $e(n)$ is used to update all the tap weights once every symbol period. The physical spacing between the antennas is strictly greater than half a wavelength and in practice will depend on the carrier frequency and environmental conditions. The tap spacing of the FSEs and the number of antennas is not fixed and simulation results which will be presented later shall illustrate their effect on performance.

In the MAME system, angle-of-arrival techniques *are not* used to overcome interference. Since the spacing between the antennas is strictly greater than half a wave-

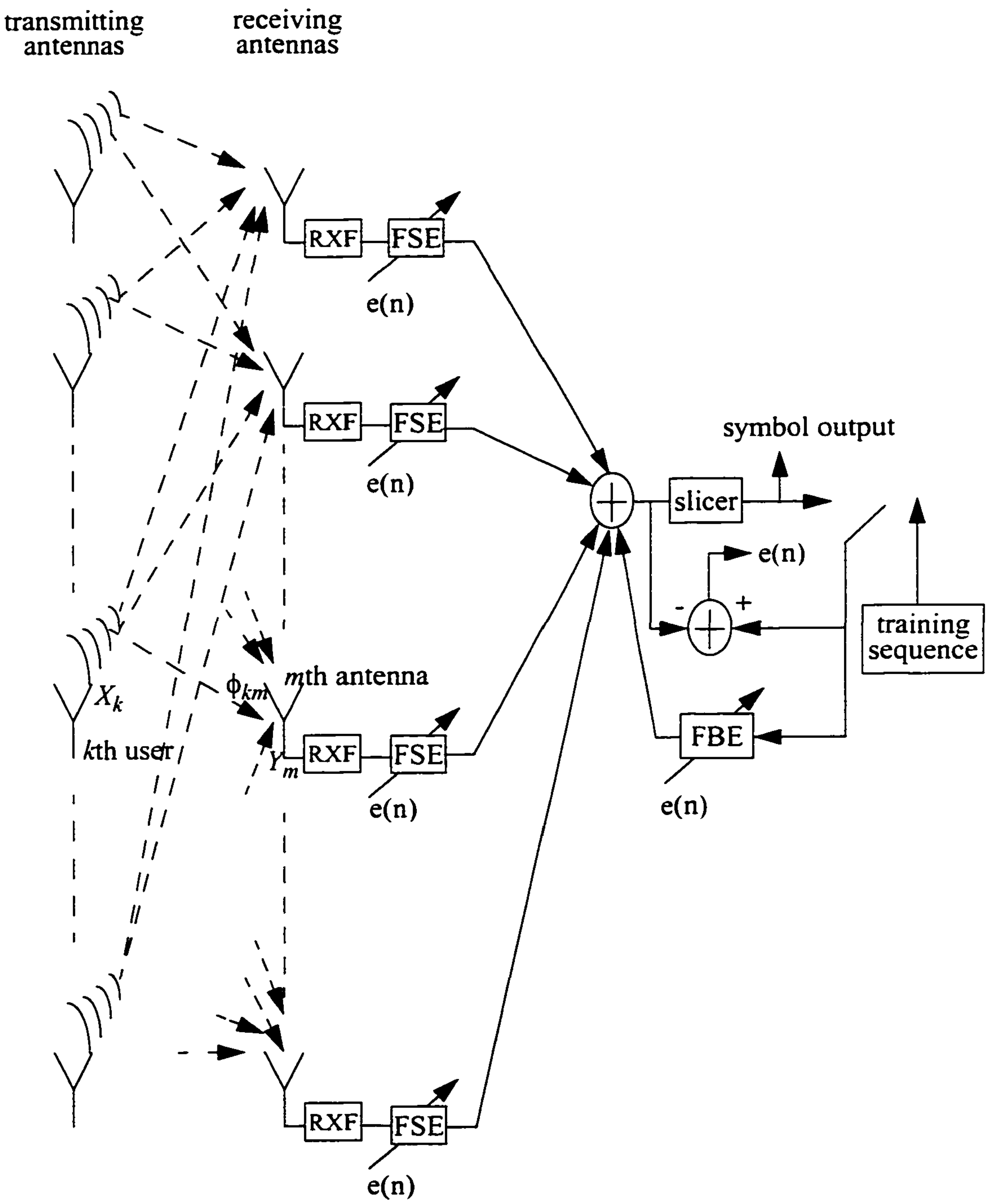

Figure 3.1 Block diagram illustration of the MAME system.

length, angle-of-arrival techniques are not applicable. The appearance of multiple grating lobes at large antenna spacings makes the conventional notion of array patterns meaningless, as in the optimum combining techniques investigated in [24]. The real purpose of multiple antennas is to obtain *independent* copies of the different user's signals. These are then separately processed by the FSEs at each antenna and this is the reason for the superior interference suppression capability of the MAME system as compared with a single FSE. This is an important difference between the proposed system and the space-time processing systems which are prevalent in the literature [26][22][41].

3.3 Effect of Spectral Correlation

We have proposed the MAME system based on the predictions of the interference suppression capability of a generalized zero-forcing equalizer [28]. However, one could also interpret the interference suppression capabilities of the MAME system in terms of the spectral correlation present in user signals.

Signals in digital communication systems are cyclostationary and have *inherent* spectral correlation [18], i.e., symbol-rate frequency-shifted versions of the signal are completely correlated in the case of a PAM signal. If $S_k^m(t)$ is the received signal at the input of the FSE from the kth user at the mth antenna, then $S_k^m(f)$ and $S_k^m(f+i/T_b)$ are completely correlated for integer values of i. As a consequence, frequency-shift filtering can be used to overcome interference. This can be achieved by frequency-shifting the received signal and then suitably weighting the frequency-shifted components depending on the spectral strengths of the desired user's and the interferer's signals at different frequencies [21].

Each *individual* signal, i.e., the signal from each user at each antenna $S_k^m(t)$, is cyclostationary. However, the statistics of the net signal $Z_m(t)$ at each antenna, which is the sum of several users' signals, approaches a stationary Gaussian distribution especially in the case of an asynchronous system with several active users. The cyclostationarity of the *individual* signals $S_k^m(t)$, and consequently the spectral correlation which is present in these signals is the important characteristic that can be used by an FSE to suppress interference. The net signal at the input of an FSE at the mth antenna can be expressed as

$$Z_m(t) = \sum_{k=0}^{L-1} S_k^m(t) \tag{3.1}$$

where L is the number of users contributing to the input signal. We have omitted noise in (3.1) and the influence of the FBE in this discussion since we are interested in explaining the effect of spectral correlation in interference suppression. An FSE followed by a symbol-rate sampler is equivalent to a frequency-shift filter and the number of symbol-rate spaced frequency shifts used by the FSE before summation at the output depends on the tap spacing of the FSE which is given by T_b/δ where δ is the tap-spacing factor [21]. If $H_m(f)$ is the frequency response of the FSE at the mth antenna, then the output of this FSE can be expressed as

$$Y_m(f) = \sum_{i=-\infty}^{\infty} H_m\left(f + \frac{i}{T_b}\right) Z_m\left(f + \frac{i}{T_b}\right) \qquad \left(0 \le |f| \le \frac{1}{2T_b}\right) \tag{3.2}$$

where, in practice, the number of summation terms is dependent on the tap spacing of the FSEs and will be finite due to the finite bandwidth of the FSE. By using (3.1) we can express (3.2) as

$$Y_m(f) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{L-1} H_m\left(f + \frac{i}{T_b}\right) S_k^m\left(f + \frac{i}{T_b}\right) \tag{3.3}$$

It can be seen from (3.3) that an FSE can use the spectral correlation of the individual signals $S_k^m(t)$ by suitably weighting the frequency shifted components before summation at the output. Since all individual signals in (3.3) have spectral correlation between components spaced at multiples of the symbol rate it is imperative that distinctness between users should exist for successful use of spectral correlation in an FSE used for interference suppression [18]. In the multiple antenna case, the system output $Y(f)$ can be expressed as

$$Y(f) = \sum_{m=1}^{A_r} \sum_{i=-\infty}^{\infty} \sum_{k=0}^{L-1} H_m\left(f+\frac{i}{T_b}\right) S_k^m\left(f+\frac{i}{T_b}\right) \tag{3.4}$$

where A_r is the number of antennas used. It is interesting to note that $S_k^m(f)$ and $S_k^m(f+i/T_b)$ are completely correlated for all values of m because the same information signal modulates different pulses at the different antennas. This means that the right-hand side of (3.4) is nothing but a weighted combination of spectrally correlated bands of the various user signals. Hence, the superior interference suppression capability of the MAME system is due to the processing of spectrally correlated bands of the various user signals. Note that if the interference was modeled as noise then only the spectral correlation present in the desired user's signal can be used.

Hence, the interference suppression capability of the MAME system can be interpreted either in terms of the zero-forcing equalizer concepts or in terms of the inherent spectral correlation present in user signals. The zero-forcing concepts help us visualize interference suppression in the time domain while the spectral correlation view enables understanding of interference suppression in the frequency domain.

3.4 Diversity

The interference suppression capability of the MAME system can also be explained by using the concept of diversity. In the MAME system, both bandwidth and spatial diversity are used. The two outermost summation indices in (3.4) refer to diversity from these different domains. The m indexed summation relates to spatial diversity due to multiple antennas. In a CDMA system, the excess bandwidth of the transmitted signal can be interpreted as bandwidth diversity. This is because in general, one does not need much more than the Nyquist rate for communication. Hence, every Nyquist rate increase in the bandwidth of the transmitted signal can be interpreted as the addition of an extra diversity branch. The i indexed summation in (3.4) relates to bandwidth diversity. Therefore, the MAME system is a *dual-domain diversity combiner.*

The notion of diversity branches can be used to understand the interference suppression capability of the MAME system. Note that in this work when we discuss the interference suppression capability of the MAME system, we shall not consider the effects of noise and the finite order of the filters. The total number of diversity branches processed in the MAME system is equal to the product of the tap spacing factor δ and the number of antennas A_r. This statement assumes that the bandwidth of the transmitted signal is greater than $\delta/2T_b$ and the user signals experience independent fading at the different antennas. Thus, the interference suppression capability of the MAME system is related to the number of diversity branches that are processed and the number of interferers that can be suppressed is equal to δA_r -1. This interpretation reiterates the importance of diversity in communications and is a confirmation of many results which can be summarized as follows: M diversity branches can be used to suppress M-1 interferers.

The number of diversity branches which are processed in the MAME system can be increased in two ways. The tap-spacing factor δ can be increased to δ_{new}, provided that the bandwidth of the transmitted signal is greater than $\delta_{new}/2T_b$. Note that we do not consider the existence of any adjacent channel interference. The number of antennas can be increased to achieve the same objective provided that the independent fading assumption is valid. Note that all the diversity branches associated with each user in (3.4) are correlated, i.e., in theory, it does not matter whether new branches are added in either the bandwidth or the spatial domain. However, if interference were modeled as noise, even though the number of diversity branches will remain the same, these diversity branches will not be spectrally correlated. Noise is not correlated in the bandwidth-domain since it is modeled as a stationary signal. Moreover, there is no inherent spectral correlation between noise components at different antennas since noise is assumed to be independent at the different antennas. Hence, the importance of modeling interference is crucial while investigating the performance of the MAME system.

There is an inherent *limitation* in the number of bandwidth-domain diversity branches that can be used at each antenna and this is dependent on the bandwidth of the transmitted signal. This means that there is no significant advantage in increasing the tap-spacing factor of the FSEs without a commensurate increase in the bandwidth of the transmitted signal. In CDMA systems, the processing gain limits the number of bandwidth-domain diversity branches that can be used at each antenna which implies that there is a upper bound on the tap-spacing factor of the FSEs above which significant performance gains cannot be achieved. Hence, to enhance the interference suppression capability under this restriction, spatial diversity can be combined with bandwidth-domain diversity as in the MAME system.

The bandwidth-domain diversity combining or the operation of the FSE can be considered to be equivalent to sub-band filtering. The signals $S_k^m(f+i/T_b)$ for different values of i and for the same value of m are different subbands of the signal $S_k{}^m(t)$ and the operation of *each* FSE can be interpreted as in Fig. 3.2. Hence, the operation of the

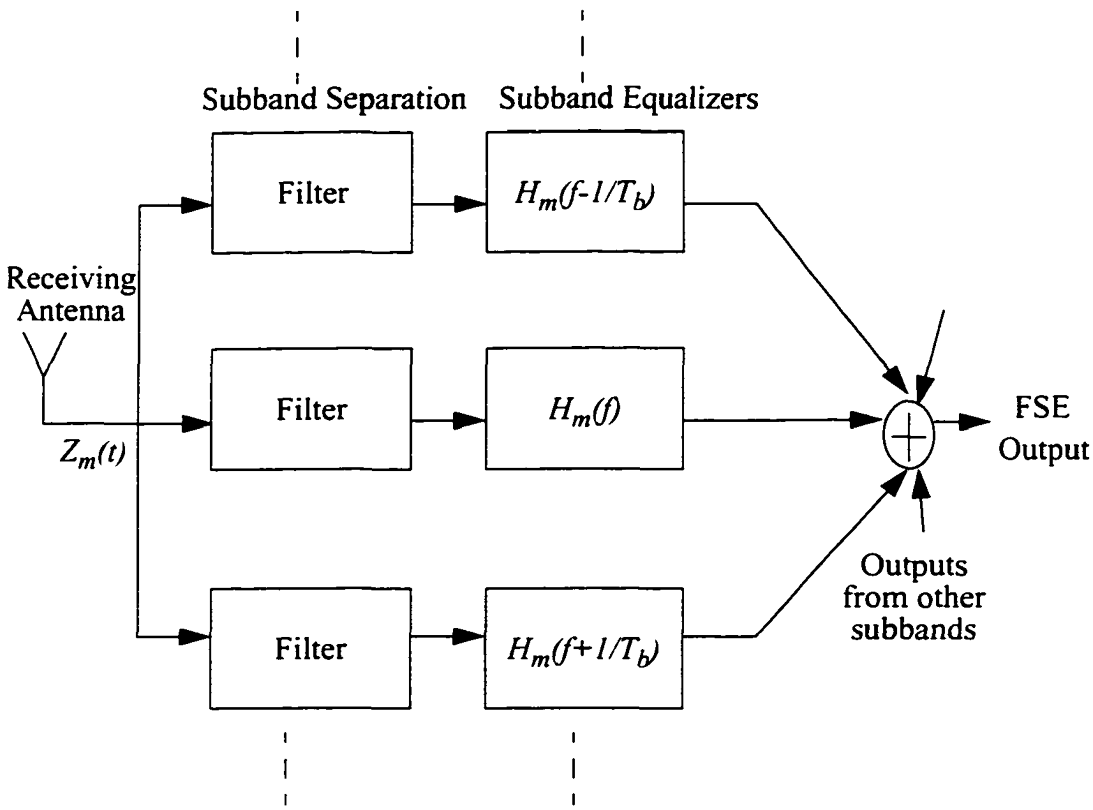

Figure 3.2 Illustration of the operation of the FSE as a subband equalizer.

MAME system can also be interpreted as subband filtering at each antenna and spatial diversity combining.

3.5 The Near-Far Condition

An important concern among designers of CDMA systems is the near-far problem. Unlike in FDMA or TDMA systems where the users are separated either in frequency or in time, cochannel users in CDMA systems are not separated in either of these domains. Code sequences are the only distinguishing factor among the different cochannel users and typically, the crosscorrelation properties of the code sequences determine CCI suppression performance. Due to this, a unique problem arises in

CDMA systems. Power variations in the user signals can affect the CCI suppression performance [11] and the effect can be described as follows: An interferer with M times increase in power manifests itself as M extra interferers [14] resulting in performance degradation. This situation is called the near-far condition based on the outdoor cellular wireless environment. In an indoor wireless environment, because of the multipath fading nature of the channel, the near-far condition can also occur. This problem is tackled using complex and elaborate power control measures in many CDMA systems [42].

The theoretical interference suppression capability of the MAME system can be predicted based on the generalized zero-forcing equalizer conditions which can be expressed as

$$\left| \sum_{m=1}^{A_r} \sum_{i=-\infty}^{\infty} H_m\left(f+\frac{i}{T_b}\right) S_k^m\left(f+\frac{i}{T_b}\right) \right|^2 = P\delta(k), \quad k = 0, \ldots, L-1 \qquad (3.5)$$

where $\delta(k)$ is the discrete impulse function, k=0 corresponds to the desired user, P is a constant and we assume that the user data sequences are white. As can be seen in (3.5), the number of equations that need to be satisfied is equal to the number of users. The theoretical interference suppression capability of the MAME system is dependent on the number of unknowns available such that a solution to (3.5) can be achieved [28]. The near-far condition could affect the combined channel impulse response(s) and consequently change the corresponding $S_k^m(f+i/T_b)$. However, there is no increase in the number of equations or in the number of unknowns in (3.5). This means that the theoretical interference suppression capability of the MAME system is not affected by the near-far condition. In another sense, the inherent spectral correlation present in each individual signal is not affected. This is because each $S_k{}^m(t)$ is still a PAM signal but with some changes in characteristics like power. Hence, the MAME system could offer solutions to effectively deal with a crucial problem in many CDMA systems. The performance in near-far conditions shall be considered in later sections.

3.6 Mathematical Model

In this section, we present steps and formulae which are used to calculate the MMSE of the MAME system [16][29]. Some signals are shown in the block diagram illustration of the MAME system in Fig. 3.1. Let $a_k(nT_b)$ be the transmitted symbol sequence of the kth user and $C_k(nT_c)$ be the code sequence of the kth user. The transmitted signal of the kth user can be represented as

$$X_k(t) = \sum_i a_k(iT_b)c_k^*(t-iT_b)$$

where $c_k^*(t)$ is the complex conjugate of the pulse-shaped code sequence given by

$$c_k(t) = \sum_{i=0}^{N-1} C_k(iT_c)g_f(t-iT_c+\psi_k) \tag{3.6}$$

In (3.6), N is the system processing gain, $g_f(t)$ is the impulse response of the code pulse shaping filter, and ψ_k is the delay of the kth user's pulse shaping filter. Let $\phi_{km}(t)$ be the complex multipath impulse response coupling the kth user to the mth antenna, given by

$$\phi_{km}(t) = \sum_{i=0}^{P-1} v_{km}^*(iT_c)\delta\langle t-iT_c\rangle$$

where $v_{km}(iT_c)$ is the complex weighting factor of the ith chip-spaced multipath component. The combined channel (cochannel) impulse response as seen by the FSE at the mth antenna from the kth user is given by the convolution of the pulse-shaped code sequence, multipath response, and the RXF $r_f(t)$ as

$$h_{km}(t) = c_k(t) \otimes \phi_{km}(t) \otimes r_f(t) \tag{3.7}$$

The signal received by the FSE at the output of the mth antenna is given by

$$Z_m(t) = \sum_{k=0}^{L-1} \sum_i a_k(iT_b)\,(\,h_{km}^*(t-iT_b)\,) + n_{fm}(t)$$

where $n_{fm}(t)$ is the noise at the mth antenna which has been processed by the receive filter. The receive filtered signal at each antenna is processed by an FSE and the outputs from these FSEs are summed along with the output of the FBE as shown in Fig. 3.1. Let N_f and N_b be the number of taps used in each FSE and the FBE, respectively. We can then define input vectors to each FSE at any symbol instant iT_b as

$$z_m^T = \left[Z_m(iT_b)\ Z_m(iT_b - T_b/\delta) \ldots Z_m(iT_b - (N_f - 1)(T_b/\delta))\right]$$

where δ determines the tap spacing and the superscript T denotes transpose. The input vector to the FBE at any symbol instant iT_b can be represented as

$$\boldsymbol{u}^T = \left[a_d(iT_b - (D+1)T_b) \ \ldots \ a_d(iT_b - (D+1)T_b - (N_b - 1)T_b)\right]$$

where D is the delay used in obtaining the desired response for calculating the error at every symbol interval and a_d is the desired user's symbol sequence. The FSEs and the FBE are considered together as a single equalizer since the same error signal is used in adapting all the individual equalizers at each symbol instant. Hence, the input vector of the *net* equalizer at each symbol instant can be represented as

$$z^T = \left[z_1\ z_2 \ldots z_{A_r}\ \boldsymbol{u}\right]$$

where A_r is the number of antennas. The MMSE of the system can be calculated using the autocorrelation matrix $\boldsymbol{R}$ and the crosscorrelation vector $\boldsymbol{p}$ which are represented using the combined channel and cochannel impulse responses as follows. The representation for the elements of the autocorrelation matrix is derived using the following steps:

$$\boldsymbol{R} = E\left[zz^H\right]$$

$$R = \begin{bmatrix} E[z_1 z_1^H] & \dots & E[z_1 z_{A_r}^H] & E[z_1 u^H] \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ E[z_{A_r} z_1^H] & \dots & E[z_{A_r} z_{A_r}^H] & E[z_{A_r} u^H] \\ E[u z_1^H] & \dots & E[u z_{A_r}^H] & I_{N_b} \end{bmatrix} \tag{3.8}$$

$$R = \left[\begin{array}{ccc|c} R_{11} & \dots & R_{1A_r} & R_1 \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ R_{A_r 1} & \dots & R_{A_r A_r} & R_{A_r} \\ \hline R_1^H & \dots & R_{A_r}^H & I_{N_b} \end{array}\right]$$

The matrix R in the MAME system can be partitioned as shown in (3.8). The submatrices of R in the top left partition referred to by two subscripts are the crosscorrelation matrices of the signals at the input of the FSEs at antennas referred to by these subscripts and are of dimension (N_f, N_f). The (r,s) element of these submatrices is given by

$$R_{ij}^{r,s} = \sum_{k=0}^{L-1} \sigma_{ak}^2 \sum_l \left(h_{ki}^*(lT_b - rT_b/\delta) \right) h_{kj}(lT_b - sT_b/\delta) \ + \\ \sigma_{nm}^2 \sum_g r_f^*\left(g\frac{T_b}{\delta} + r\frac{T_b}{\delta}\right) r_f\left(g\frac{T_b}{\delta} + s\frac{T_b}{\delta}\right)$$

where $r, s = 0, \ldots, N_f - 1$ and $i, j = 1, \ldots, A_r$. The standard deviation of the kth user's data sequence is represented by σ_{ak} and the standard deviation of the noise source at the mth antenna is represented by σ_{nm}. Note that noise at the different antennas is assumed to be uncorrelated, and hence, the second term in the above equation is zero when i is not equal to j.

The top right partition of matrix $\boldsymbol{R}$ contains crosscorrelation matrices between the input vectors of each FSE and the input vector of the FBE. Here, the index in each submatrix refers to the appropriate antenna and the submatrices are of dimension $(N_f; N_b)$. The (r,s) element of these submatrices can be expressed as

$$\boldsymbol{R}_i^{r,s} = \sigma_{ad}^2 \; h_{di}^*((D+1)T_b + sT_b - rT_b/\delta)$$

where $r=0, \ldots, N_f - 1$ $s=0, \ldots, N_b - 1$, $i=1, \ldots, A_r$ and σ_{ad} is the standard deviation of the desired user's data sequence. The bottom left partition contains the Hermitian transpose of these submatrices. The bottom right partition is the correlation matrix of the input vector of the FBE and is assumed to be the identity matrix of dimension (N_b, N_b) for independent and uncorrelated symbols.

The expression for the crosscorrelation vector $\boldsymbol{p}$ is derived as

$$\boldsymbol{p} = \left[E[z_1 a_d^*(nT_b - DT_b)] \ldots E\left[z_{A_r} a_d^*(nT_b - DT_b)\right] E[\boldsymbol{u}\, a_d^*(nT_b - DT_b)]\right]^T$$

$$\boldsymbol{p} = \left[\boldsymbol{p}_1^T \ldots \boldsymbol{p}_{A_r}^T \; \boldsymbol{0}^T\right]^T \tag{3.9}$$

and the rth element of each sub-vector $\boldsymbol{p}_i$ can be expressed as

$$p_i^r = \sigma_{a_d}^2 h_{di}^*(DT_b - rT_b/\delta)$$

These expressions for the components of the matrix $\boldsymbol{R}$ and the vector $\boldsymbol{p}$ enable us to calculate the optimum tap weights of the *net* equalizer and the MMSE given the impulse responses of the combined channels and combined cochannels and other associated parameters (filter orders, delay etc.). The expression for the MMSE is given by

$$e_{min} = \sigma_{a_d}^2(1 - p^H R^{-H} p) \tag{3.10}$$

and was used in the calculations.

3.7 Conclusions

The MAME system has been proposed for CCI suppression in CDMA indoor wireless systems and the differences with existing multiple-antenna strategies are explained. It is shown that the inherent spectral correlation present in user signals is the reason for the superior interference suppression capability achieved. The MAME system is also interpreted as a dual-domain diversity combiner. These discussions offer clear insights into the operation of the MAME system. It is also shown that the near-far condition will not affect, in theory, the interference suppression capability. A detailed mathematical model was then presented and was used in the calculation of the MMSE which will be the focus of the next chapter.

Chapter 4

Optimum Performance

4.1 Introduction

So far we have discussed the superior interference suppression capabilities of the MAME system. Our focus in this chapter is to present and discuss MMSE performance results under various conditions. We first present details of the simulation model used to calculate the MMSE. Results are then presented and discussed. These results and discussions confirm the CCI suppression capabilities of the MAME system and offer insights into its many characteristics and properties.

4.2 Simulation Model

In this section, we outline the details of the simulation model used to obtain the MMSE. The block diagram in Fig. 4.1 illustrates the various quantities influencing the MMSE calculation. The mathematical model presented in the previous chapter showed that the elements of the autocorrelation matrix **R** and the crosscorrelation vector **p** are dependent on the composite channel and cochannel impulse responses. The formulae presented in the previous chapter were used to calculate the matrix **R**, vector **p**, and the MMSE. Matrix **R** is calculated by separately calculating the various submatrices outlined in (3.8). The elements of these submatrices are calculated using the different composite channel and cochannel impulse responses. This is shown in Fig. 4.1 where the various quantities are input to the autocorrelation matrix calculator which is

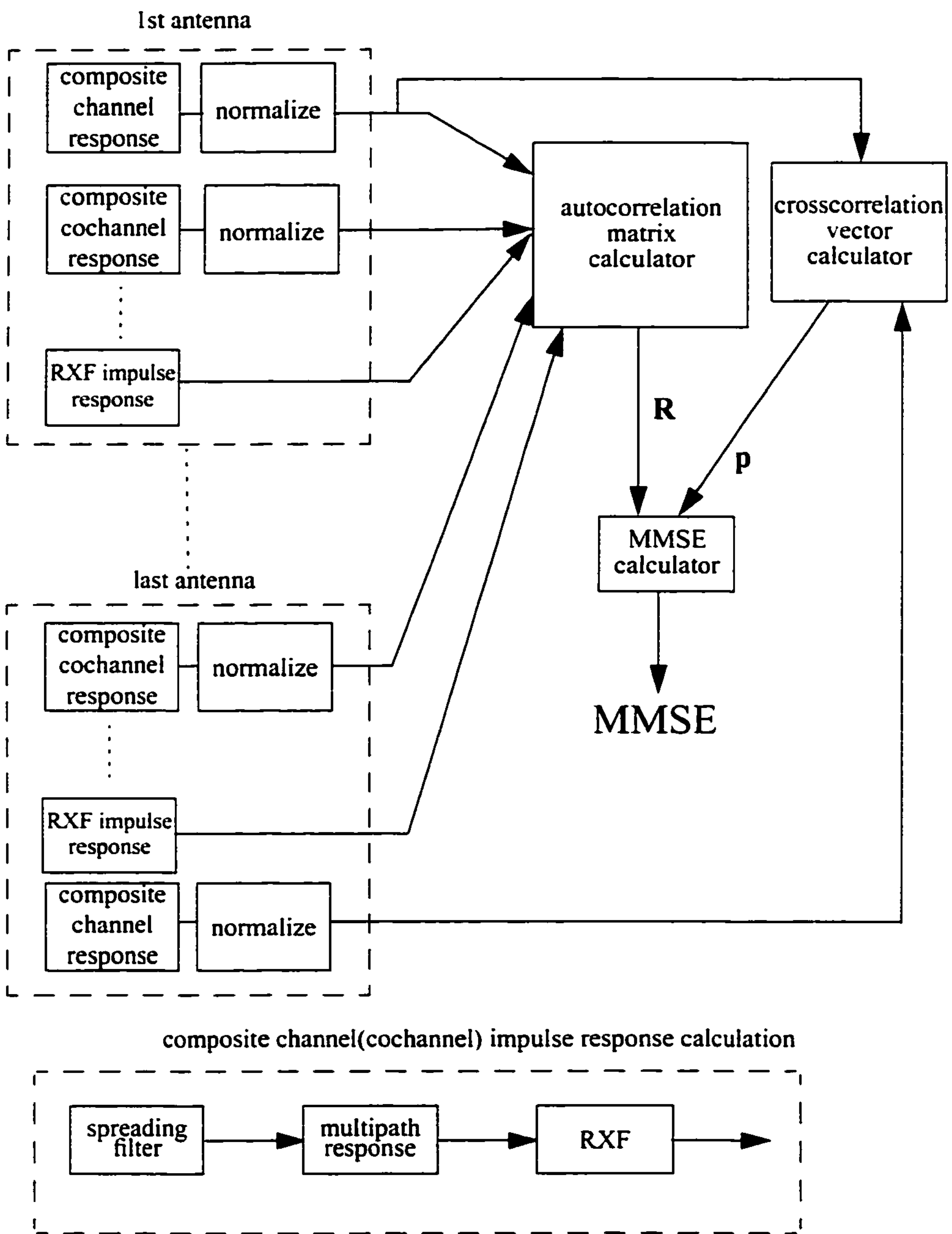

Figure 4.1 Illustration of the MMSE calculation.

used to obtain the matrix **R**. It should be noted that although only one composite cochannel impulse response block is shown in each antenna block, the actual number of them depends on the number of users. The effect of receive filtered noise is also considered in the calculation as reflected by the RXF impulse response block in each antenna. Each composite channel (cochannel) impulse response is calculated by convolving the corresponding spreading filter, multipath channel, and the RXF impulse responses as illustrated at the bottom of Fig. 4.1.

The crosscorrelation vector **p** is partitioned as in (3.9) and each sub-vector in the partition is calculated separately. These sub-vectors are calculated using only the composite channel impulse responses. The matrix **R** and the vector **p** are used to obtain the MMSE using (3.10). We now present details of the various components in the simulation model.

4.2.1 Code sequence

The pseudo-random sequence which was used to spread the signal at the transmitters is the Walsh-Hadamard sequence [43]. The processing gain of the system investigated was 8. We are considering the use of the MAME system in indoor wireless applications where the data rates are high and are expected to increase in the future [1]. In the MAME system, the tap spacing of the FSEs should be equal to the chip period for achieving maximum interference suppression performance. This means that the chip rate of the CDMA system should not be too large as compared with the data symbol rate so as to keep the tap spacing of the FSEs to within practical limits. This implies that small processing-gain systems are more suitable. The code sequence was pulse shaped using the square-root raised-cosine (SRRC) LPF with 0% excess bandwidth [44]. The samples of the impulse response of the spreading filter of the kth user are obtained from the samples of the corresponding pulse shaped code sequence. We shall consider the influence of code sequences in detail in chapter 6.

4.2.2 Channel model

There are many environments for which WLANs are presently being considered [8]. One such application emphasizes networking among a small number of users in a local indoor area [2]. The data rates for WLANs depend on the application and can range from a few to tens of Mbits/s [8]. The delay spreads and the number of multipaths vary with different conditions depending on several factors [38]. The delay spreads in indoor wireless environments can be in the range of 10-100 ns and up to 3 significant multipaths can occur [16].

We have used a quasi-static fading channel model which is typical of the conditions we are investigating [16]. In such a model, the impulse response of the multipath channel was simulated to be invariant for a particular run, but can vary from run to run. All performance studies were averaged across several runs thus taking into account the changing nature of the multipath environment. In each run, the real and imaginary values of each tap was obtained from independent normal distributions with zero mean and unit variance. Thus, each path in the multipath impulse response was simulated to vary in accordance with the Rayleigh fading model [43].

We have investigated two multipath channel models. The first was simulated to have 3 chip-period spaced complex taps which have equal energy and is called the ch_1 model. The second, called the ch_2 model, was simulated to have the same number of taps. However, the time location of the taps, which reflects the time of occurrence of the multipaths, was simulated to vary in each run such that they could occur randomly between $0T_c$ and $5T_c$. Hence, for different data and chip rates, the delay spreads of these channels will vary. For example, for a data rate of 1.25 Mbits/s, which corresponds to a chip rate of 10 Mbits/s, the median rms delay spreads of the 2 channel models are equal to 58 ns and 100 ns, respectively. These channel models were simulated to have equal strength in the multipaths as this is a worst-case condition as compared with an exponential strength profile when interference is considered [45].

4.2.3 Interference

An important difference here from most studies in CDMA systems is that interference is modeled as shown in Fig. 2.5. It should be noted that modeling interference as noise means that the interference suppression capability of the MAME system cannot be realized. We have only considered the effects of CCI from users of the same service and operating at the same data rate as the desired user. The cochannel multipath impulse responses which couple the signal from the interferers to the different antennas were simulated just like the channel multipath impulse response. The data stream and the multipath impulse responses of each user was assumed to be independent from those of the other users.

The cyclostationarity of the received signal can be examined by observing the signal power over several symbol periods. In Fig. 4.2, the input signal power at the receiver is illustrated over 3 symbol periods with different numbers of users. The abscissa is the number of chips and it can be seen in all three cases that the period of the input signal power variation is equal to 8 chip periods since this is equal to the symbol period. This demonstrates the cyclostationarity of the input signal. This experiment was performed with the ch_2 model and an SRRC LPF at the receiver for a single antenna system with a chip rate equalizer. The results were obtained from a single run for each particular case, and investigation of other runs showed similar characteristics.

The degree of cyclostationarity of a signal can be quantified by the amount of power variation in a symbol period [36]. In Fig. 4.3, the power variation of the input signal over a symbol period is quantified and is illustrated for various numbers of users. In this experiment, 1000 runs were carried out for each case, and in each run, the ratio of the maximum to minimum value of the input signal power was calculated, which was then used to obtain an average value. It can be seen from Fig. 4.3 that as the number of users increases, the *cyclostationarity* of the signal at the receiver is reduced. This is also reflected in Fig. 4.3. This means that the net interference can be

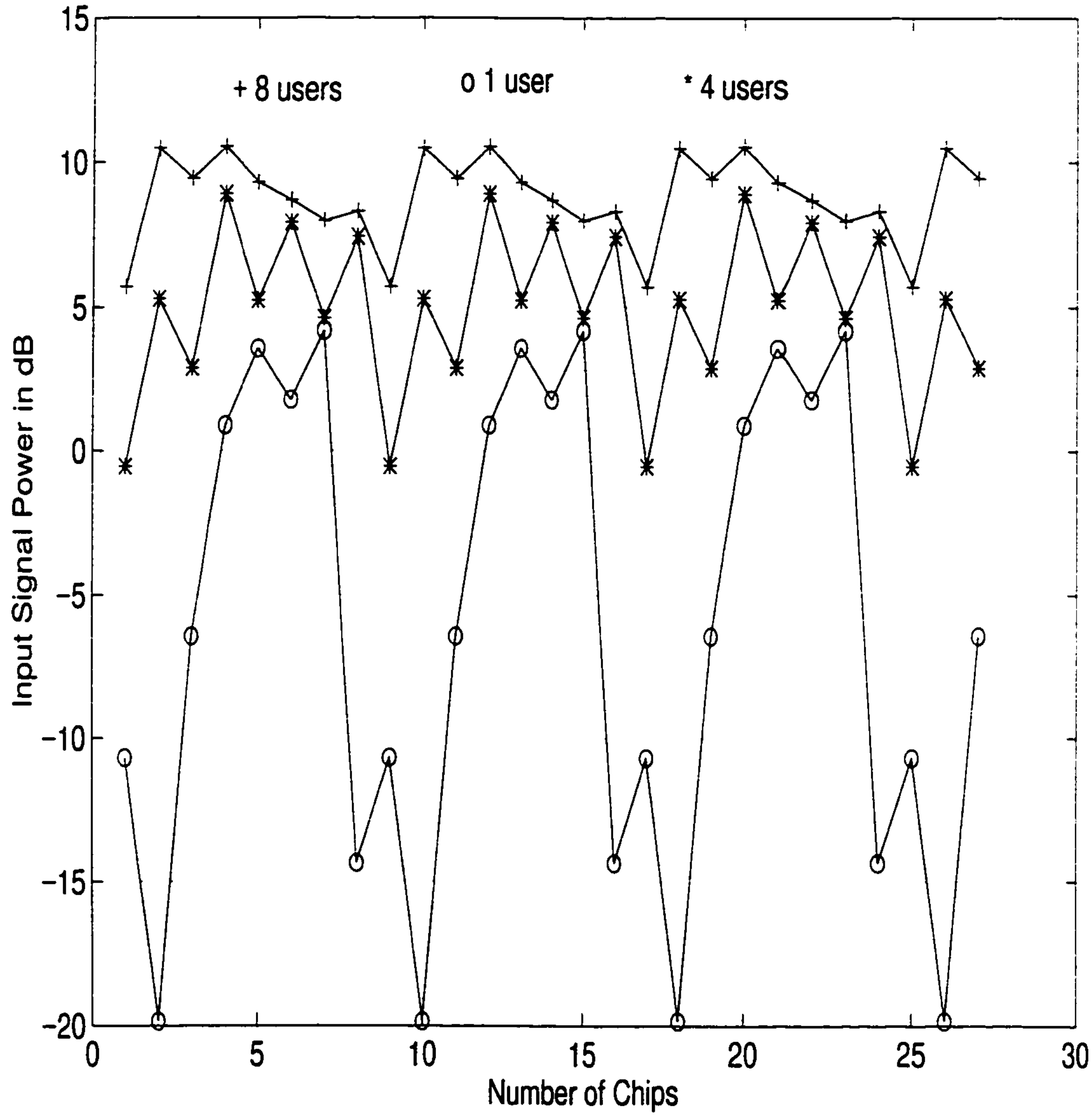

Figure 4.2 Input signal power variation for different numbers of users.

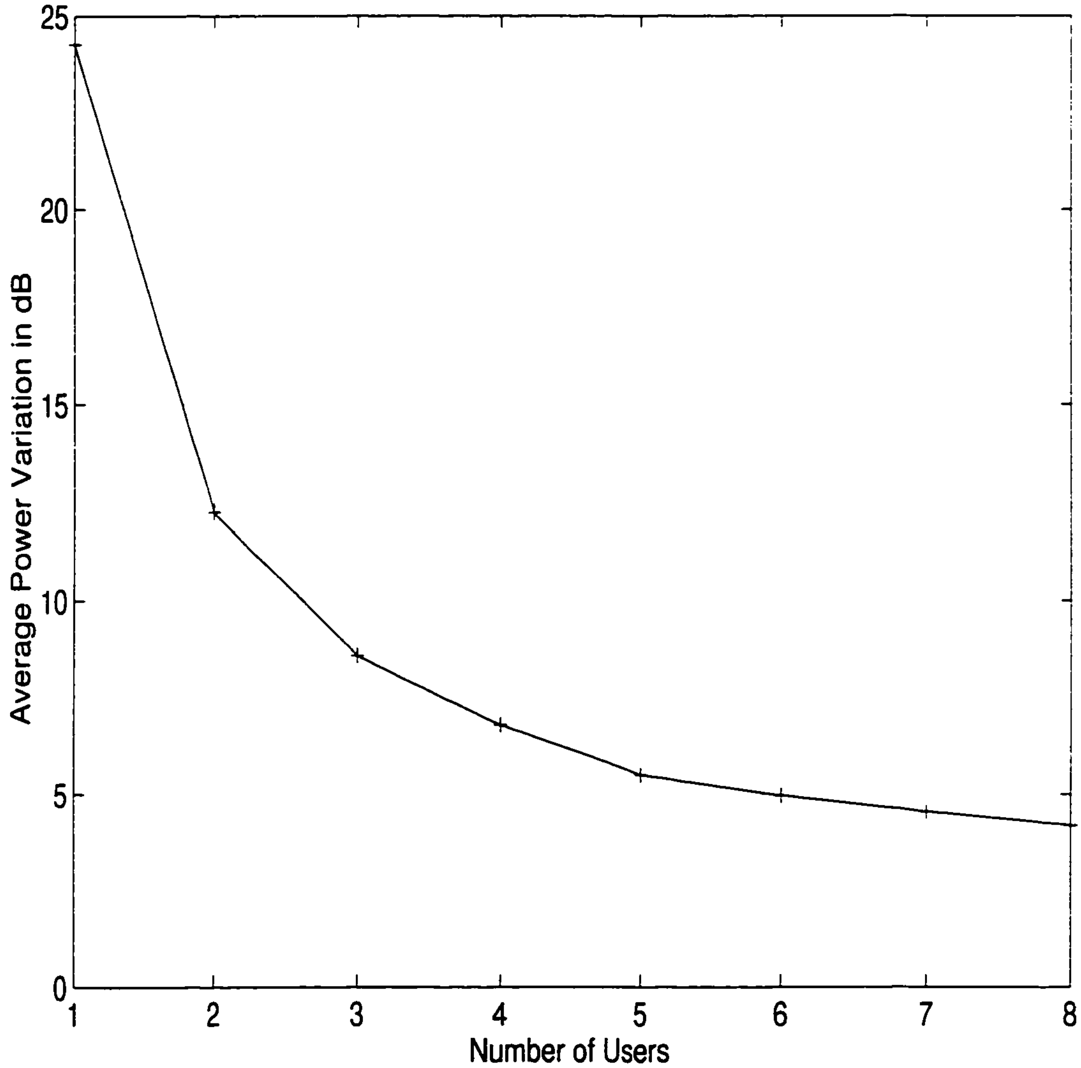

Figure 4.3 Power variation of the input signal over a symbol period for different numbers of users.

modeled as stationary noise especially as the number of users increases. However, it should be noted that the cyclostationarity of the individual signals is *not* dependent on the number of signals.

The relative power of the interferers is an important issue in CDMA systems and could result in the near-far problem [42]. We have investigated various conditions with respect to the power of the interferers but for the general case we have assumed all the users to have equal power at all the antennas. White Gaussian noise of power 20 dB below the desired user's signal was added at each antenna.

4.3 Results and Discussion

The MMSE performance of the MAME system is considered under various conditions in this section. All MMSE results were obtained by averaging the performance over 1000 independent runs. The order of the FBE used was fixed at 2 since there was no significant improvement in performance for higher orders of the FBE. Moreover, it should be noted that the FBE *does not directly* influence the interference suppression performance. In all experiments the CDMA system was simulated to operate at full or 100% capacity, i.e., 8 users were simulated to share the same spread bandwidth for a processing gain of 8. The delay D which was used in calculating the MMSE was obtained by using the order of the FSE and a constant dependent on the channel model. The constant was chosen by experimentation such that the MMSE was best in an average sense. However, note that the delay might not be the best for each individual case. This means that one might obtain better performance for some system conditions by experimenting with the delay in each case. It has been noticed that this procedure can produce a noticeable difference in performance when low-order FSEs are considered. Note that the performance is sensitive to the delay.

To our knowledge, there are no methods available at present in the literature for determining the theoretical bit-error rate (BER) performance based on the MMSE for a system where the interference is modeled as shown in Fig. 2.5 and it has been noted in [45] that such a technique would involve complicated procedures. In [14], the MMSE is used to approximate the BER as

$$P_e = Q\left(\frac{1}{\sqrt{MMSE}}\right) \tag{4.1}$$

where P_e is the BER corresponding to the MMSE value and $Q(x)$ is the standard Gaussian integral [14]. The reasoning behind using the above mentioned approach in calculating the BER is that the residual interference can be modeled as Gaussian noise especially when a system is specifically designed to suppress interference. We do not make this assumption as for low values of the MMSE, we are using the tails of the Gaussian curve where the assumption might not result in accurate BER predictions.

In this work, we assume that a lower MMSE *translates* into a better BER performance but we will not strive to predict the BER based on the MMSE values. In consequence, we present the MMSE under various conditions and focus on the *trend* in the performance and not on a particular value as the goal. In practice, many techniques like error-correction coding can improve the BER performance in many situations. However, we have not investigated or taken the influence of such techniques into consideration in our simulations.

It should be noted that the MMSE criterion has been used in the simulations whereas the zero-forcing condition has been used in the explanation of the theoretical capability of the MAME system. In practice, when additive noise is present, the MMSE equalizer has been shown to perform better than the zero-forcing equalizer [34]. It should also be noted that the simulation results are presented for finite-length equalizers whereas the interference suppression capability predicted from theoretical considerations is based on infinite-length equalizers.

The outage probabilities were calculated by assuming a MMSE criterion of -11 dB as the condition for an outage based on discussion in [45]. Therefore, an outage is recorded if the calculated MMSE value in a particular run exceeds -11 dB. The outage probability is calculated as the ratio of the number of outages to the total number of runs.

4.3.1 Effect of antennas

In this section, we concentrate on the influence of multiple antennas. One of the main advantages predicted from theoretical considerations is that the interference suppression capability of the MAME system increases with the number of antennas. This effect was investigated for 2 different tap spacings of the FSEs. The performance with FSEs which have a tap spacing of $T_b/8$ (chip-rate FSEs) with increasing number of antennas is illustrated in Fig. 4.4 and Fig. 4.5 for the ch_1 and ch_2 models, respectively. The performance with FSEs which have a tap spacing of $T_b/4$ is illustrated in Fig. 4.6 and Fig. 4.7. The RXF used was an SRRC filter with 0% excess bandwidth. The abscissa is the "Total FSE Order" which refers to the total number of taps used in all of the FSEs. This implies that for the same abscissa value, a MAME system with a greater number of antennas will have a lower number of FSE taps at each antenna.

As can be seen from the plots, there is a noticeable improvement in the performance as the number of antennas is increased in all the cases. These results demonstrate the performance improvements possible by using multiple antennas and equalizers as compared with a single equalizer. There are some inherent limitations in the single antenna system. In the case of a chip-rate FSE, all the available bandwidth-domain diversity branches have been used. Consequently, any further increase in the bandwidth of the equalizer will not significantly improve performance because of the limitation due to the signal bandwidth. It should be noted that in many WLAN applications, the required BER can be on the order of 10^{-9} [3]. This means that a sufficiently low MMSE value might be necessary to achieve this criterion. As a consequence, techniques which aid in reducing this value are important. Typically, error-correction coding schemes are used to improve performance in several wireless systems [11]. However, because of the low MMSE values that are possible due to the MAME sys-

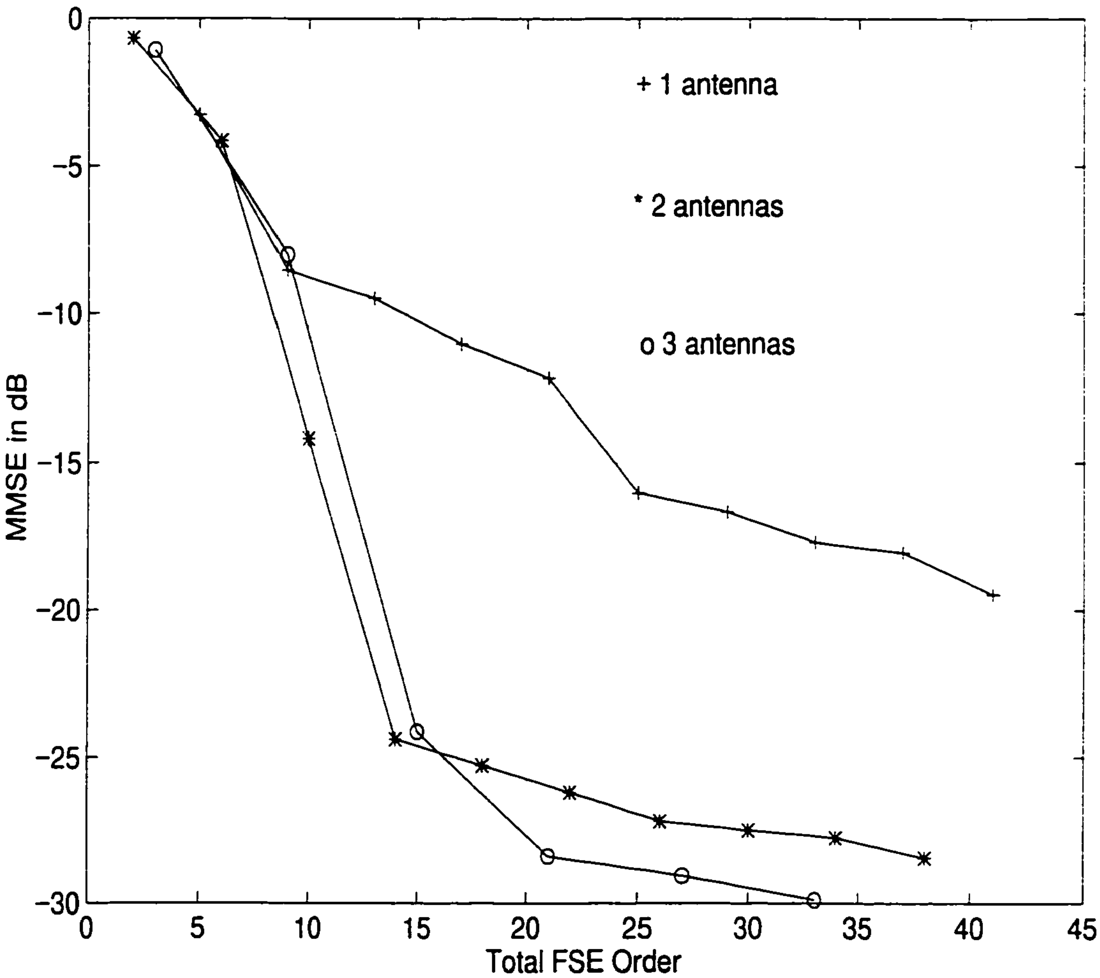

Figure 4.4 MMSE performance with chip-rate equalizers for the ch_1 model.

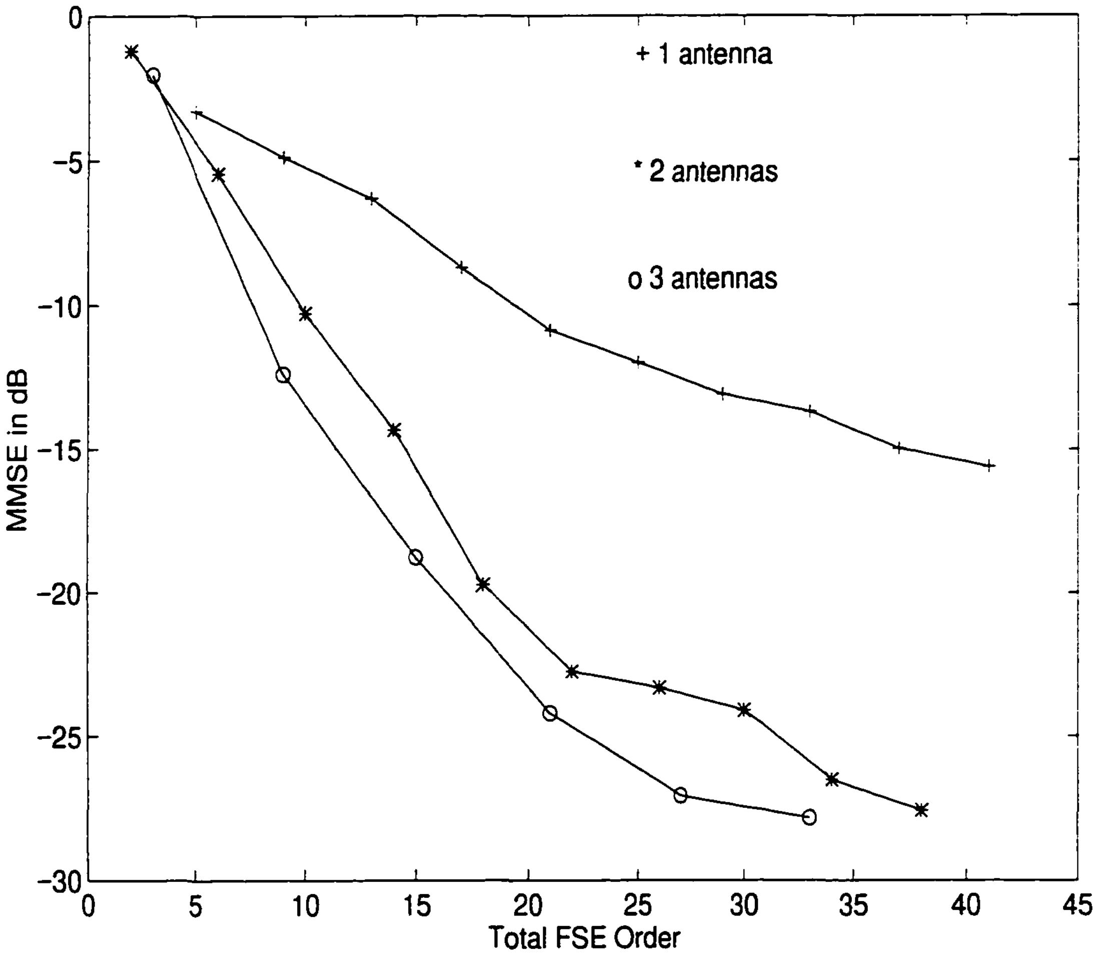

Figure 4.5 MMSE performance with chip-rate equalizers for the ch_2 model.

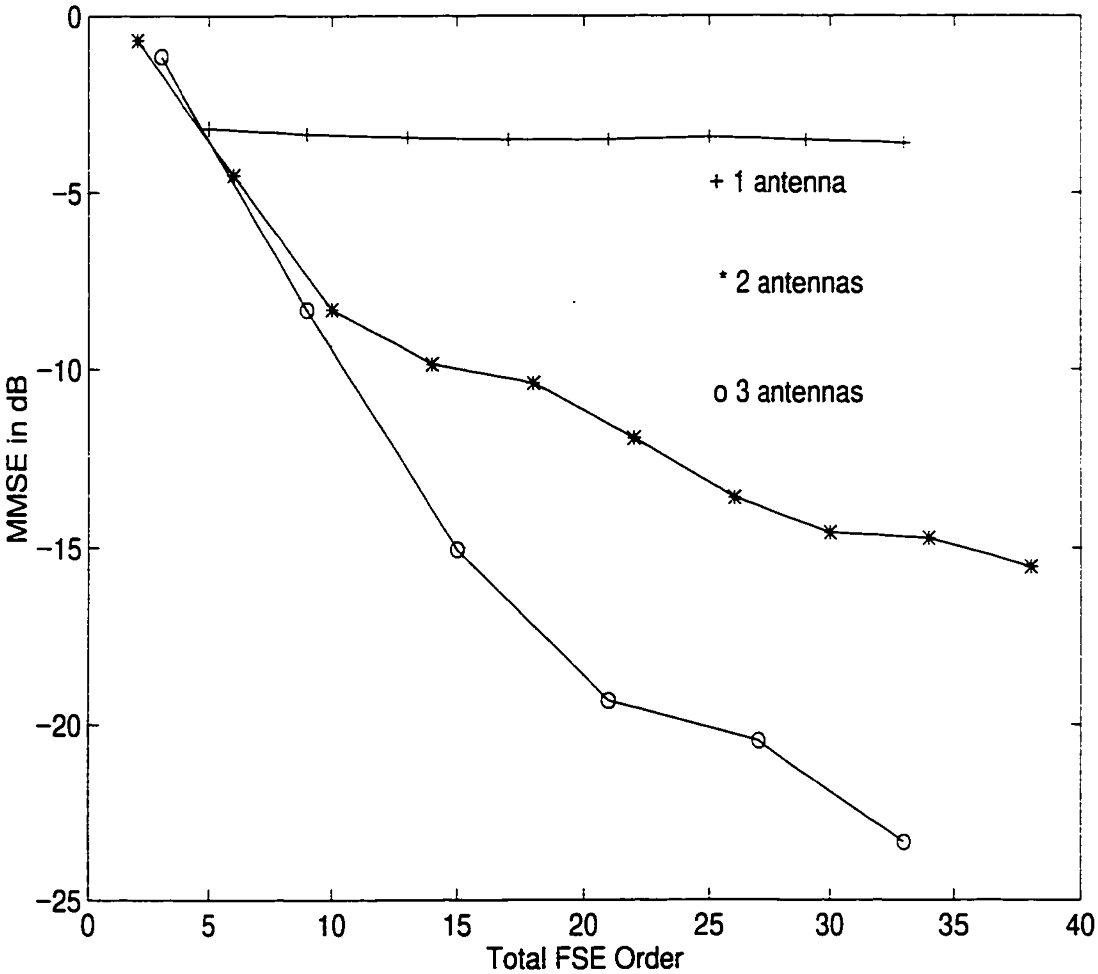

Figure 4.6 MMSE performance with half-chip-rate equalizers for the ch_1 model.

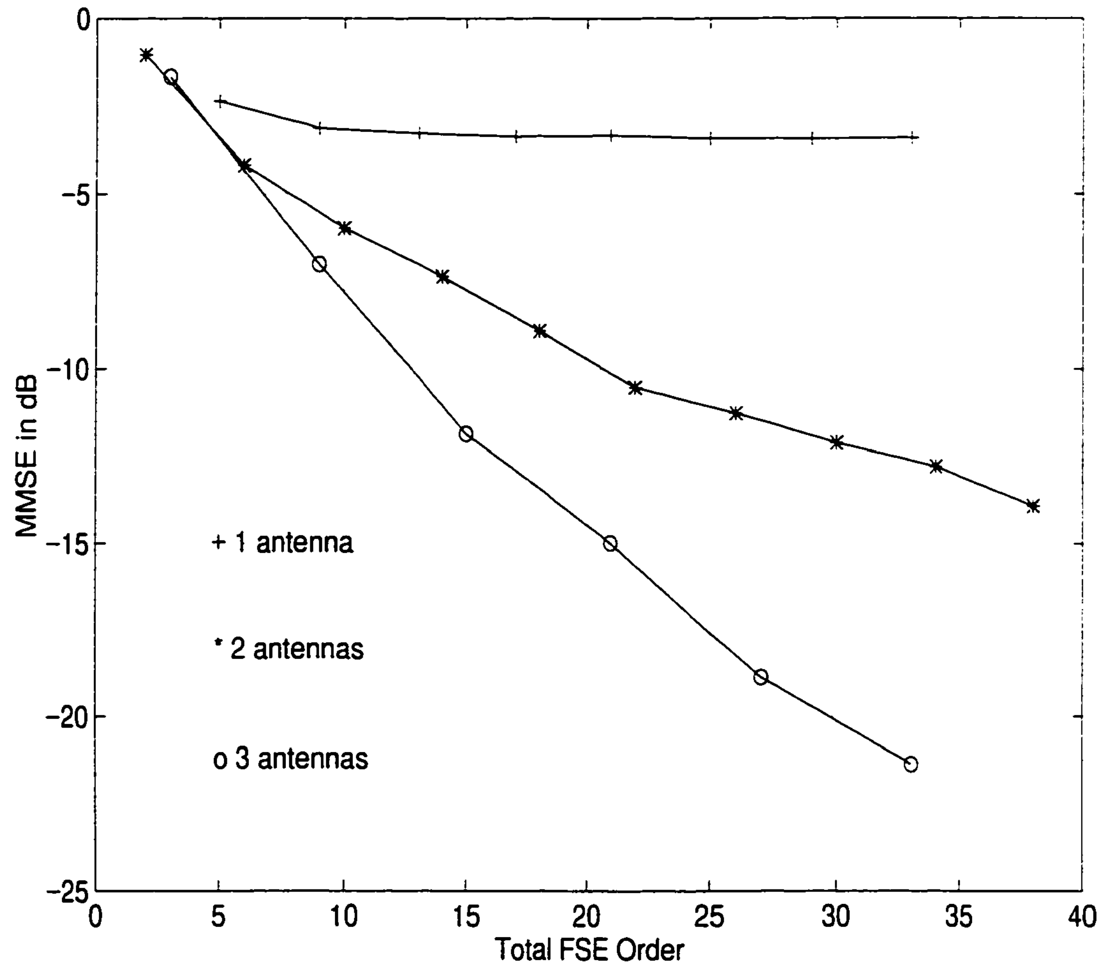

Figure 4.7 MMSE performance with half-chip-rate equalizers for the ch_2 model.

tem, it is likely that the complexity of error-correction coding schemes will be lesser than without the MAME system. In the case of half-chip-rate FSEs, the single antenna system does not have the capability to deal with the number of interferers. As a consequence, the performance does not improve noticeably as the order of the FSE is increased. These results illustrate that the MAME system can be used to boost interference suppression performance over that achieved with a single FSE and thus increase the capacity of the CDMA system.

The plots also illustrate some interesting characteristics of the MAME system. For example, it can be noticed that the performance of the 2- and 3-antenna systems with chip-rate FSEs is not significantly different. This is due to the fact that the multiple-antenna systems with chip-rate FSEs have *more than needed interference suppression capability* for the CDMA system considered here. Their limitations are the finite filter order and the noise. The 2- and 3-antenna systems can, in theory, suppress 15 and 23 interferers, respectively, whereas the system modeled has only 7 interferers. It is therefore clear that these systems have access to more diversity branches than necessary for tackling the interference. These can be used effectively provided that enough processing capability is available, i.e., a sufficient number of FSE taps is used at each antenna. It should be noted that for a given abscissa value, a system with fewer antennas will have better capability to process the diversity branches because of the higher-order FSE. This is the reason for the close tracking in performance of the 2- and 3-antenna systems and this trend has been observed for similar conditions which have been investigated [46]. Note that with the ch_1 model, there are some abscissa values for which the 2-antenna system has better performance than the 3-antenna system. This is because for the same abscissa value the 2-antenna system has better processing capability due to the higher order FSE used. However, there is no close matching in performance of the 2- and 3-antenna systems in Figs. 4.6 and 4.7 where half-chip-rate FSEs are used. Here, there is a clear difference in the MMSE curves as the number of antennas is increased. The 1-antenna system can, in theory, suppress only 3 interferers while the number of interferers is equal to 7. As a consequence, the performance of the 1-antenna system does not improve noticeably as the order of the FSE is increased. The 2- and 3-antenna systems can, in theory, suppress 7 and 11 interferers, respectively. As a consequence, the 3-antenna system has a noticeably better performance. The performance with the ch_1 model is clearly better than with the ch_2 model. This is because of the higher delay spread of the latter. The outage performance for the different cases which are shown in Figs. 4.8-4.11 follow a similar trend as the MMSE curves.

4.3.2 Effect of tap spacing

The tap spacing of the FSEs can crucially influence the performance as can be seen from the results presented in the previous section. This is clearly illustrated in Figs. 4.12 and 4.13 for the ch_1 and ch_2 models, respectively. It can be noticed that there is a performance degradation in all the cases when the tap spacing is increased. However, multiple-antenna systems with wider tap spacing can have a better performance than a single antenna system with a chip-rate FSE. This means that by using the MAME system, a designer has the flexibility in the choice of tap spacing of the FSEs. Moreover, as the number of antennas is increased, there is a wider range of tap spacings that can be used to achieve sufficient interference suppression performance.

4.3.3 Effect of receive filter

In most CDMA systems, the desired user's code sequence is used at the receiver for despreading the received signal before detection. Typically, the received signal is crosscorrelated with a local copy of the desired user's code sequence. Since cochannel users are assigned different code sequences, the crosscorrelation properties of the code sequences crucially determine the CCI suppression performance. However, we have used an SRRC lowpass filter (LPF) at the receiver until this stage and no knowledge of

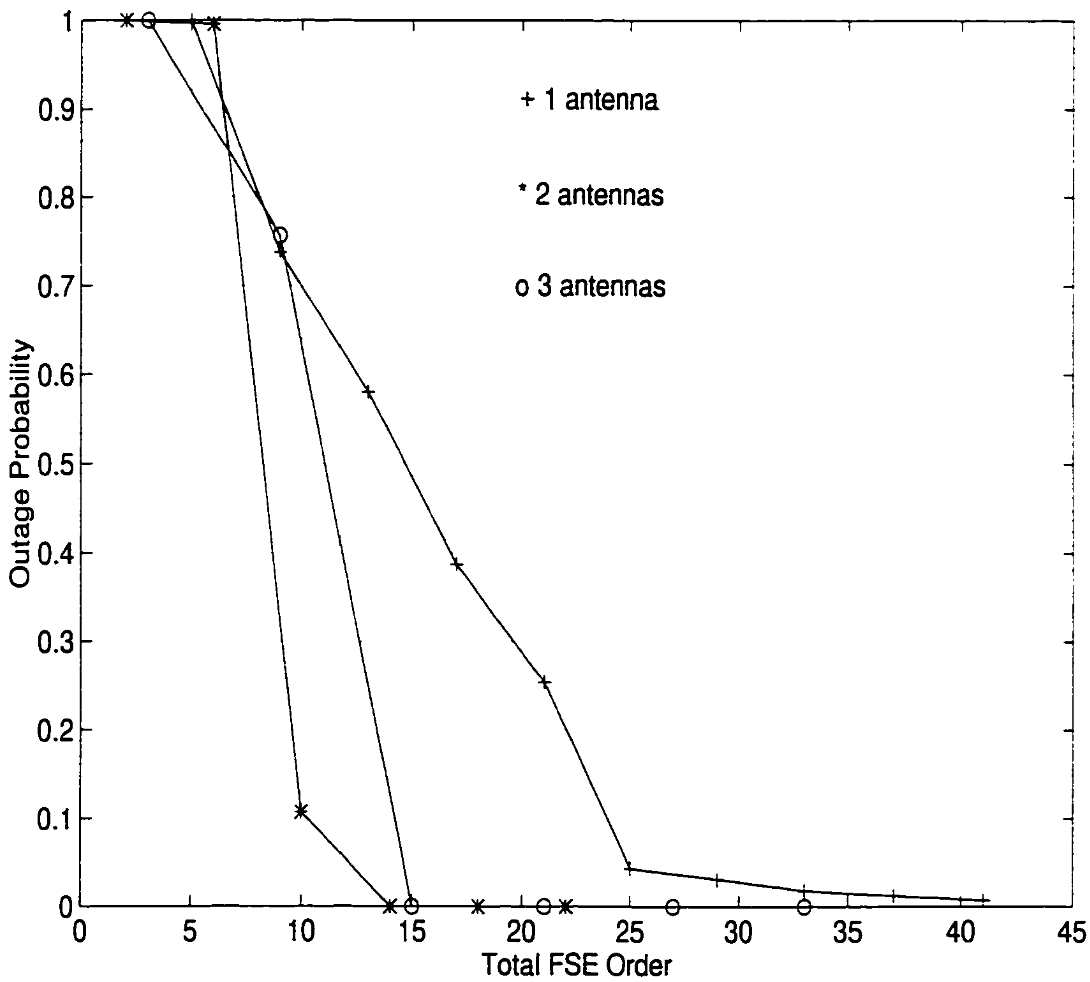

Figure 4.8 Outage performance with chip-rate equalizers for the ch_1 model.

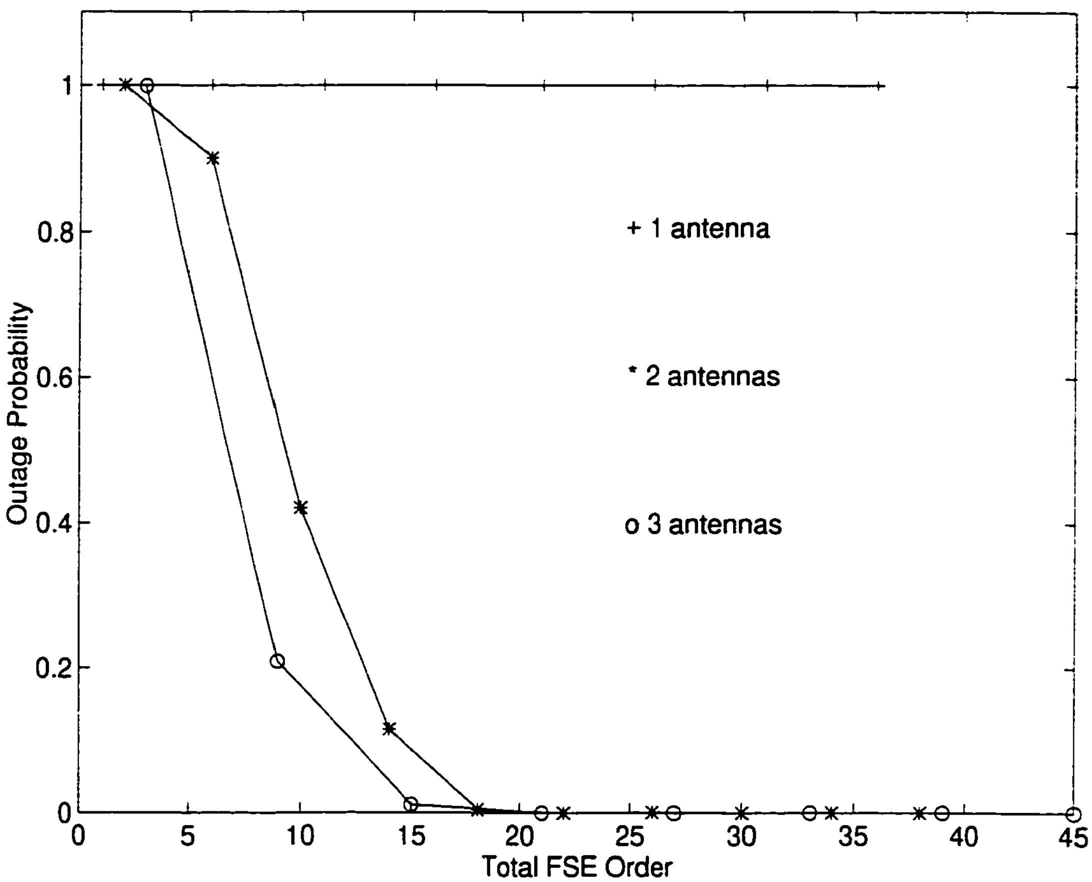

Figure 4.9 Outage performance with chip-rate equalizers for the ch_2 model.

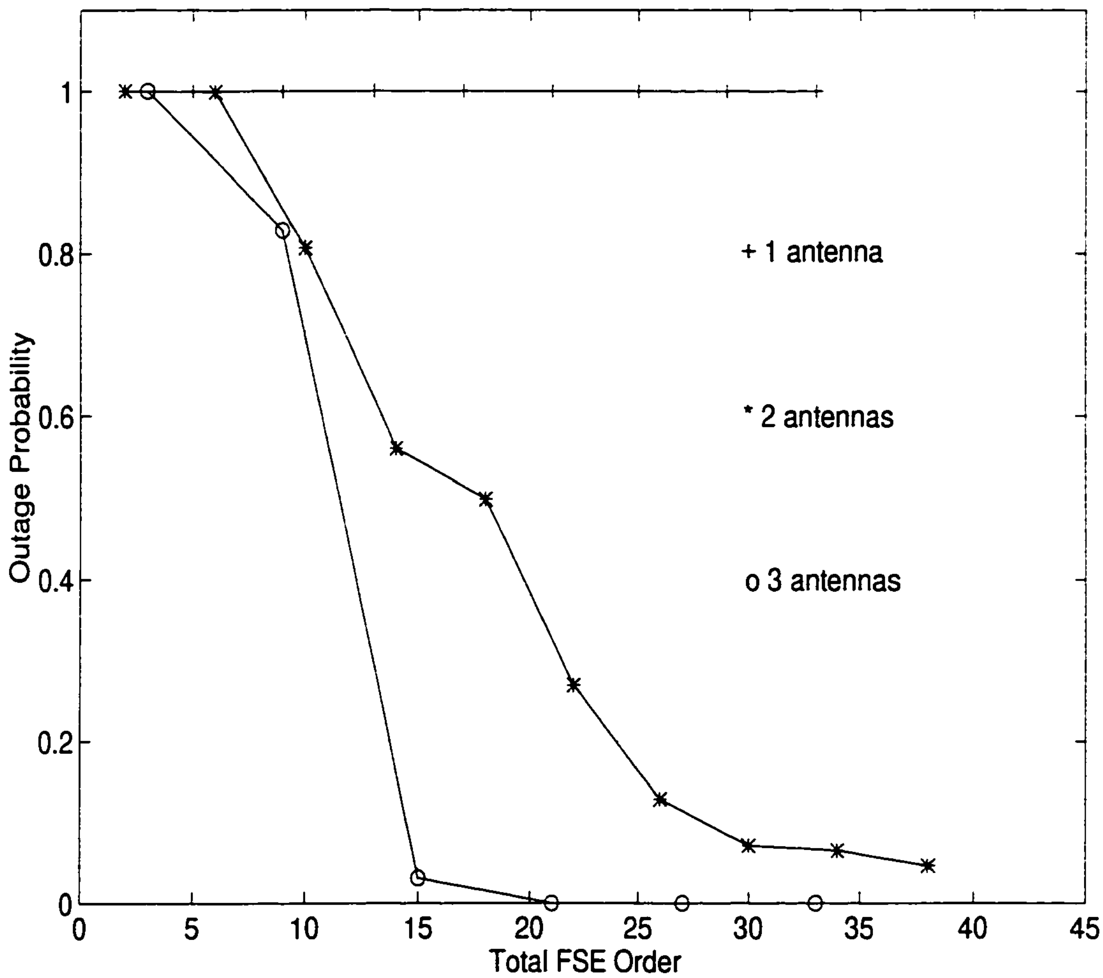

Figure 4.10 Outage performance with half-chip-rate equalizers for the ch_1 model.

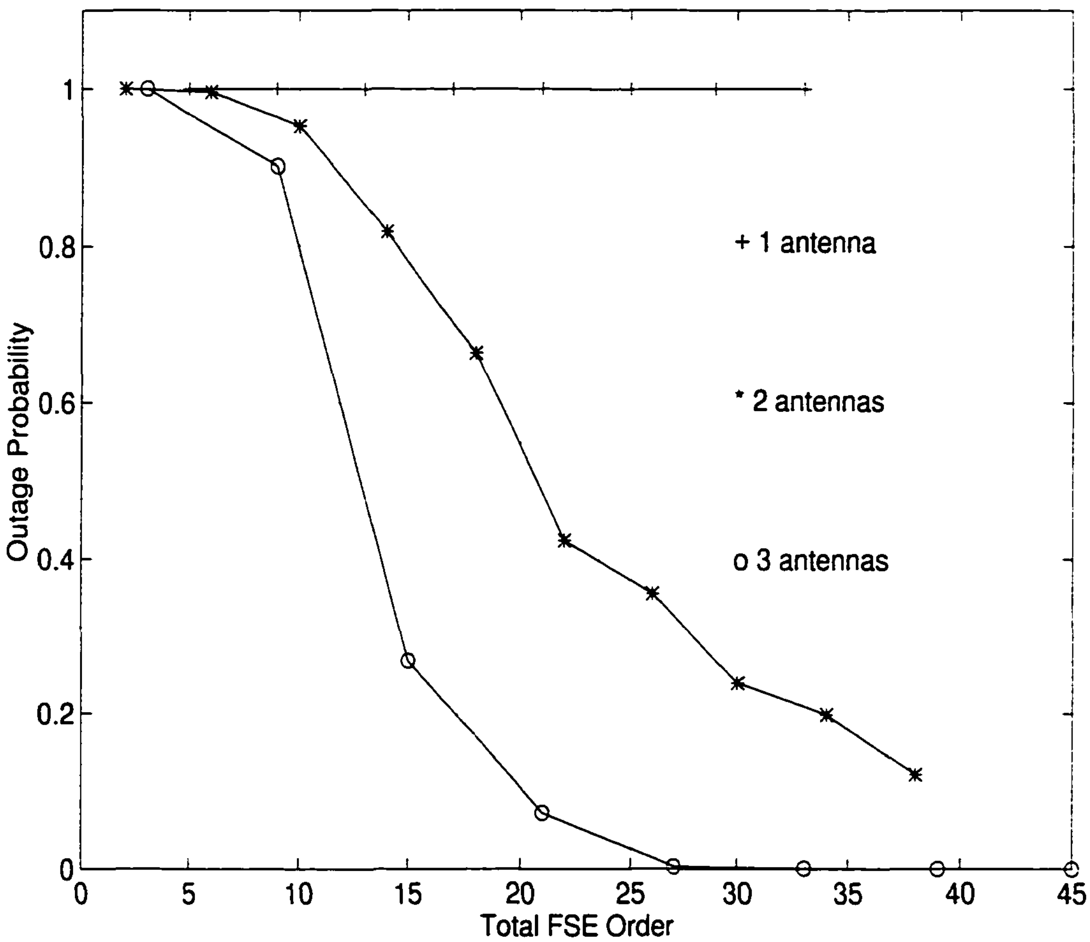

Figure 4.11 Outage performance with half-chip-rate equalizers for the ch_2 model.

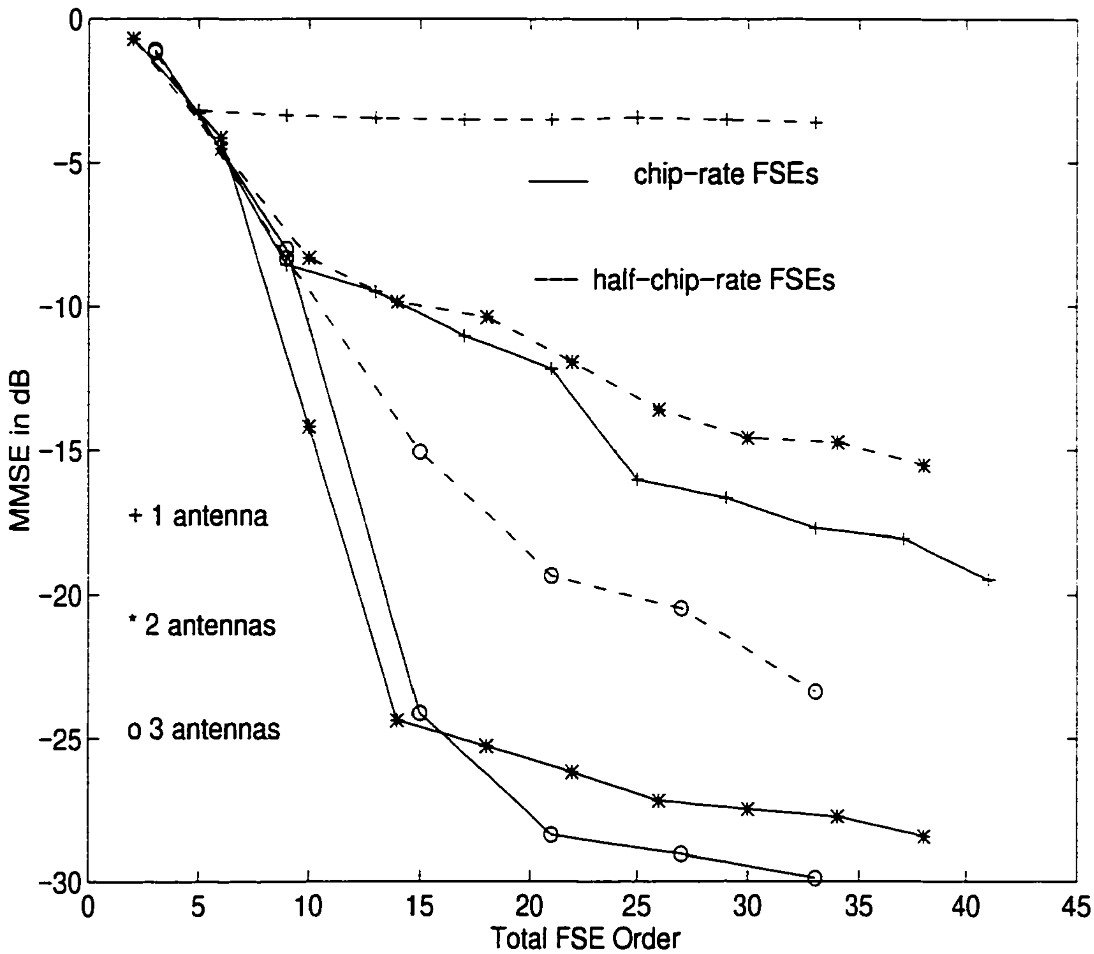

Figure 4.12 Effect of tap spacing on performance for the ch_1 model.

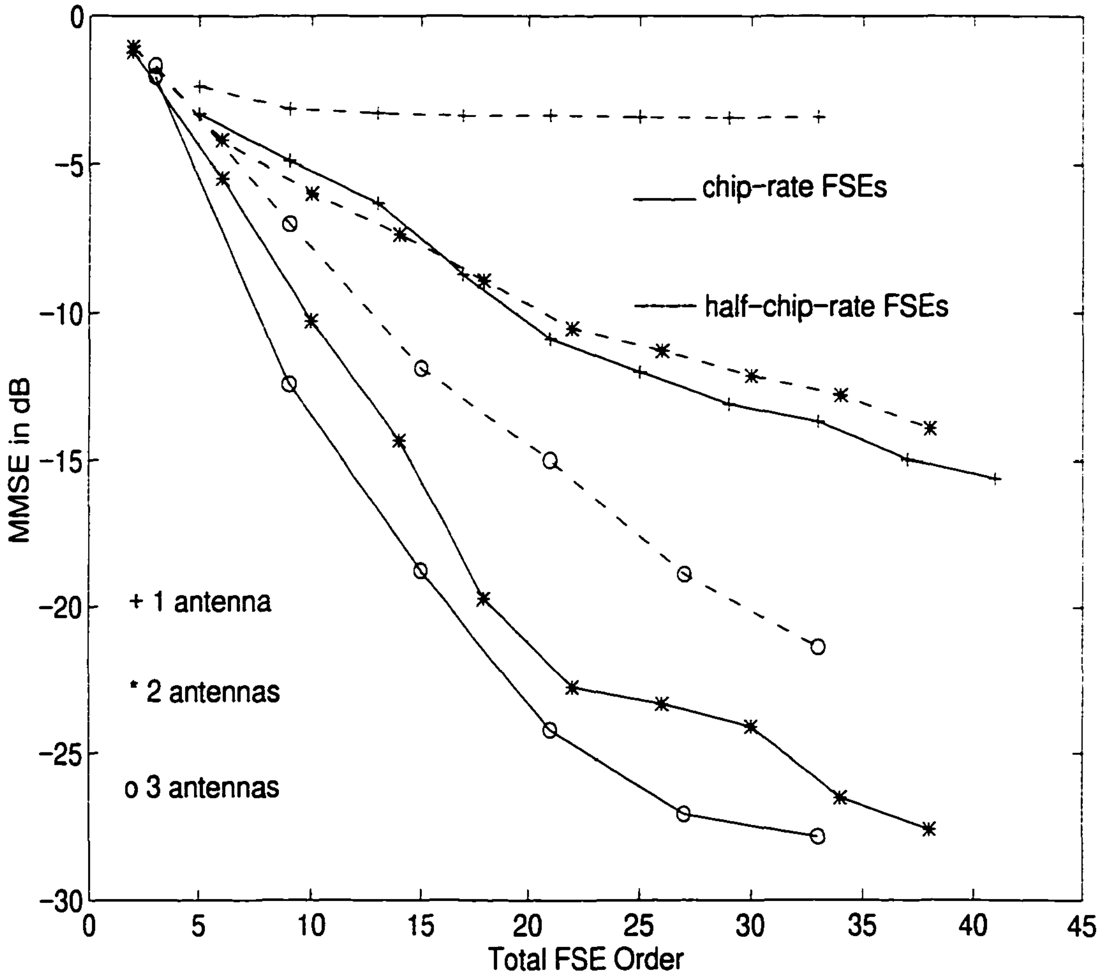

Figure 4.13 Effect of tap spacing on performance for the ch_2 model.

code sequences at the receiver is assumed. Such an approach has been investigated in [16]. It should be noted that the MAME system is specifically proposed to counteract interference and this forms the motivation for investigating the LPF based strategy.

The comparison of the performance with the SRRC LPF and with a filter matched to the desired user's code sequence for a 2- and 3-antenna system with half-chip-rate and chip-rate FSEs, respectively, is illustrated in Figs. 4.14 and 4.15. We shall use the same 2 systems for illustrating various results unless otherwise specified. It can be seen from the plots that the performance with the LPF is better than that with the matched filter. The better performance is *most likely* due to the fact that the LPF is less biased against interfering users. As a consequence, the combined channel and cochannel impulse responses are more conducive to achieving better performance. It should be noted that the results might vary in different conditions (processing gain, code sequences, channel models etc.). We have investigated several conditions and the performance using the SRRC LPF has been better than that with the matched filter. Hence, we have used the SRRC LPF as the RXF in this work. We shall elaborate on this subject in Chapter 6.

4.3.4 Effect of spectral correlation

It was shown earlier that the inherent spectral correlation present in user signals is the reason for the interference suppression capabilities of the MAME system. Here, we illustrate the effects of spectral correlation. The plots in Figs. 4.16 and 4.17 illustrate that the performance is better when simulated with interference than with respect to an equivalent amount of noise. This is because, interference was modeled as the sum of user signals each of which was simulated as a data-like signal which has inherent spectral correlation. Moreover, as explained earlier, the signals from a user at different antennas are spectrally correlated. However, noise signals at the different antennas are not spectrally correlated since independent noise sources are assumed at each antenna. Hence, in a MAME system where only symbol-rate equalizers are used, there will be

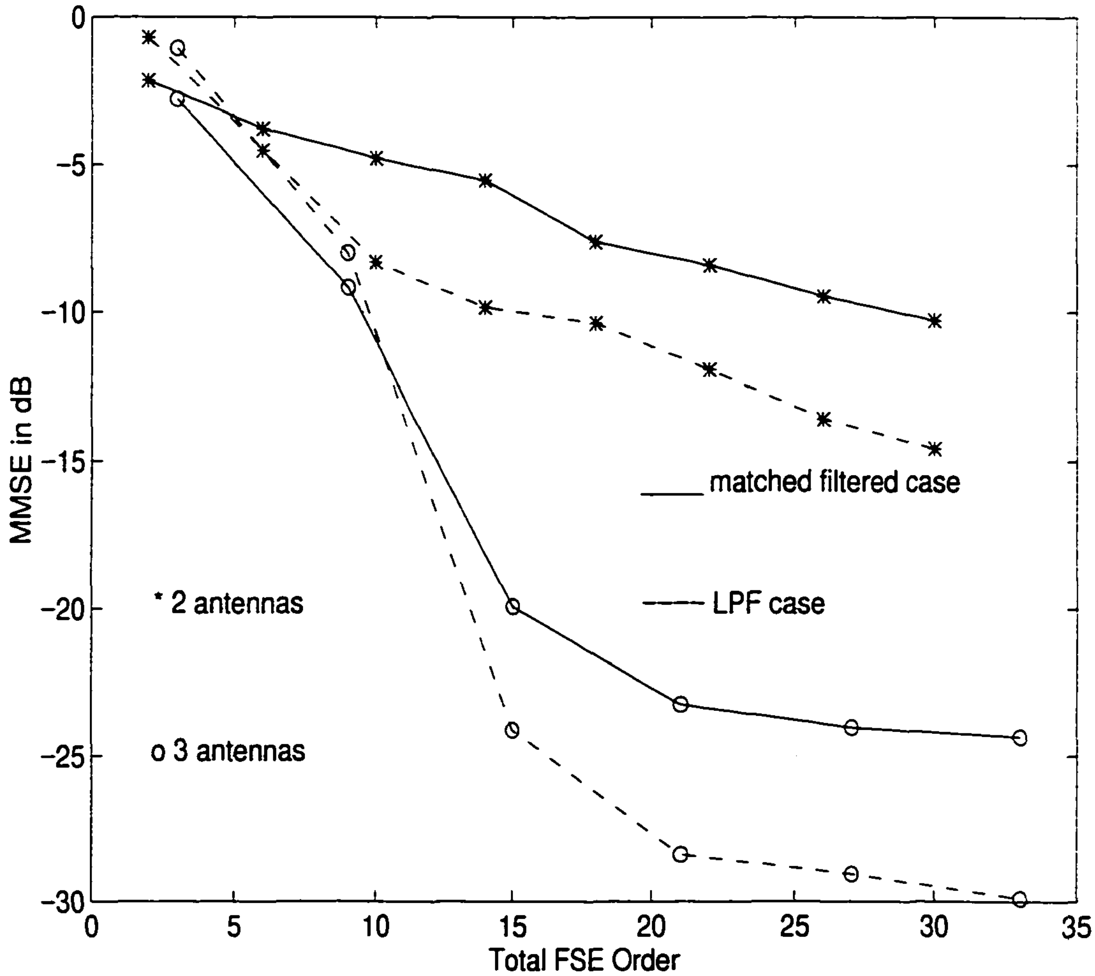

Figure 4.14 Effect of receive filter on performance for the ch_1 model.

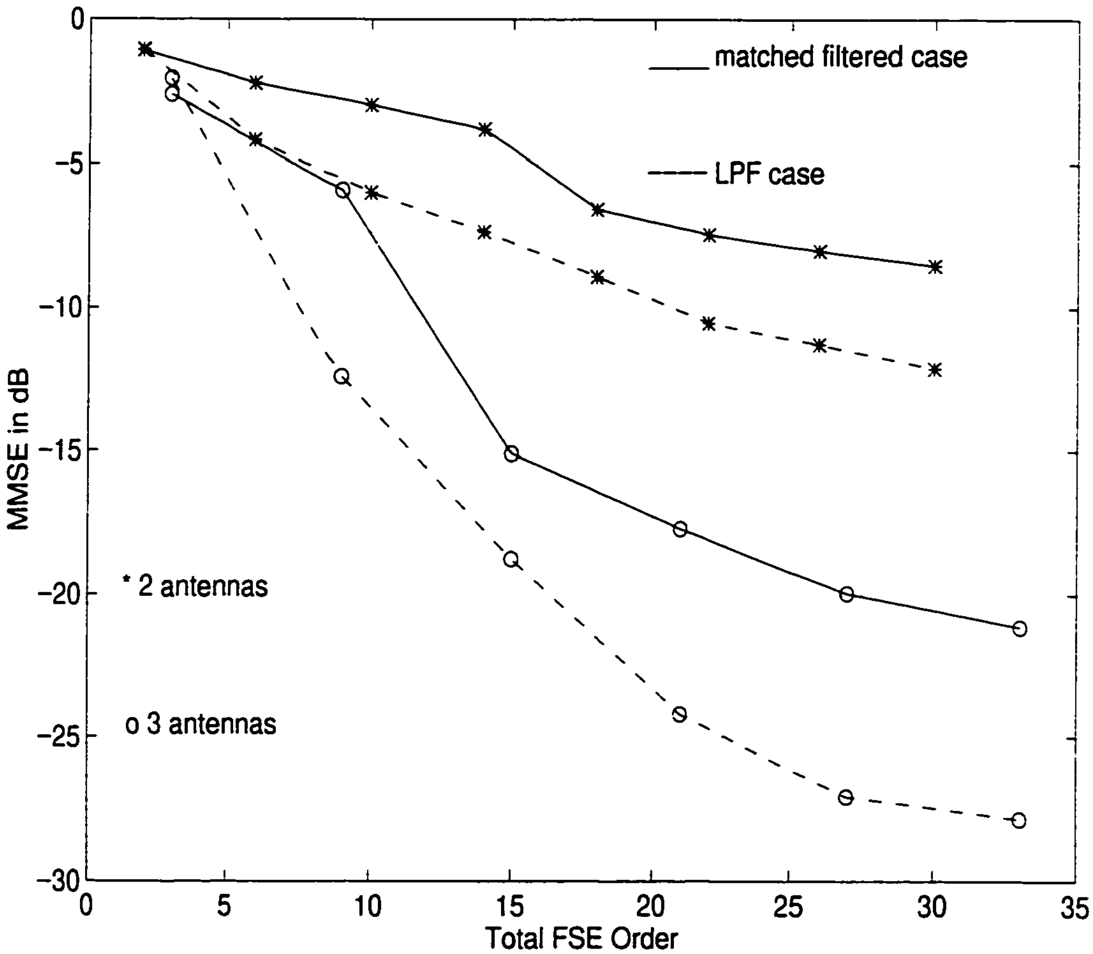

Figure 4.15 Effect of receive filter on performance for the ch_2 model.

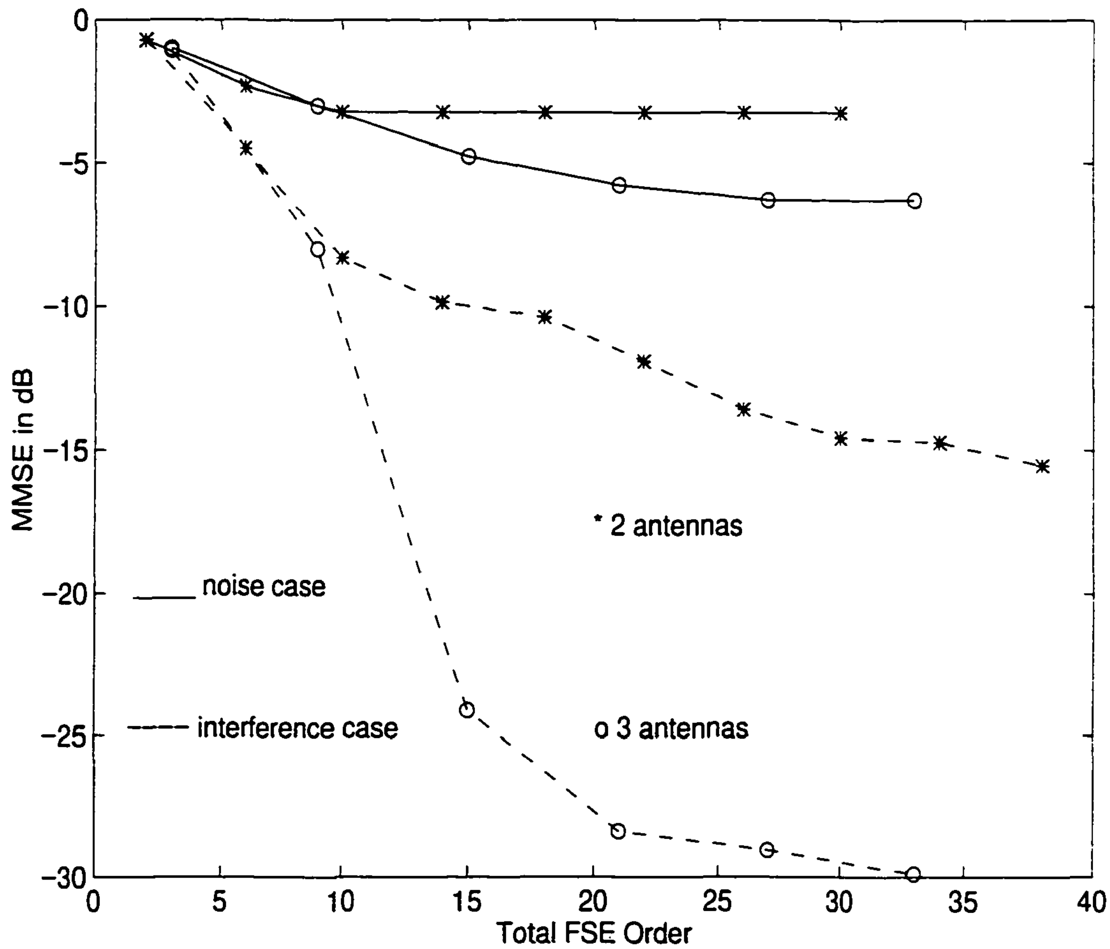

Figure 4.16 Effect of spectral correlation for the ch_1 model.

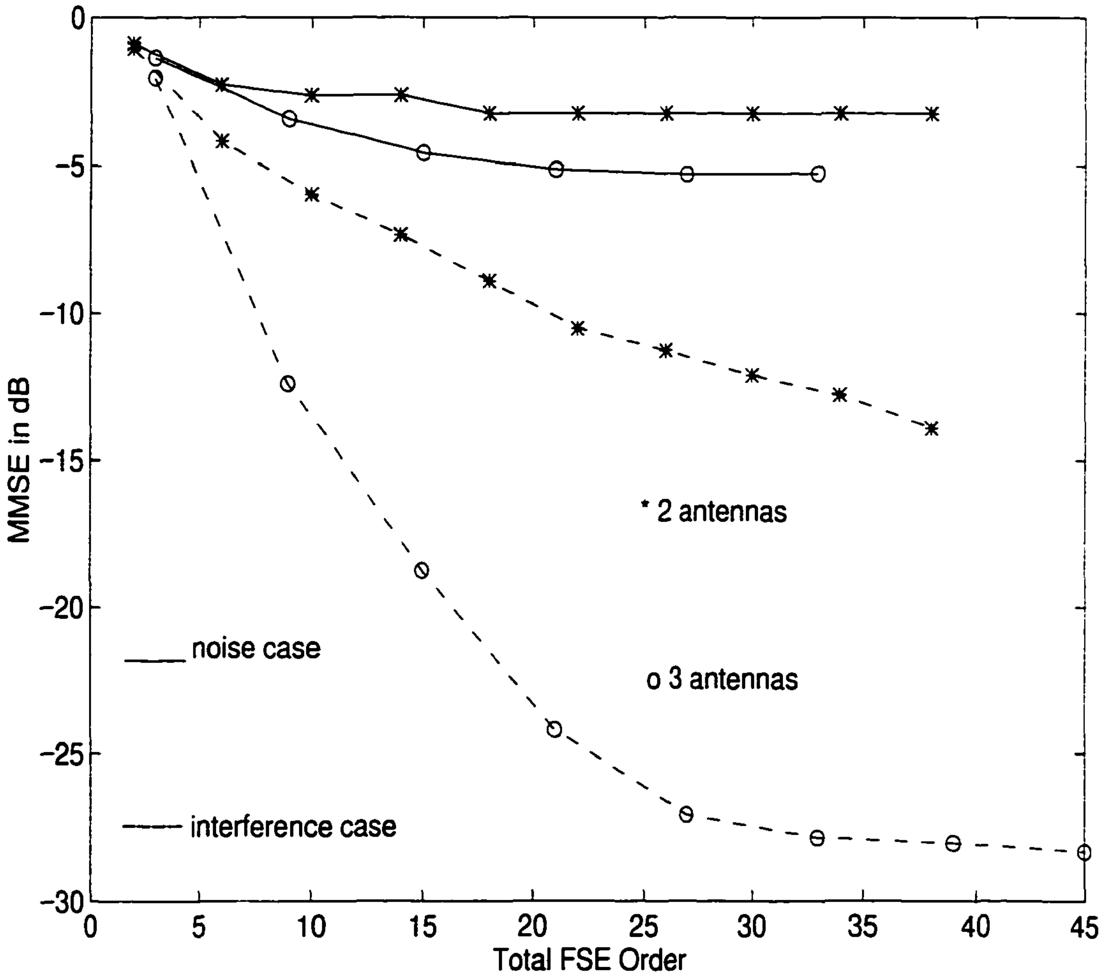

Figure 4.17 Effect of spectral correlation for the ch_2 model.

performance advantages when interference is simulated as compared with respect to an equivalent amount of noise. The performance of an 8-antenna system with symbol-rate equalizers demonstrates this point in Figs. 4.18 and 4.19. In this system, only the spectral correlation between signal components at the different antennas is used, and the performance is clearly better when studied in interference than with respect to an equivalent amount of noise.

These results illustrate that the spectral correlation present in user signals is the main reason for the superior interference suppression performance of the MAME system. One can also interpret these results using the argument that the zero-forcing conditions are not applicable for noise. In terms of diversity, these results demonstrate that there will be better performance when the diversity branches of the desired user's signal and each interferer's signal are spectrally correlated. The diversity will be less effective when there is no spectral correlation in the interferer's signal as is the case when interference is modeled as noise. In summary, the modeling of interference is crucial when studying the performance of the MAME system. By lumping all interference together as noise, performance enhancements which can be achieved will be lost.

4.3.5 Effect of noise

The signal-to-noise ratio (SNR) was assumed to be 20 dB at each antenna in all the previous experiments. The effect of increased noise power on the performance is illustrated in Figs. 4.20 and 4.21 where the SNR was simulated to be 0 dB. It can be seen from these plots that the performance gains possible using multiple antennas, which are illustrated for a higher SNR value in Figs. 4.4 and 4.5, are reduced as the SNR is decreased. Hence, the SNR crucially determines the performance gains achievable using the MAME system and these gains can be expected to decrease as the SNR is decreased. In most studies on CDMA systems, noise and interference are usually lumped together and hence the SNR values quoted in these studies are not valid in the context of this work. Our main motivation is to demonstrate the interference suppres-

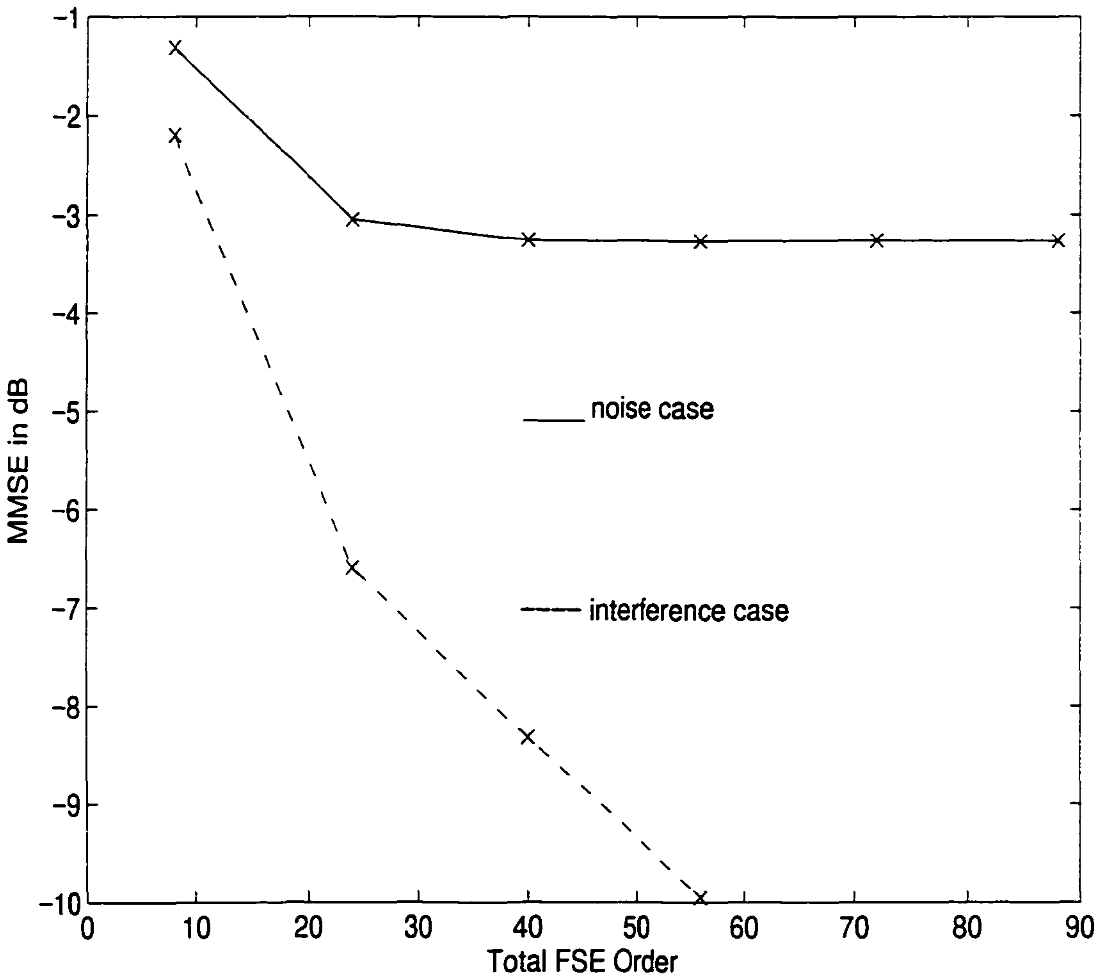

Figure 4.18 Noise vs. interference performance comparison for an 8-antenna system with the ch_1 model.

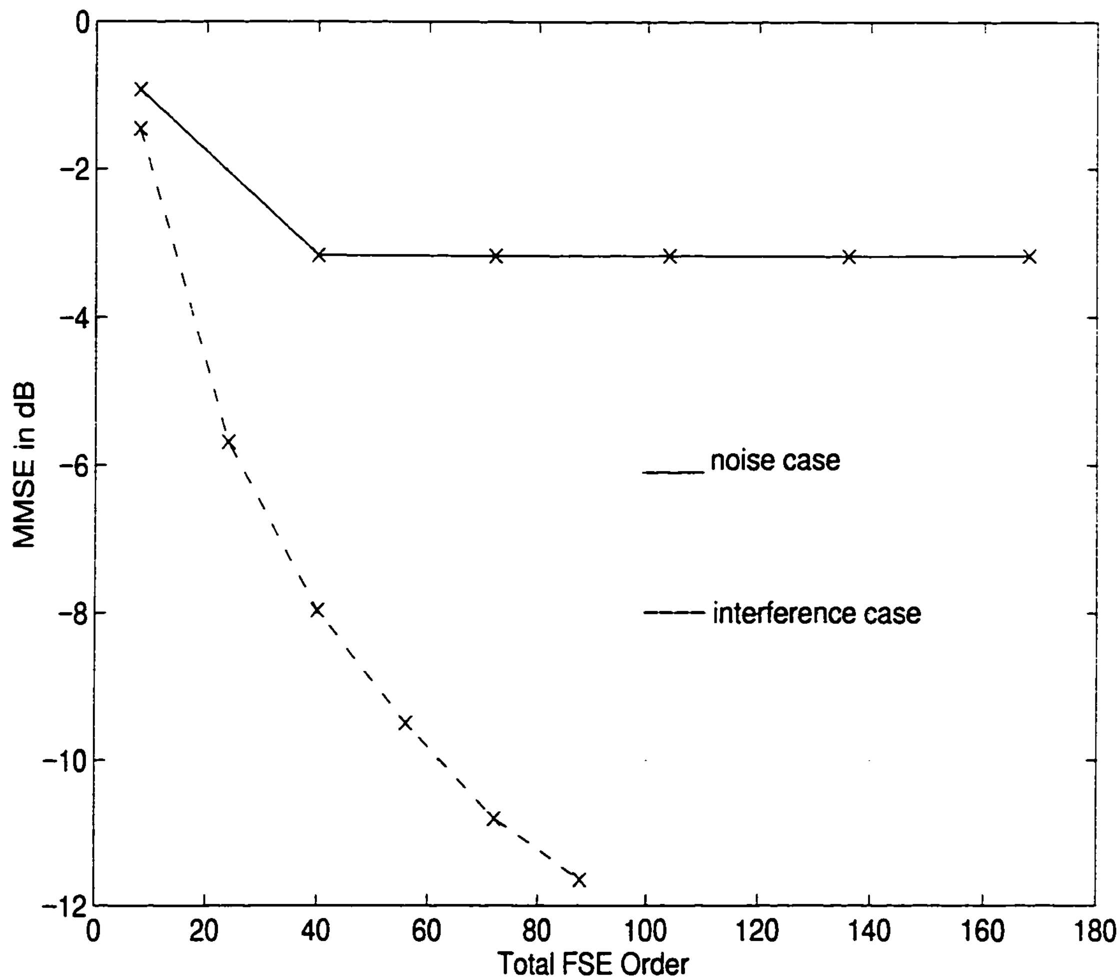

Figure 4.19 Noise vs. interference performance comparison for an 8-antenna system with the ch_2 model.

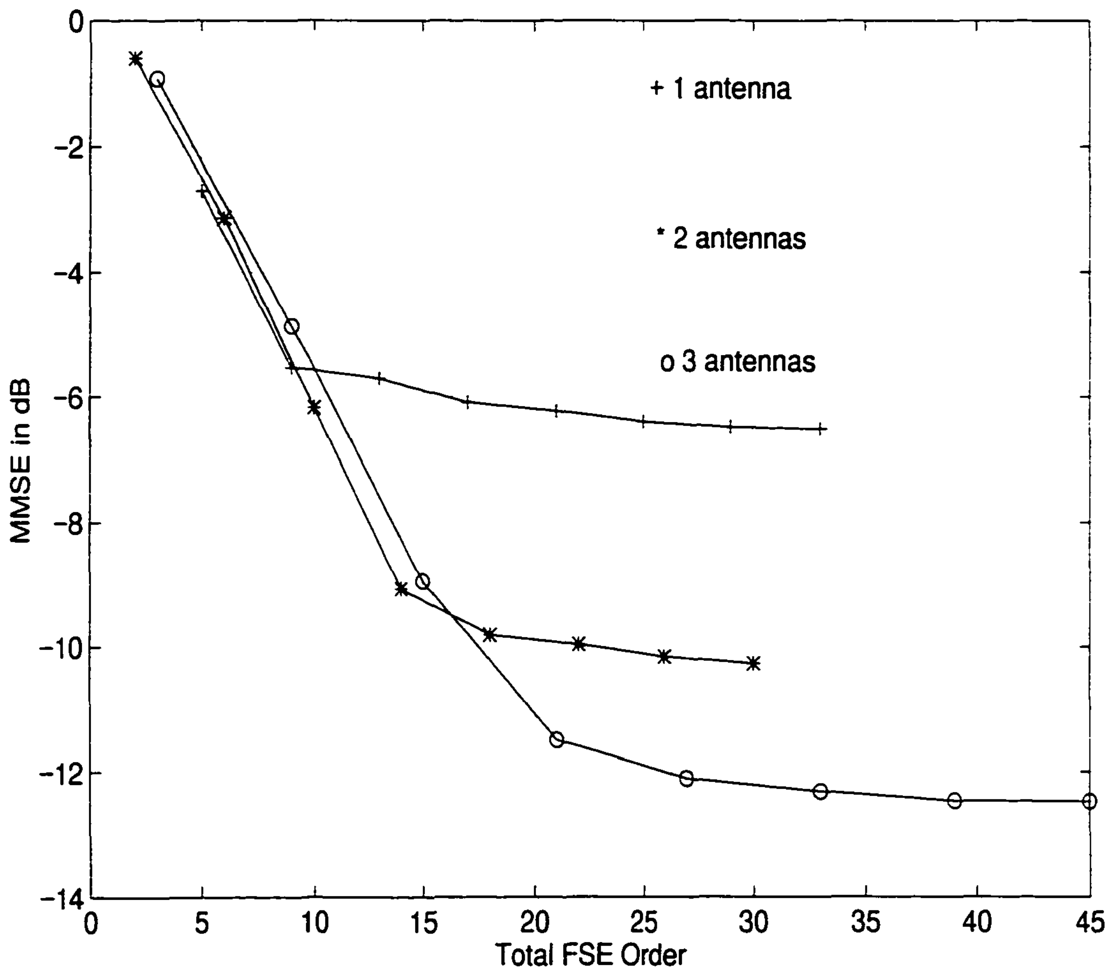

Figure 4.20 Effect of increased noise on performance for the ch_1 model.

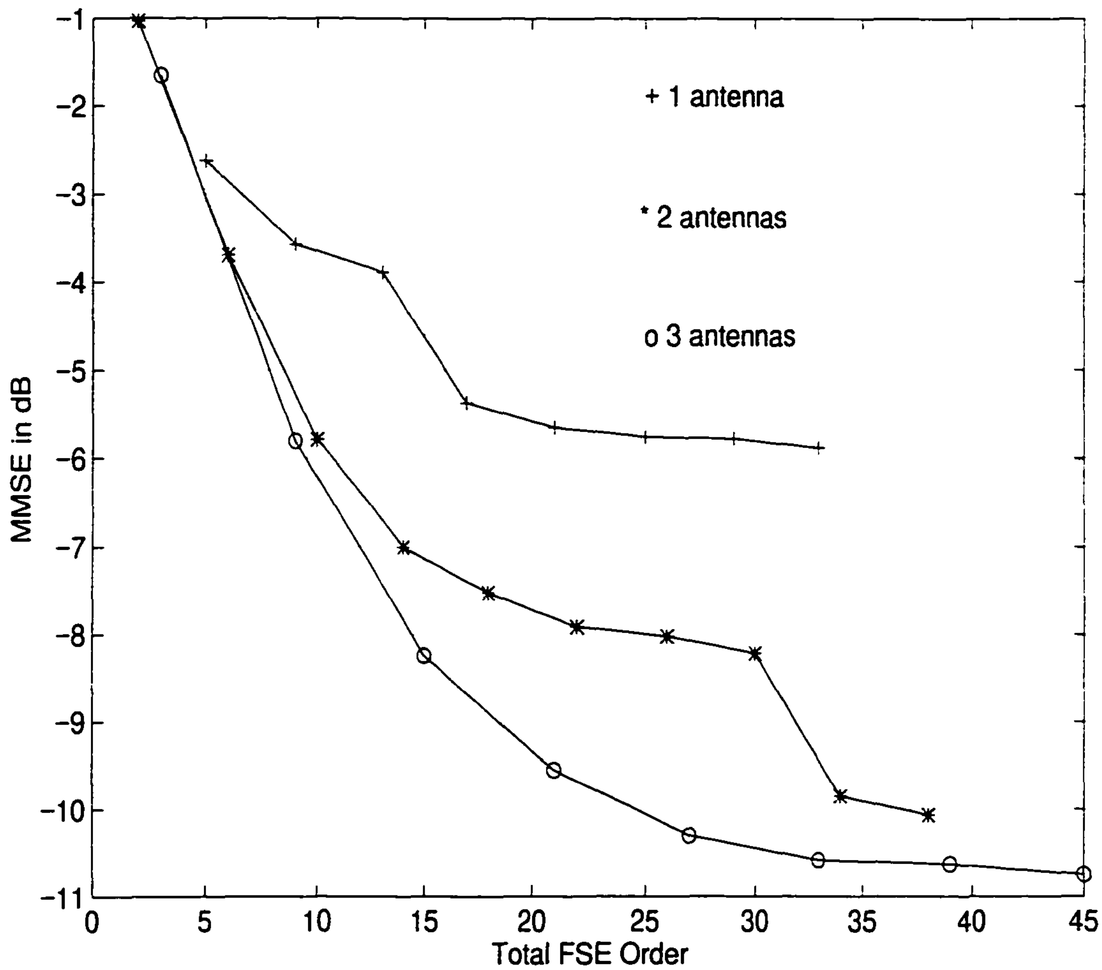

Figure 4.21 Effect of increased noise on performance with the ch_2 model.

sion capability of the MAME system. Hence, we have considered an SNR of 20 dB so that the effect of noise does not mask the interference suppression characteristics of the MAME system. Ultimately, noise will be the limiting factor as in the investigation of equalization for interference suppression in TDMA systems in [47]. The effect of SNR on the performance of a 3-antenna system with chip-rate equalizers illustrates the effect of SNR on performance in Figs. 4.22 and 4.23.

4.3.6 Effect of diversity domains

We have seen that the MAME system can be interpreted as a dual-domain diversity combiner. The relative influence of the diversity domains is the focus of this section. We have simulated the performance of 4 different MAME systems: a 1-antenna system with chip-rate FSEs where eight bandwidth-domain diversity branches are processed; a 2-antenna system with half-chip-rate FSEs in which four bandwidth-domain branches are processed at each antenna; a 4-antenna system with FSEs which had a tap-spacing of $T_b/2$ in which two bandwidth-domain branches are processed at each antenna and an 8-antenna system with symbol-rate equalizers where eight spatial-domain diversity branches are used. Thus, in all the systems, the total number of diversity branches is the same and is equal to 8 and hence, in theory, all the systems have the same interference suppression capability. However, the diversity branches are obtained in different ways in the 4 systems and we move from a strictly bandwidth-domain diversity combiner in the case of the 1-antenna system to a strictly spatial-domain diversity combiner in the case of the 8-antenna system.

The performance of the 4 systems is compared in Figs. 4.24 and 4.25. Results illustrate that to obtain a better performance under the conditions considered, it is preferable to increase the tap-spacing factor of the FSEs than the number of antennas. Note that even though the performance of the 2-antenna system is better than the performance of the 1-antenna system at some points, it is most likely due to the wider tap spacing of the FSEs used in the 2-antenna system. For a *fair* comparison, the time

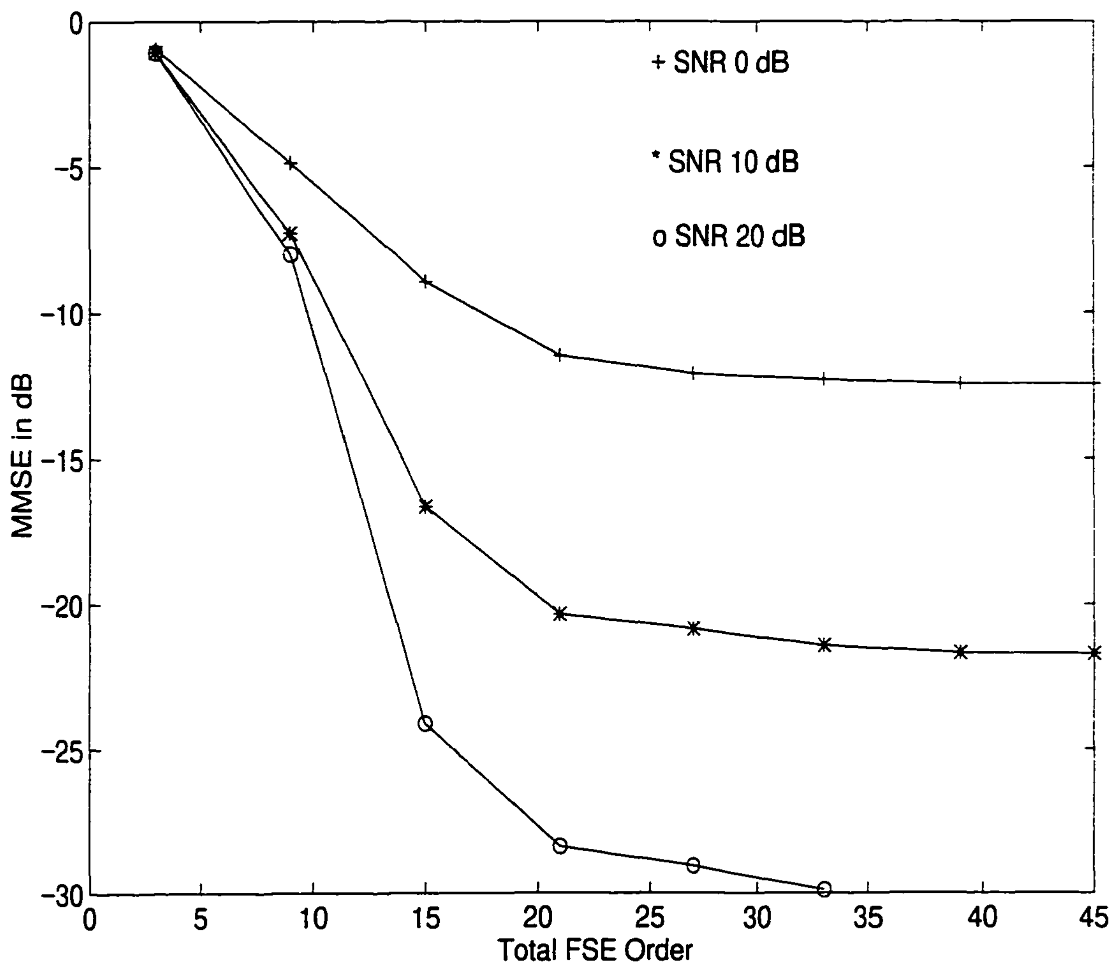

Figure 4.22 Effect of noise on performance of a 3-antenna system for the ch_1 model.

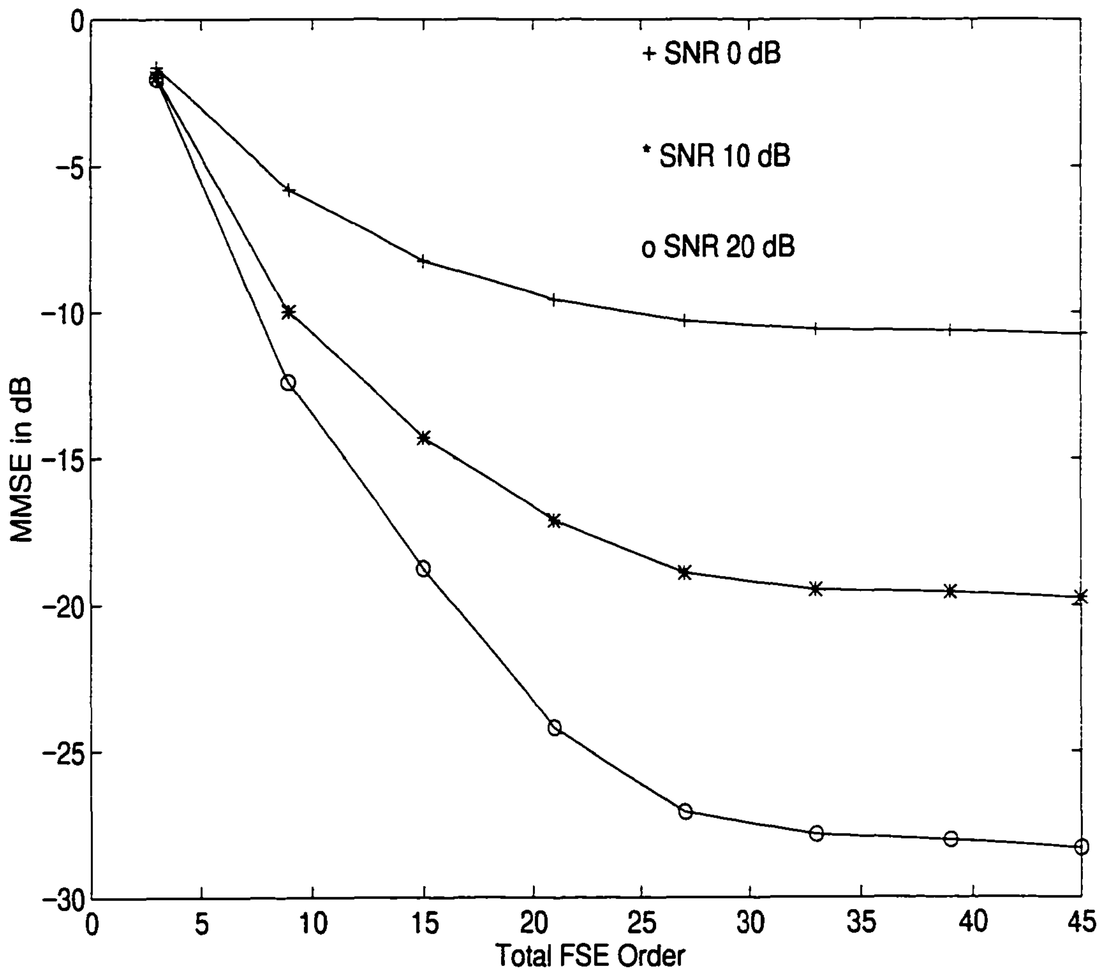

Figure 4.23 Effect of noise on performance of a 3-antenna system for the ch_2 model.

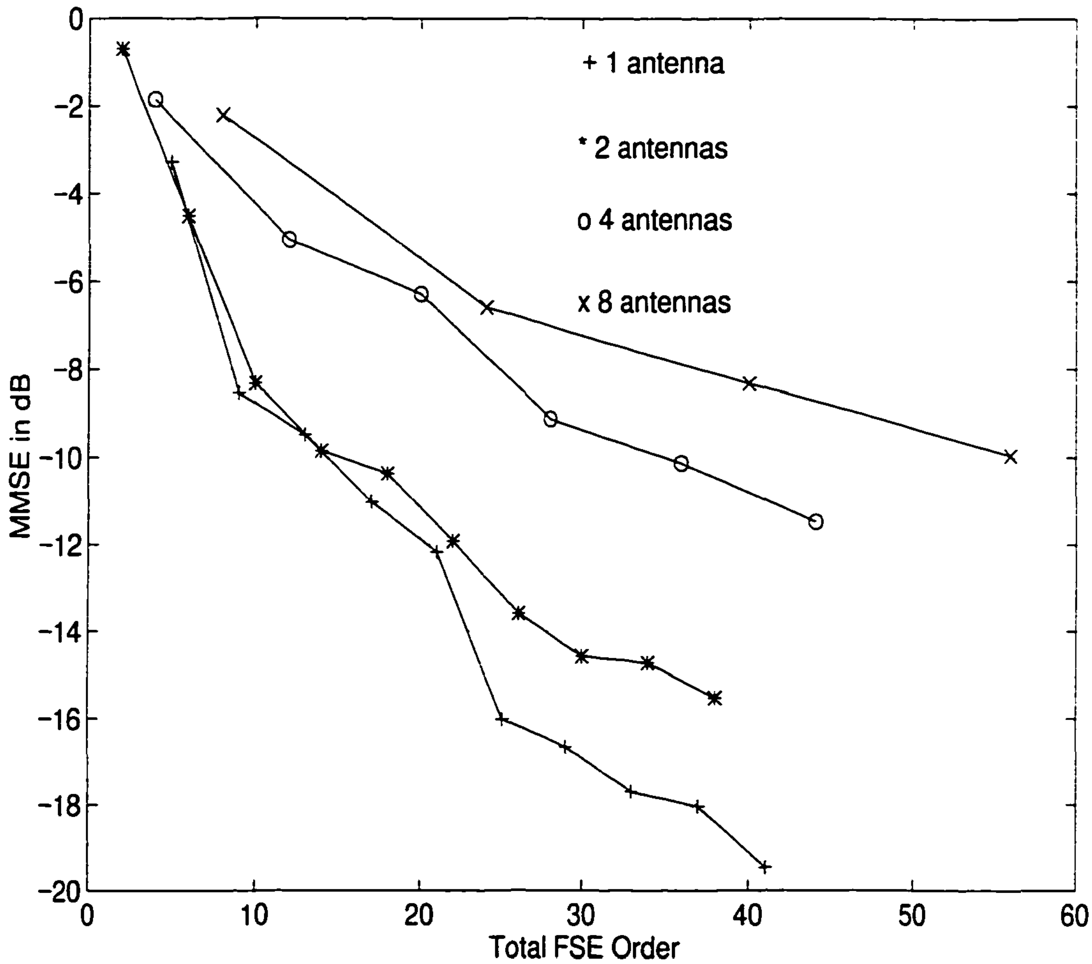

Figure 4.24 Influence of diversity domains on performance for the ch_1 model.

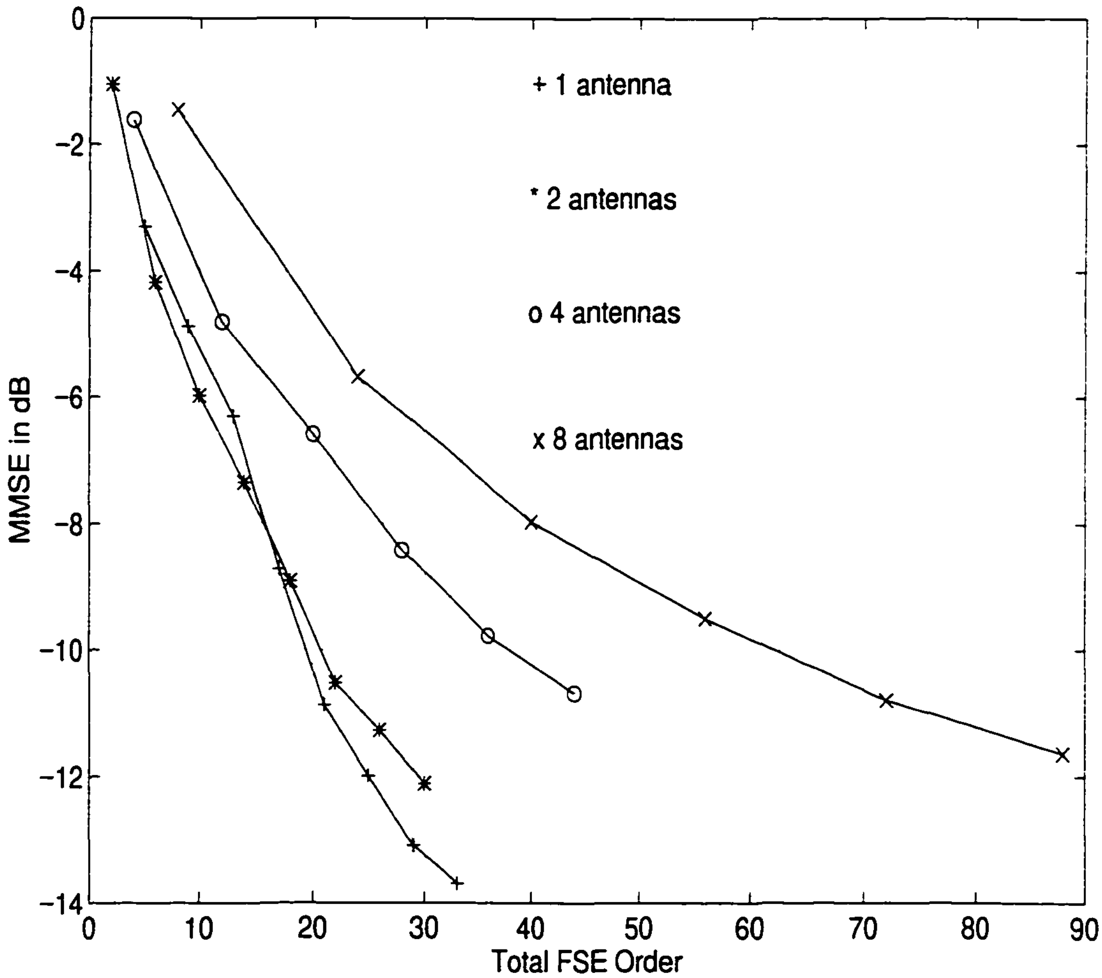

Figure 4.25 Influence of diversity domains on performance for the ch_2 model.

span of the FSEs should also be taken into account. For the same abscissa value, the FSEs in the 2-antenna system had twice the time span of the FSE used in a single antenna case. Therefore, for a particular abscissa value in the 1-antenna system, one has to consider the performance with an abscissa value which is reduced by half for the 2-antenna case. One can then notice that the performance of the 1-antenna system is clearly better. These results demonstrate that for the conditions considered, one can expect diminishing gains as the number of antennas is increased.

4.3.7 Effect of near-far condition

In many CDMA systems, the crosscorrelation properties of the code sequences determine the CCI suppression capability. Unlike in TDMA and FDMA systems, the performance of CDMA systems have been shown to be vulnerable to the varying power levels of different users [42]. We have shown earlier that, in theory, the interference suppression capability of the MAME system is immune to the near-far problem present in many CDMA systems. However, it *can* influence the MMSE performance and it is therefore considered in this section.

A sudden change in the power of a signal $S_k^m(t)$ (for particular user(s) and antenna(s)) can cause the near-far condition. In a wireless radio system operating in a multipath fading environment, as in an indoor wireless system, this condition can occur because of signal fading. Though this change does not affect the theoretical interference suppression capability, the MMSE performance will most likely be affected due to the use of finite-length filters and the presence of noise. The changes in the signal due to the near-far condition can affect the optimum solution and since there is an increase in the power of interference, a degradation in performance can be expected. However, this degradation is mainly because of using equalizers of finite order, i.e., if one could use infinite-length filters and there was no noise, there would be no degradation. This is because the near-far condition *does not* manifest as an increase in the number of interferers. This is an important point concerning interference suppression using the MAME system as compared with the conventional approach in most CDMA systems.

We have investigated the effect of near-far condition for two MAME systems. To simulate the near-far condition, we increased the power of an interferer by 20 dB by increasing the variance of the data corresponding to that user. This means that there is a 20 dB increase in the power of this interferer at all antennas. This is a worst-case situation, since with independent fading, one can expect the power of the signal to be different at different antennas. All other users were simulated to have equal power. The plots in Figs. 4.26 and 4.27 illustrate the effect of near-far condition on performance. It can be seen that there is a performance degradation due to the increased power of an interferer. However, the degradation is negligible compared to the 20 dB increase in power of the interferer. Moreover, the degradation in performance decreases as higher filter orders are used especially in the 3-antenna case. This is because, by using higher filter orders, the increased interference power can be dealt with in an improved fashion. These results demonstrate that by using the MAME system, the near-far condition does not manifest itself as an increase in the number of interferers. The order of the FSEs and the interference suppression capability of the particular MAME system can influence performance. In summary, it is expected that a MAME system with a superior interference suppression capability will be capable of dealing with the near-far condition more effectively.

4.4 Conclusions

The MMSE performance of the MAME system has been studied. The simulation model used to obtain the results was outlined. The MMSE performance under various conditions was then presented and discussed. The effects of number of antennas, tap spacing, receive filtering, noise power, spectral correlation, diversity domains, and the near-far condition were investigated. Results and discussions which were presented

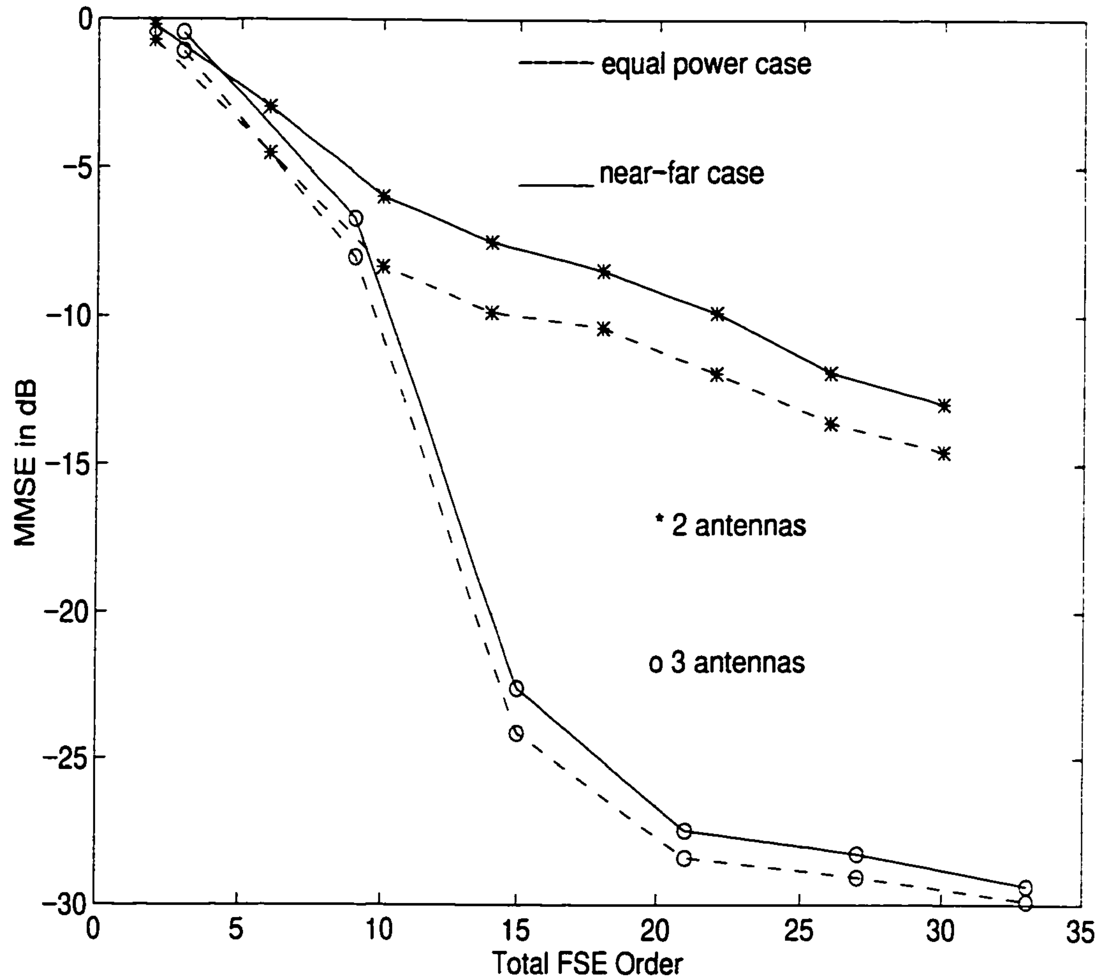

Figure 4.26 Performance in near-far conditions for the ch_1 model.

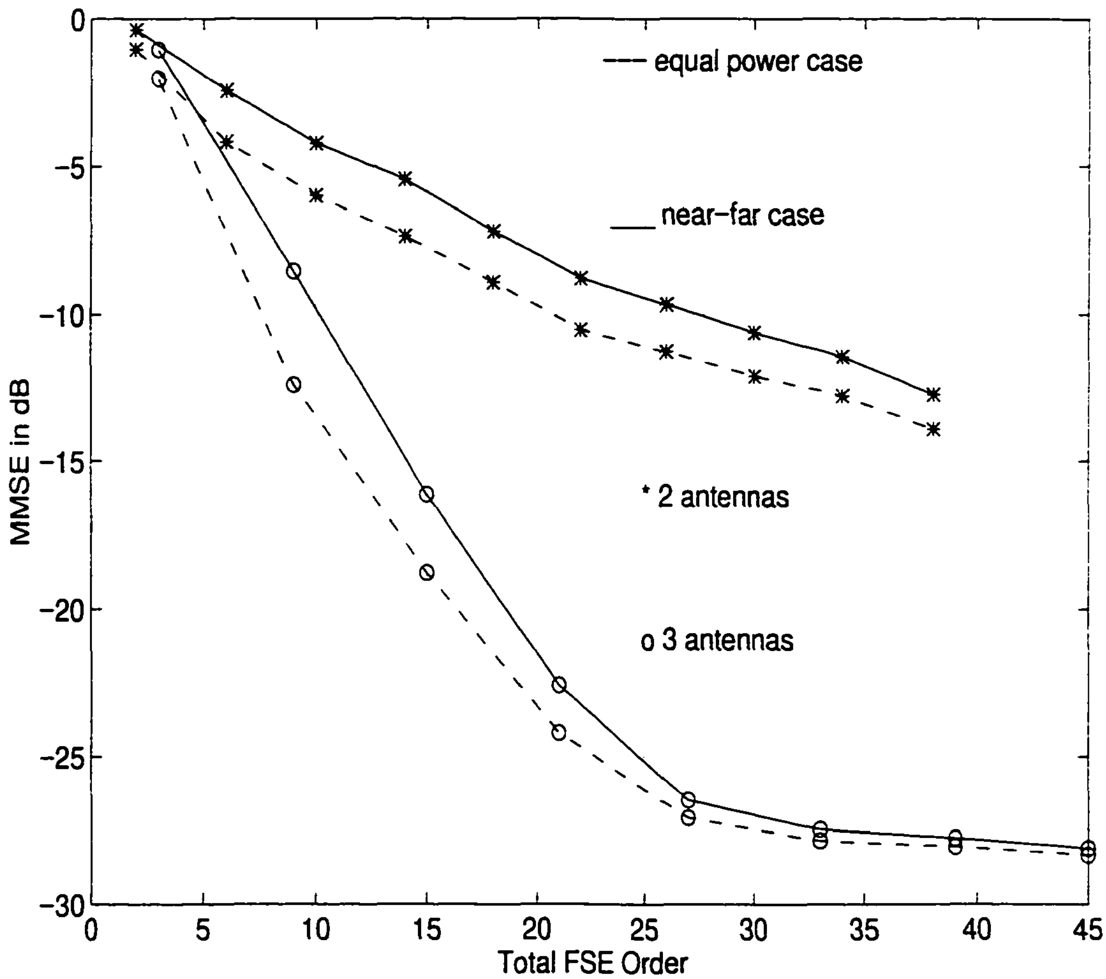

Figure 4.27 Performance in near-far conditions for the ch_2 model.

with respect to these topics give a clear idea of the properties and advantages of the MAME system. The MMSE performance is the first step in the investigation and leads to the discussion on the MSE performance.

Chapter 5

Adaptation and Bit-Error Rate Performance

5.1 Introduction

We have discussed the interference suppression capability of the MAME system in terms of the zero-forcing criterion, spectral correlation of user signals, and in terms of diversity. The MMSE performance has demonstrated many properties and advantages. In practice, the FSEs and the FBE would be implemented as adaptive filters. It is clear from Fig. 3.1 that all the equalizers in the MAME system are designed to use the same error for adaptation, and hence, they are considered together as a single adaptive filter. The MSE convergence performance of the adaptive filter is crucial in determining the practical utility of the MAME system. This is because of the time-varying multipath fading nature of the radio communications channel, which means that continuous adaptation of the tap coefficients is necessary to maintain satisfactory performance. The BER performance is the most important measure used in evaluating any digital communications system. Here, we examine the MSE and BER performance of the MAME system under various conditions.

5.2 Condition Number of the Autocorrelation Matrix

The MSE convergence performance is an important indicator in most adaptive filtering applications. This can be crucially dependent on the choice of adaptation algorithm and the condition number of the autocorrelation matrix. It has been noted that when interference is modeled as shown in Fig. 2.5, the condition number of $\boldsymbol{R}$ can be much higher when compared with the condition number in an equivalent amount of noise [47]. This effect is illustrated in Fig. 5.1 where the average condition number of the autocorrelation matrix is plotted for the two cases. The two MAME systems investigated in this experiment were a 2- and 3-antenna system with half-chip-rate and chip-rate FSEs, respectively. It can be seen that the average condition number in interference is much higher. This is because interference was modeled to include the filtering effects of the combined cochannels. As a consequence, the spectral composition of interference is different from AWGN that has a power spectral density which is nearly flat in the band of interest. It is well known that the condition number of the autocorrelation matrix is bounded by the maximum and minimum values of the power spectral density of the input signal and approaches this bound as the order of the FSE used increases [48]. This means that AWGN with an almost flat power spectrum is bound to result in a smaller condition number and this is confirmed by the plots in Fig. 5.1.

The influence of the number of users on the condition number varies depending on the tap spacing of the FSEs and the number of antennas. The general trend is that as the number of users increase, the condition number decreases approaching that of the noise case [49]. The interesting observation is that for different MAME systems, interference *manifests* itself as a noise-like signal under different conditions. In a MAME system which has a certain interference suppression capability, when the number of users in the CDMA system exceeds this theoretical capability, then the interference behaves like noise with respect to the condition number of $\boldsymbol{R}$. This can be seen by observing the plots in Figs. 5.2, 5.3, and 5.4 where the condition number is illustrated for different numbers of users. In a 1-antenna system with a half-chip-rate FSE, the difference in the condition number between the 1-user and the 4-user cases is much smaller when compared with the difference between the 1-user and 8-user cases, espe-

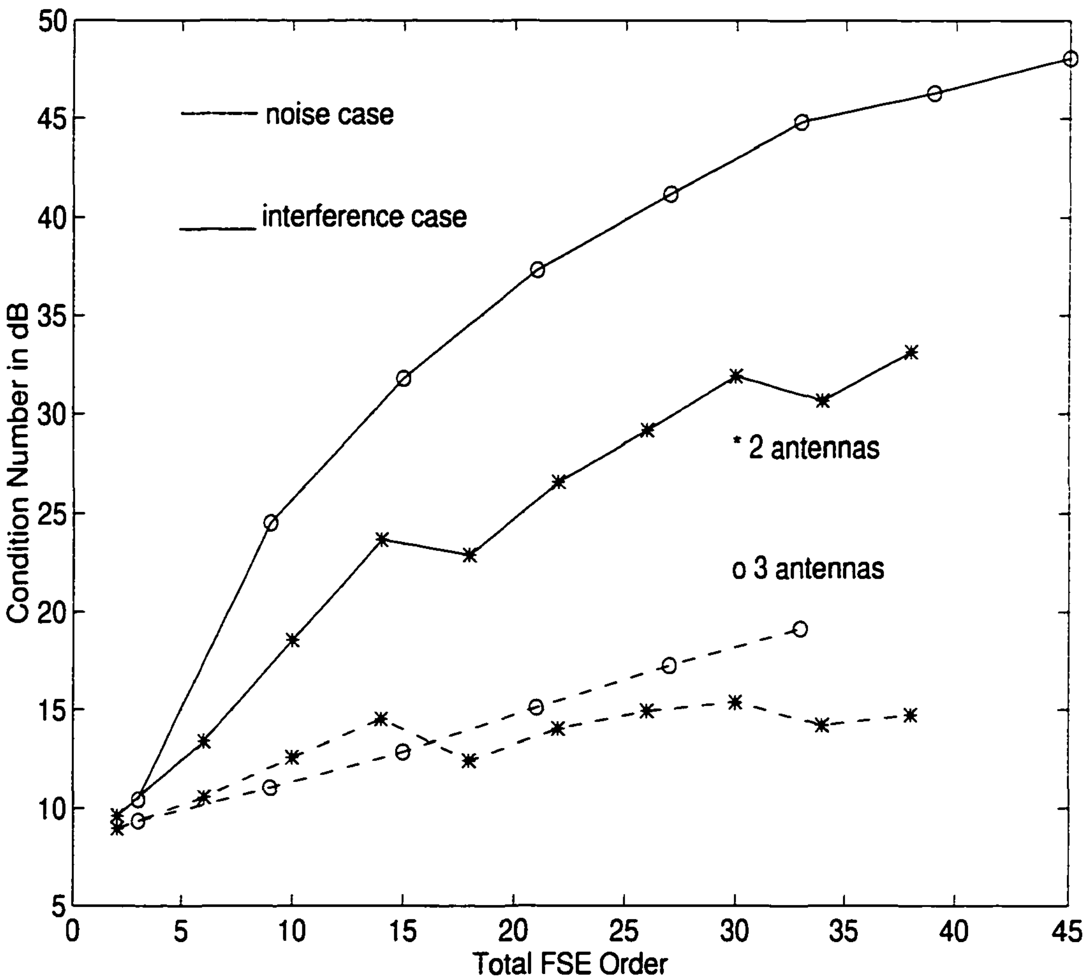

Figure 5.1 Effect of interference modeling on the condition number of the autocorrelation matrix.

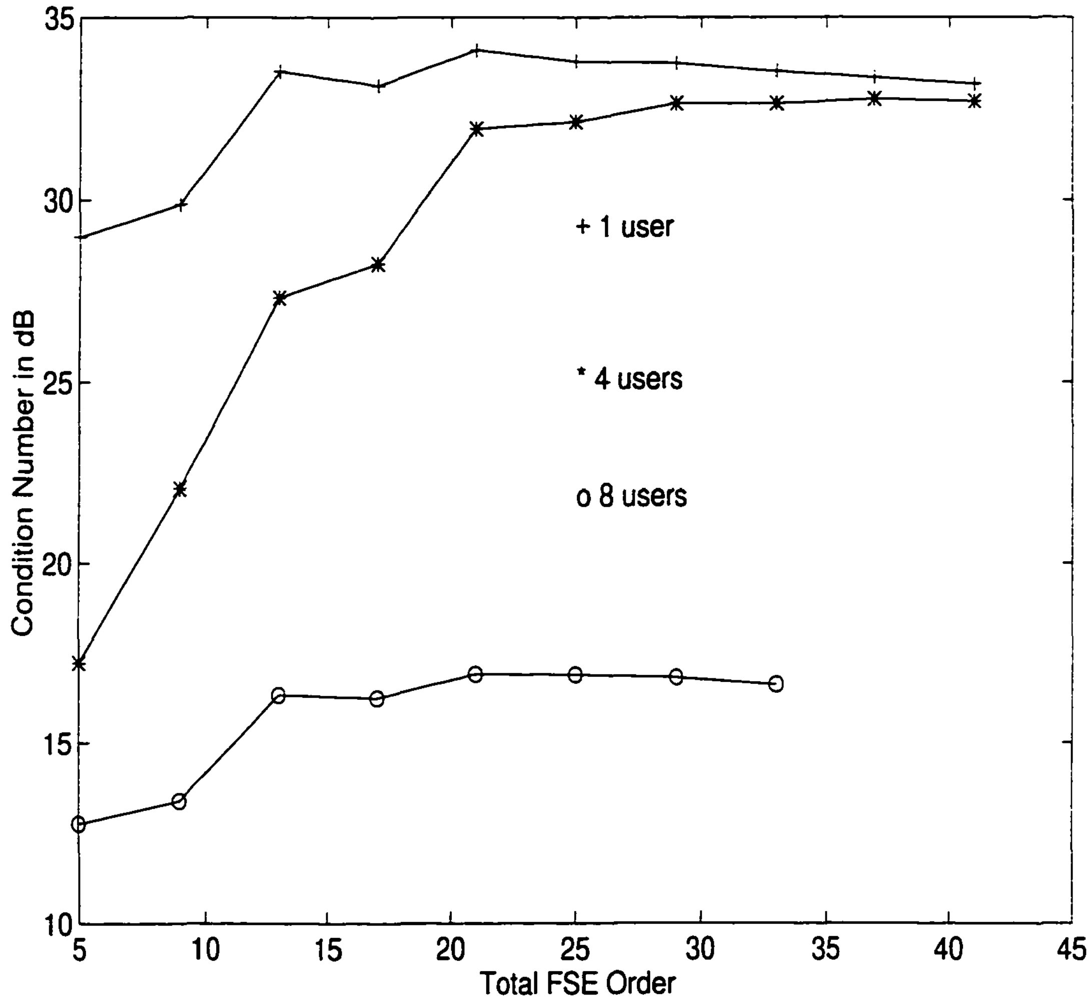

Figure 5.2 Variation in the condition number of the autocorrelation matrix with different numbers of users in a 1-antenna system.

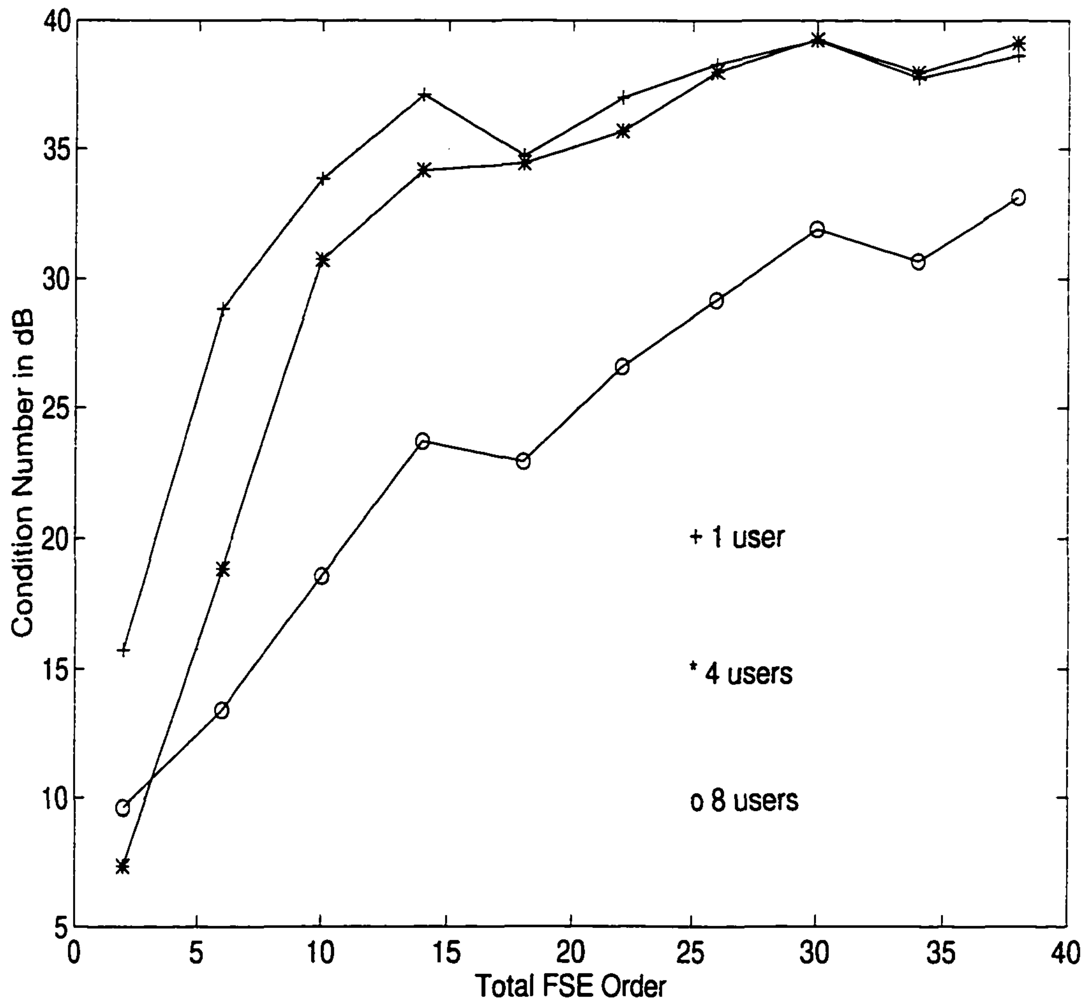

Figure 5.3 Variation of the condition number of the autocorrelation matrix with different numbers of users for a 2-antenna system.

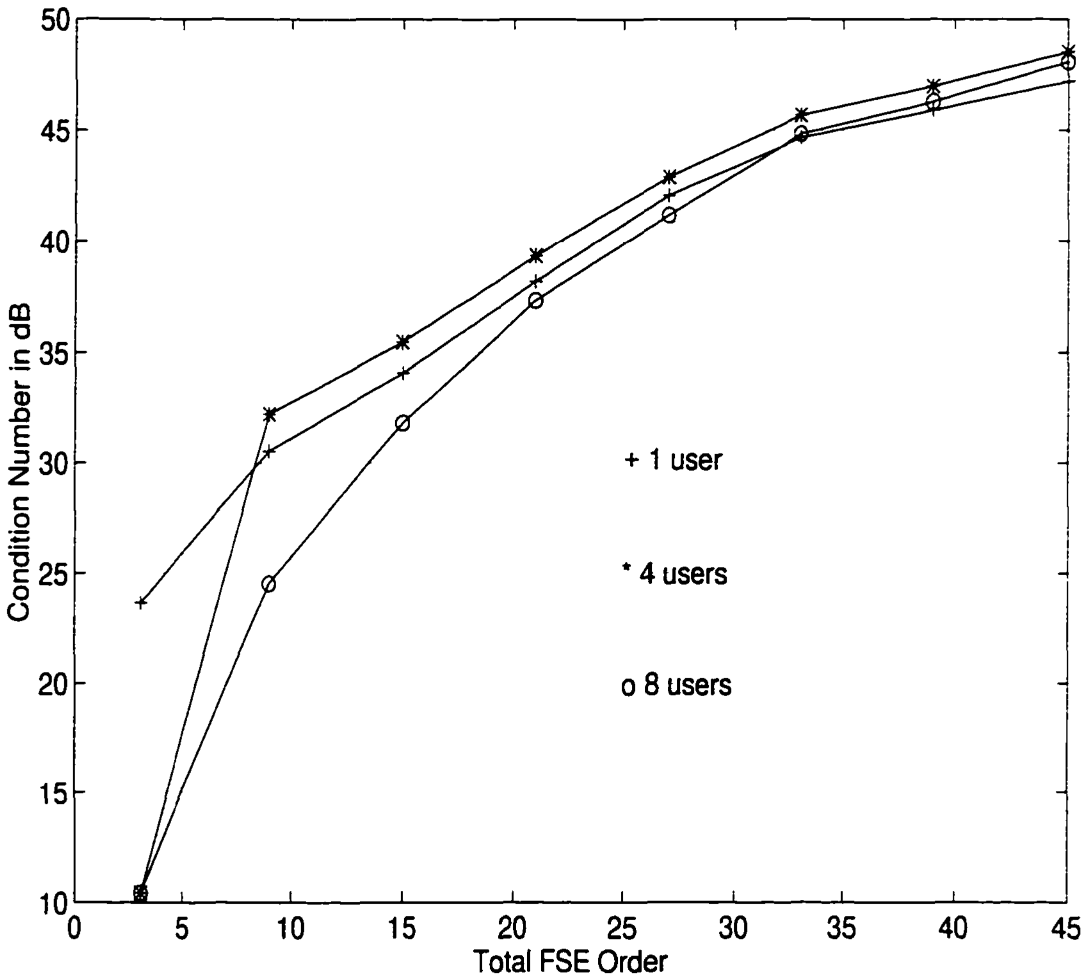

Figure 5.4 Variation of the condition number of the autocorrelation matrix with different numbers of users for a 3-antenna system.

cially as the filter order increases. Note that this 1-antenna system can, in theory, suppress three interferers and when there are seven interferers, the condition number behaves as if the interference were noise. This trend is also evident in Fig. 5.3 where the results for a 2-antenna system with half-chip-rate FSEs are illustrated. This system can, in theory, suppress seven interferers. However, there is a difference in the behavior of the condition number in the 1- and 2-antenna systems. In the 1-antenna system, the difference in condition number between the top two curves and the third is much larger than the corresponding difference in the 2-antenna system. This could be because of the superior interference suppression capability of the latter system. However, in the 3-antenna system with chip-rate FSEs, the number of users does not noticeably influence the condition number as illustrated in Fig. 5.4. This could be because this system can, in theory, suppress 23 interferers and the number of interferers in the three cases is much smaller than the interference suppression capability. Hence, the interference does not behave like noise with respect to the condition number.

5.3 Effect of Adaptation Algorithm on the MSE Performance

It is clear from the above discussion that in the MAME system there is an inherent requirement for an adaptation algorithm which will succeed under conditions of poor conditioning of the autocorrelation matrix. The popular least-mean-squares (LMS) algorithm has poor convergence characteristics in such situations and the performance can depend crucially on the convergence parameter [48]. The performance of the standard recursive least-squares (RLS) algorithm also suffers in these situations especially when finite-precision arithmetic issues are considered [50]. Many fast and stable versions of the RLS algorithm which exploit the cyclic relationship in the input vector cannot be used [14]. A recently proposed quasi-Newton (QN) algorithm performs well even when the condition number of the autocorrelation matrix is high [50]. This algorithm has several advantages including intrinsic adjustment of convergence parameters and stability when implemented using finite-precision arithmetic even when the condition number of the autocorrelation matrix is large. In view of these advantages, we have chosen this QN algorithm for use in the MAME system.

The performance of the QN and normalized LMS (NLMS) algorithms was compared for interference suppression in a TDMA system in [51] and for a CDMA system in [52] where it was demonstrated that the QN algorithm has noticeably better performance. In this work, we have simulated the performance of the QN and the NLMS algorithms and convergence curves for the two cases are presented for comparison. It is clear from Fig. 3.1 that all the equalizers in the MAME system are designed to use the same error $e(n)$ for adaptation. Hence, all the equalizers can be considered together as a *net* adaptive filter. Let $w(i)$ be the tap-weight vector of the net adaptive filter at the ith instant which can be partitioned as

$$w(i) = \left[w_1(i) \quad \dots \quad w_{A_r}(i) \quad w_f(i)\right]^T$$

where $w_m(i)$ is the tap-weight vector of the FSE at the mth antenna and $w_f(i)$ is the tap-weight vector of the FBE. The tap update equation using the NLMS algorithm is given by

$$e(i) = d(i) - w^H(i-1)z(i)$$

$$w(i) = w(i-1) + \mu e(i)\frac{z(i)}{\|z(i)\|}$$

where μ is the convergence factor used, $e(i)$ is the error, $d(i)$ is the desired symbol, and z is the vector of inputs as explained in chapter 3.

The QN algorithm is a second-order adaptation algorithm whose update equations for the tap weights are given by

$$t(i) = R_{est}^{-1}(i-1)z(i)$$

$$\tau(i) = z^H(i)\ t(i)$$

if $\tau(i) \le \delta$, then

$$\tau(i) = 0.5$$

$$R_{est}^{-1}(i) = I$$

else

$$\mu(i) = \frac{1}{2\tau(i)}$$

$$R_{est}^{-1}(i) = R_{est}^{-1}(i-1) + \frac{[\mu(i) - 1]}{\tau(i)} t(i) t^H(i)$$

$$w(i) = w(i-1) + \frac{e(i)}{\tau(i)} t(i)$$

where $R_{est}^{-1}(i)$ is the estimate of the inverse of the autocorrelation matrix.

5.3.1 Simulation details

The effect of the adaptation algorithm on the MSE performance was studied by simulation. A block diagram of the simulation model is illustrated in Fig. 5.5. The input sequences used were binary phase-shift keying (BPSK) symbols. The interference signal shown in Fig. 5.5 is the sum of signals from all the interferers each of which was simulated just like the desired user's signal. A 2-antenna system with half-chip-rate FSEs and a total of 28 taps and a 3-antenna system with chip-rate FSE and 27 taps were simulated. In all experiments related to the MSE performance, we have used the ch_2 model. The simulations were performed in 32-bit floating point arithmetic (IEEE standard) and the availability of the desired user's transmitted sequence at the receiver was assumed throughout the experiment. The NLMS algorithm was simulated with three different values of the convergence parameter.

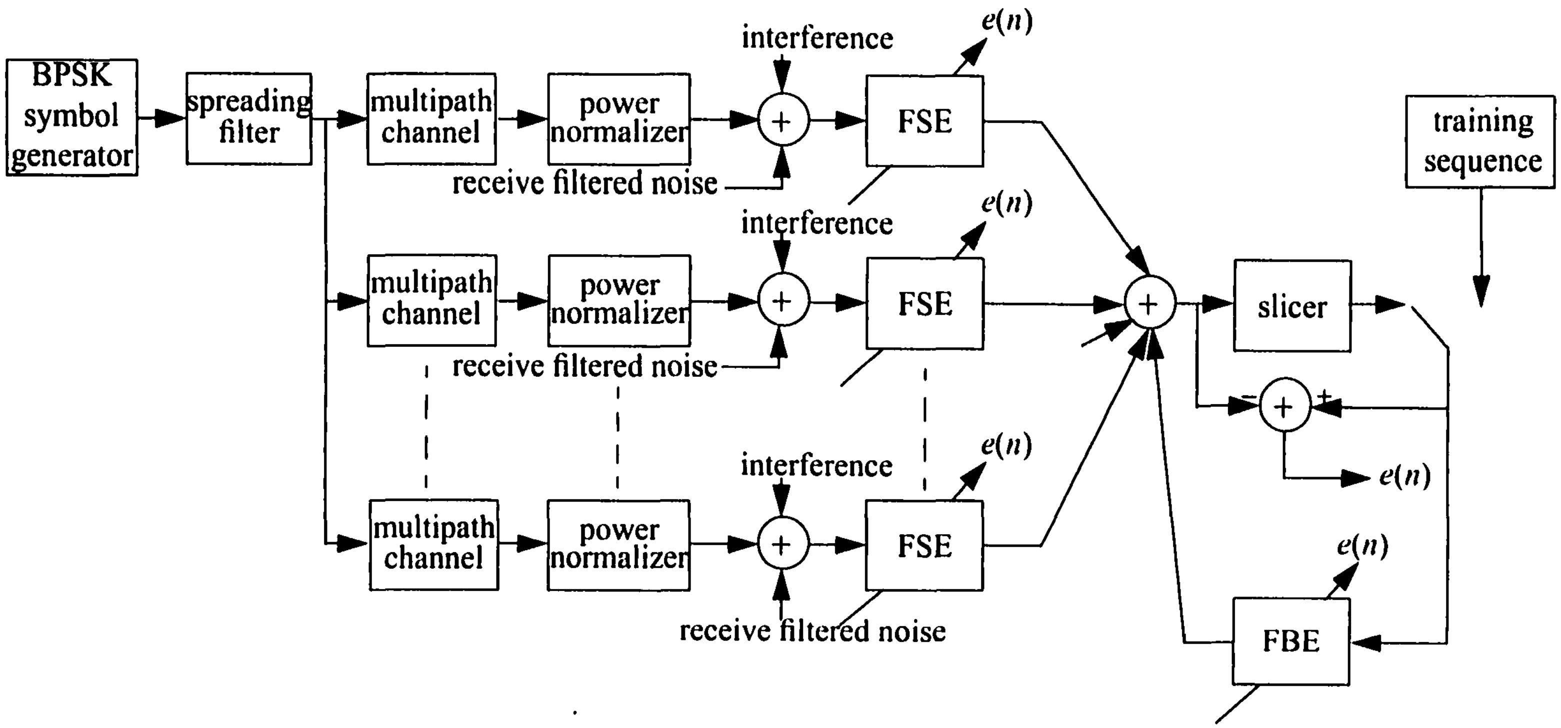

Figure 5.5 Block diagram of the MSE simulation model.

5.3.2 Results

The convergence performance of the NLMS and QN algorithms for the two systems is illustrated in Figs. 5.6 and 5.7, respectively. The three curves which are shown for the NLMS algorithm correspond to the different values of the convergence factor. It can be seen clearly that irrespective of the convergence factor used in the NLMS algorithm, the performance of the QN algorithm is superior. It can also be seen that the performance of the NLMS algorithm can depend crucially on the value of the convergence factor used due to the ill-conditioning of the autocorrelation matrix. It can also be seen that the MSE approaches the MMSE at convergence for the QN algorithm. However, note that the MSE obtained using the QN algorithm converges to a value which is greater than the MMSE. This is because, in the QN algorithm, there is an inherent tuning mechanism for adjusting the convergence parameters, which means that there is a trade-off between the convergence speed and the misadjustment [48]. Hence, when fast convergence is desired, there will be noticeable misadjustment as in our results. Misadjustment can be reduced at the expense of convergence speed [50].

These results demonstrate that for the MAME system, an adaptation algorithm that has better convergence performance when the autocorrelation matrix is ill-conditioned is more suitable. Most first-order algorithms, like the NLMS algorithm, have poor performance when the autocorrelation matrix is ill-conditioned and might need parameter tuning to achieve satisfactory convergence speed as can be seen in Fig. 5.6. Moreover, though the computational complexity of the QN algorithm is $O(N^2)$, it should not be a major concern if the order of the adaptive filter were low. Hence, the QN algorithm is a suitable choice for use in the MAME system and has been used in all further simulations.

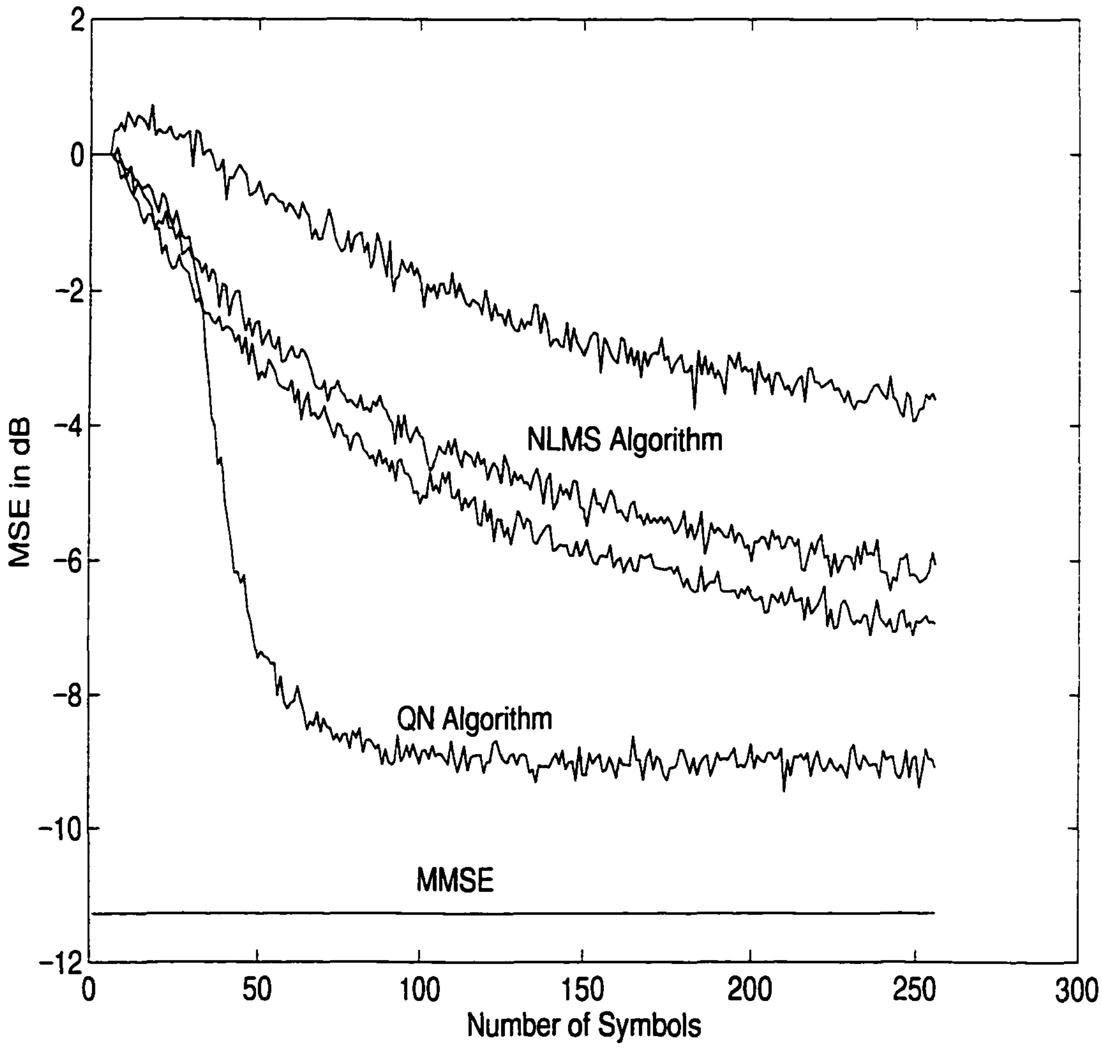

Figure 5.6 Comparison of convergence performance of the NLMS and QN algorithms for a 2-antenna system.

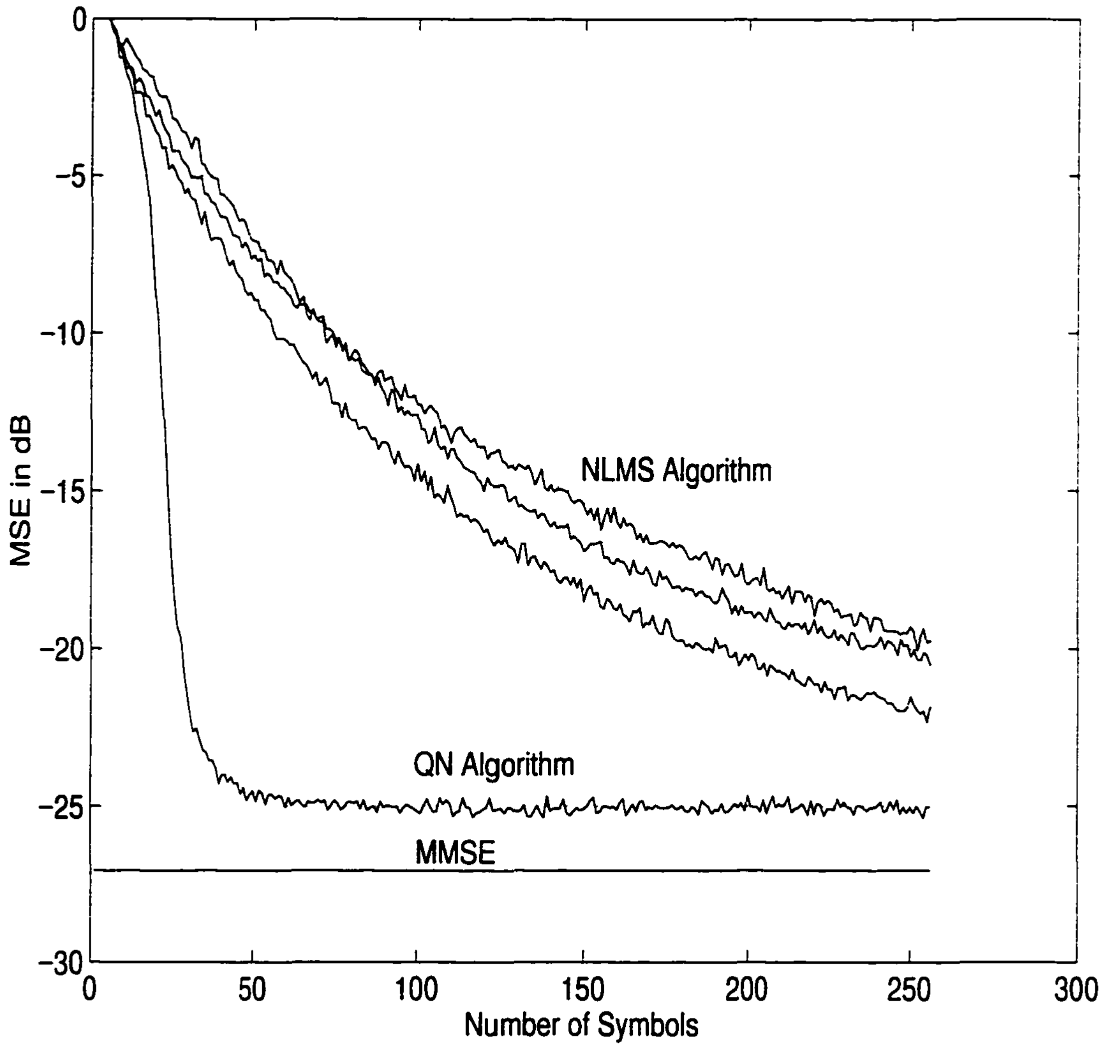

Figure 5.7 Comparison of convergence performance of the NLMS and QN algorithms for a 3-antenna system.

5.4 Near-Far Condition

We have investigated the influence of the near-far condition on the MMSE and results presented have demonstrated that there is no significant degradation in performance of two representative MAME systems. Here, we examine the influence of the near-far condition on MSE performance. To simulate this condition, the power of an interferer was increased abruptly by 20 dB after 128 symbols where the total number of symbols simulated was 256. The MSE is illustrated in Fig. 5.8 for the same 2- and 3-antenna systems investigated in the previous experiment. As can be seen from the plots, after an initial spike at the onset of the near-far condition, the MSE reconverged to a final value which approaches the MMSE. This is an advantage of the MAME system since it can adapt to situations like the near-far condition.

We have shown earlier that the near-far condition does not affect the theoretical interference suppression capability and results presented have demonstrated that the MMSE performance is not significantly degraded. The MSE results demonstrate that the MAME system is a promising solution to counter the near-far problem.

5.5 Decision-Directed Equalization

The MSE results which have been presented till this point were obtained from simulations where the availability of training sequences was assumed for the entire duration. However, in practice, most adaptive equalizers are trained for a certain period and then are switched to a decision-directed mode where the hard-limited output of the equalizer is used as the desired symbol at every instant. This is illustrated in Fig. 5.5 where the output of the slicer is used as the desired signal for calculating the error signal once training is completed. The performance of the MAME system using decision-directed equalization (DDE) is the focus of this section.

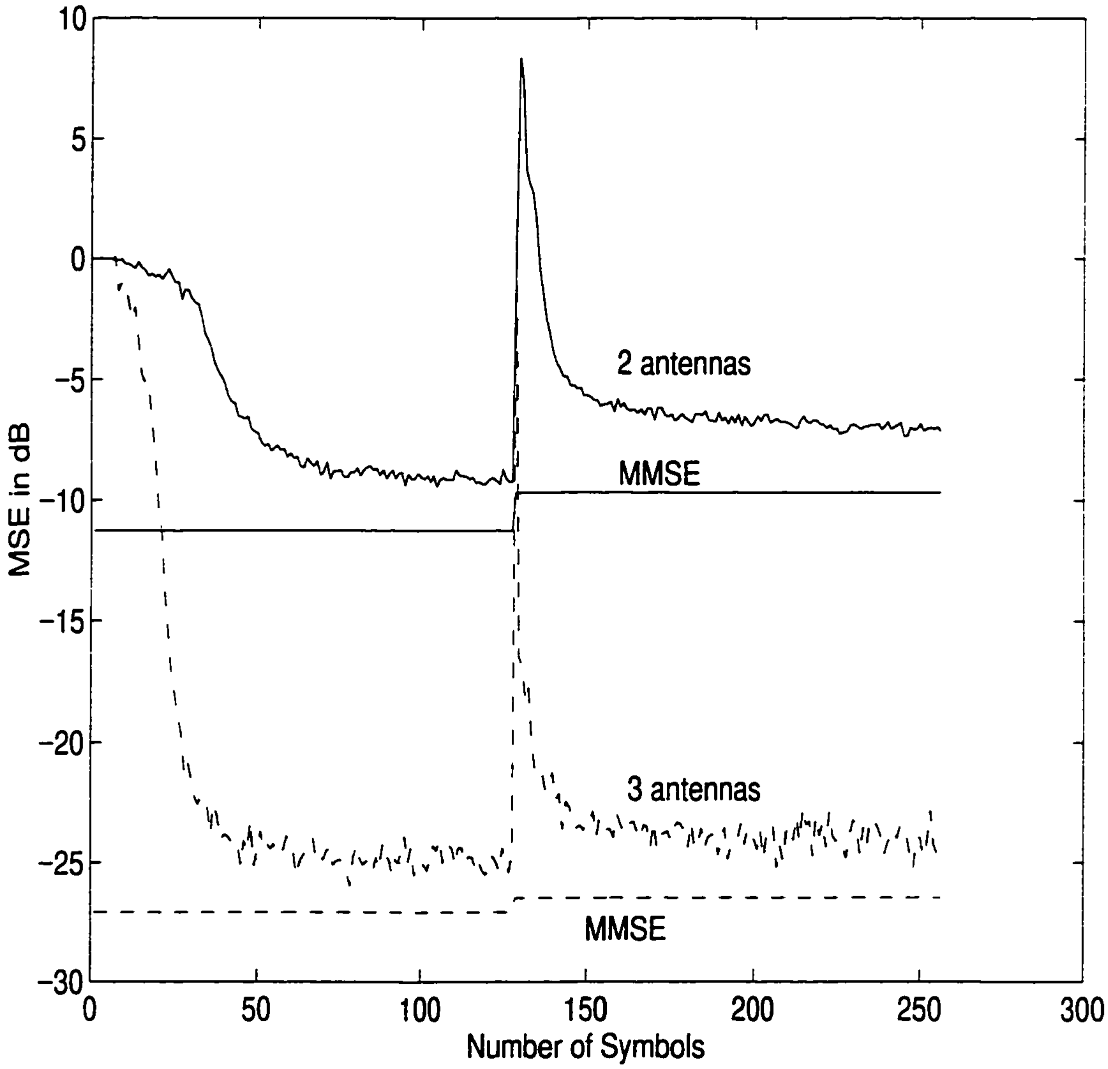

Figure 5.8 MSE Performance of the MAME system in near-far conditions.

5.5.1 Bit-error rate

The most important parameter in any digital communications system is the bit-error rate (BER). As mentioned earlier, we have not predicted the BER using the MMSE. Instead we have used simulations to calculate the BER under different conditions. The main objective is to illustrate trends in BER as a function of training length and filter order. A 2-antenna system with half-chip-rate equalizers was investigated for this purpose. The reason for using this system to obtain BER trends is because we could obtain reliable results without the use of inordinately long sequences. Other MAME systems which have a lower MMSE require very long sequences to obtain reliable BER estimates and as a consequence require a large amount of simulation time.

The BER was calculated as

$$BER = \frac{1}{N_{ens} N_{de}} \sum_{n=0}^{N_{ens}-1} \sum_{k=N_t}^{N_d-1} a_d^n(kT_b) \oplus b_d^n(kT_b)$$

where

N_{ens} = number of ensembles or runs

N_d = length of data sequence in each run

N_t = length of training sequence

N_{de} = number of symbols detected in decision-directed mode

$a_d^n(kT_b)$ = desired user's BPSK symbol at the kth instant in the nth run

$b_d^n(kT_b)$ = estimated BPSK symbol at the kth instant in the nth run

The influence of the training length and filter order on the BER is illustrated in Fig. 5.9. The results were obtained by averaging the BER from 1000 runs. It can be seen from the plots that a longer training period does result in better performance. In

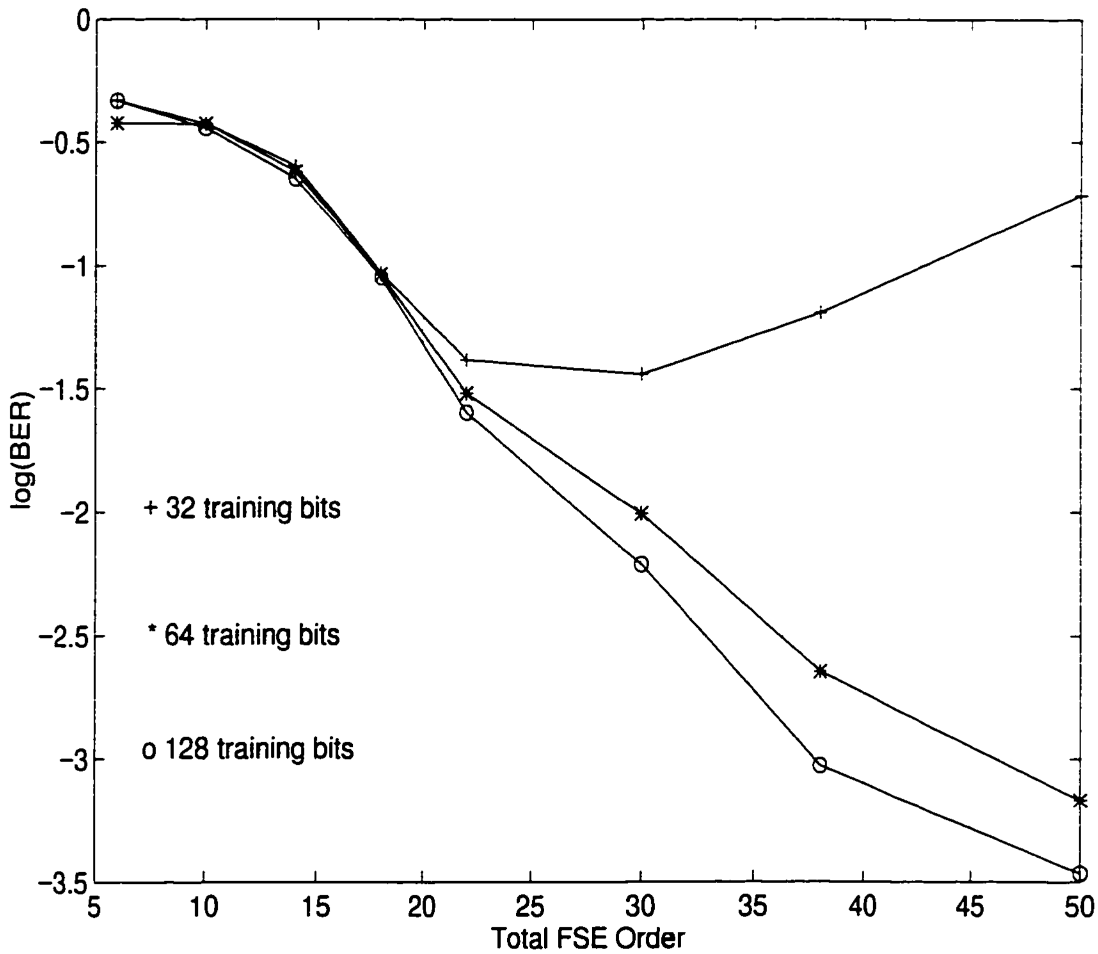

Figure 5.9 Bit-error rate performance with different training lengths and filter orders for a 2-antenna system.

particular, it can be noticed that the performance of the MAME system with a training length of 64 or 128 bits is noticeably better than with a training length of 32 bits. There is an improvement in performance for increasing filter orders except when the training length is equal to 32 bits. In this case, there is a degradation in performance for higher filter orders. These results demonstrate that, as for the MMSE, one can expect a better BER performance with increasing filter orders and training lengths. The training length can crucially influence the performance as demonstrated by the results. We have investigated the BER performance of MAME systems which have a lower MMSE than the 2-antenna system considered here. We did not observe any bit-errors even though a total of a million bits were simulated. These results indicate that a lower MMSE will most likely translate into a lower BER.

5.5.2 Outage probability

Another important parameter in digital wireless communications systems is the outage probability under different conditions. Here again, the main objective is to illustrate trends in outage as a function of training length and filter order. The outage probability was calculated as

$$P_{out} = \text{Prob}\,[Ber_{run} \geq P_{oc}]$$

$$P_{out} = \text{Prob}\left[\left[\frac{1}{N_{de}}\sum_{k=N_t}^{N_d-1} a_d^n(kT_b) \oplus b_d^n(kT_b)\right] \geq P_{oc}\right]$$

where Ber_{run} is the BER corresponding to each run and P_{oc} is the outage criterion. The influence of training length on outage probability was investigated for the same 2-antenna system with a total of 50 taps and is illustrated in Fig. 5.10. The outage results follow a similar trend as the BER results. The outage performance with a training length of 64 or 128 bits is clearly better than with a training length of 32 bits. The

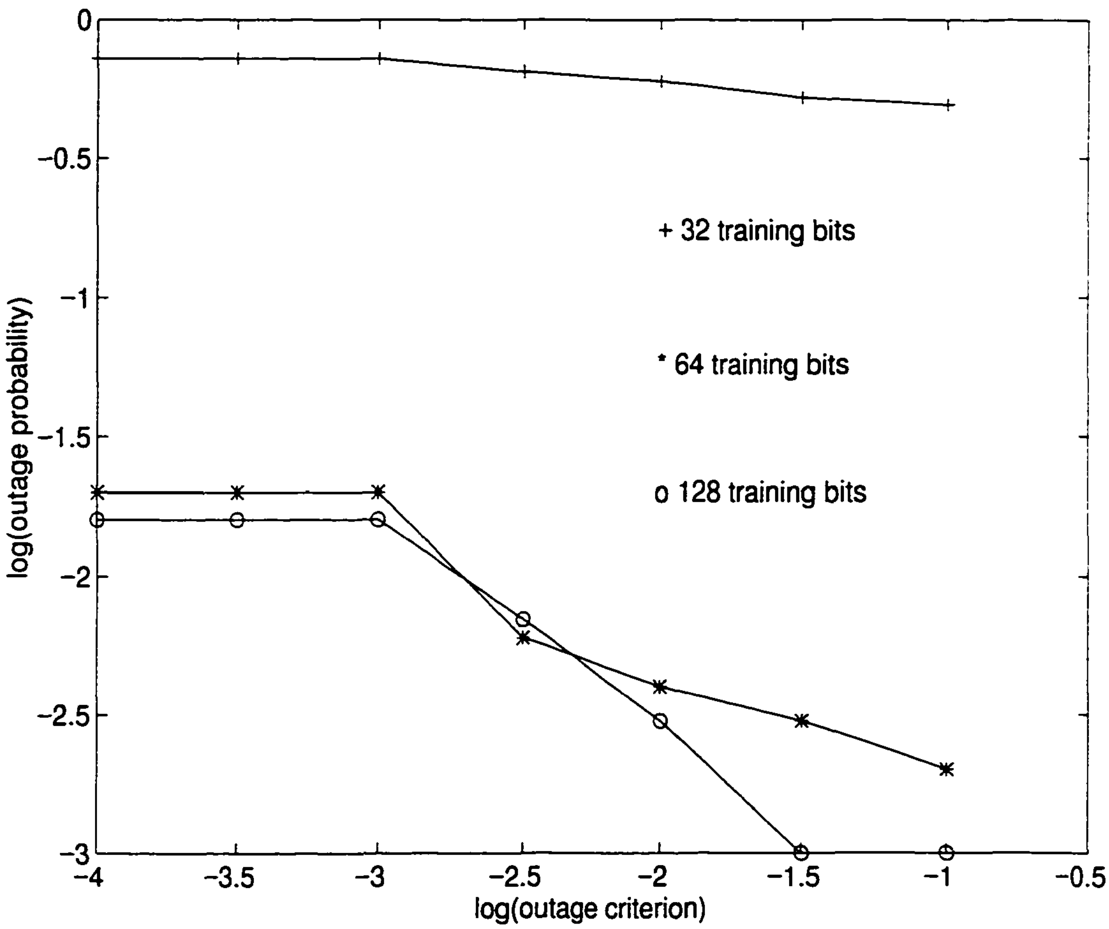

Figure 5.10 Influence of training length on outage probability for a 2-antenna system.

influence of filter order on outage probability is illustrated in Fig. 5.11 where a training length of 128 bits was assumed. The plots demonstrate that a higher filter order results in a better outage performance especially if the training length is sufficient.

5.5.3 Near-far condition

We have presented results which have shown that the MMSE performance of the MAME system is not significantly affected by a sudden increase in the power of the interferer. However, at the onset of the near-far condition, there is a sudden increase in the MSE. This means that when the MAME system is operating in the decision-directed mode, there is a potential for error bursts to occur. The effect of near-far condition on bit-error performance is illustrated in Fig. 5.12 for a 1-antenna system with a chip-rate equalizer and 27 taps. In this experiment, 1000 runs were carried out with 1024 symbols in each run and decision-directed operation was simulated after 64 training symbols. The near-far condition was simulated by a sudden increase in the power of an interferer after 256 symbols. The number of bit errors without the near-far condition for the same 1-antenna system is shown in Fig. 5.13 for comparison. It can be clearly seen that there is a significant increase in the number of bit errors when the near-far condition is simulated. The number of bit errors in each iteration for a 2-antenna system with chip-rate equalizers and 26 taps and for a 3-antenna system with chip-rate equalizers and 27 taps with near-far conditions is illustrated in Figs. 5.14 and 5.15, respectively. It can be seen that there is a significant reduction in the number of bit errors for the 2- and 3-antenna systems. Moreover, it can be noticed that the maximum number of bit errors in each iteration is equal to two for the 2-antenna system and one for the 3-antenna system. It was noticed that the bit errors in the two multiple-antenna systems occurred at the instant of the onset of the near-far condition. The adaptive

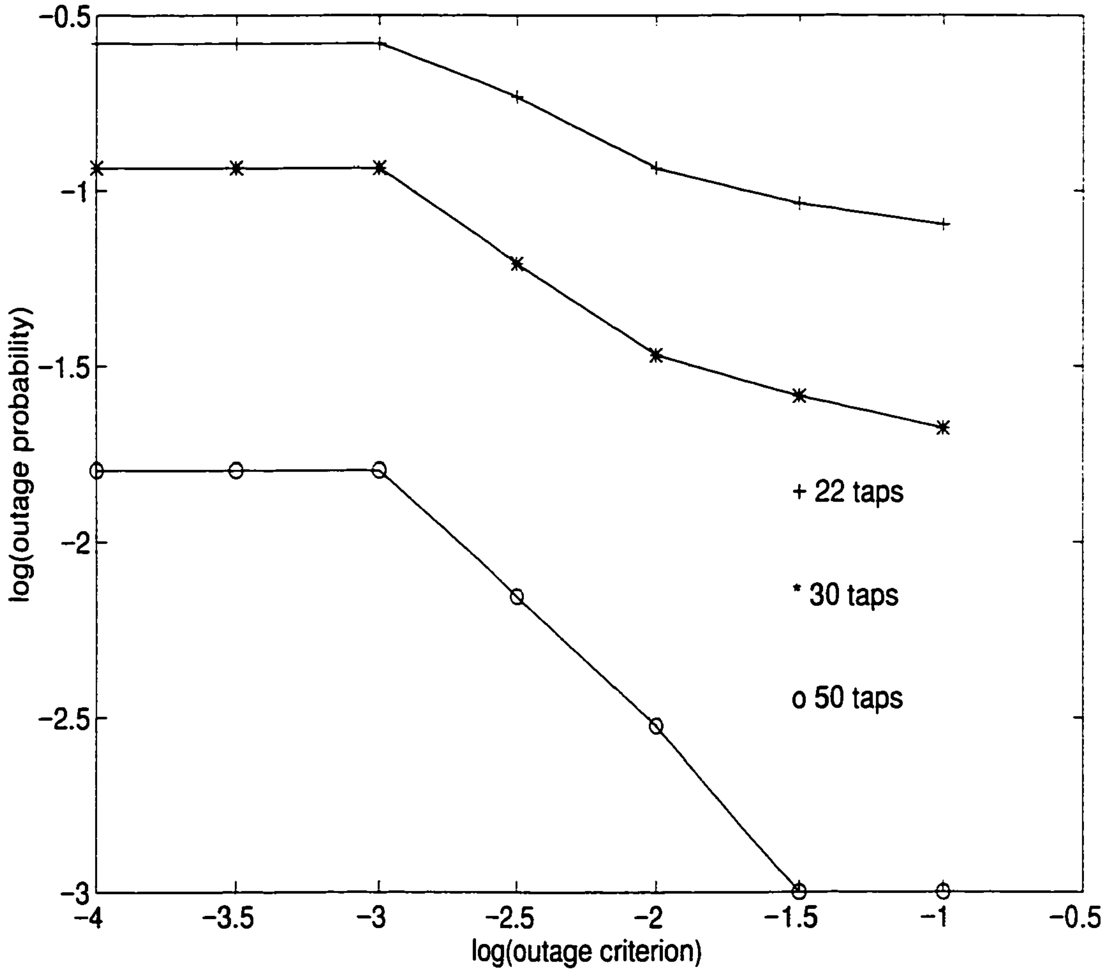

Figure 5.11 Influence of filter order on outage performance of a 2-antenna system.

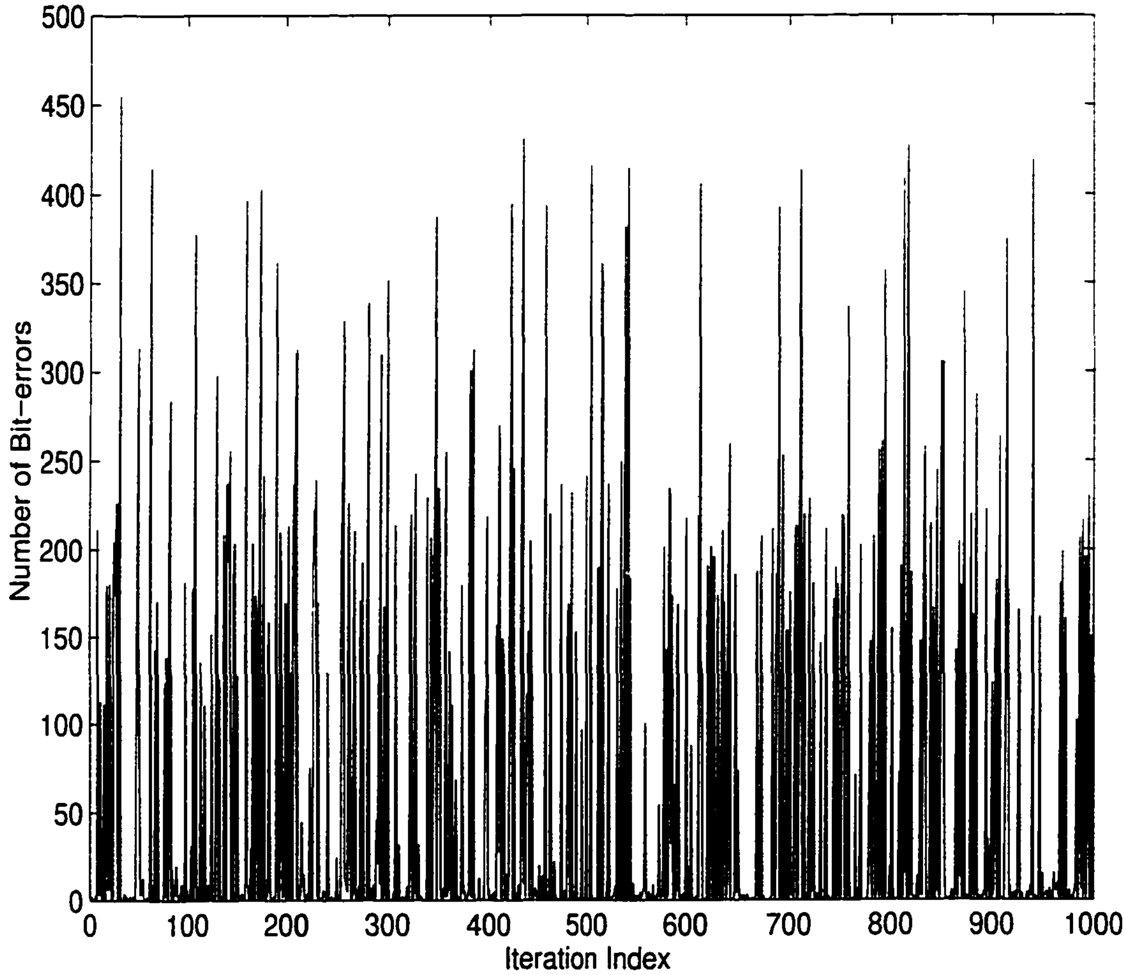

Figure 5.12 Number of bit errors in each iteration for a 1-antenna system with near-far condition.

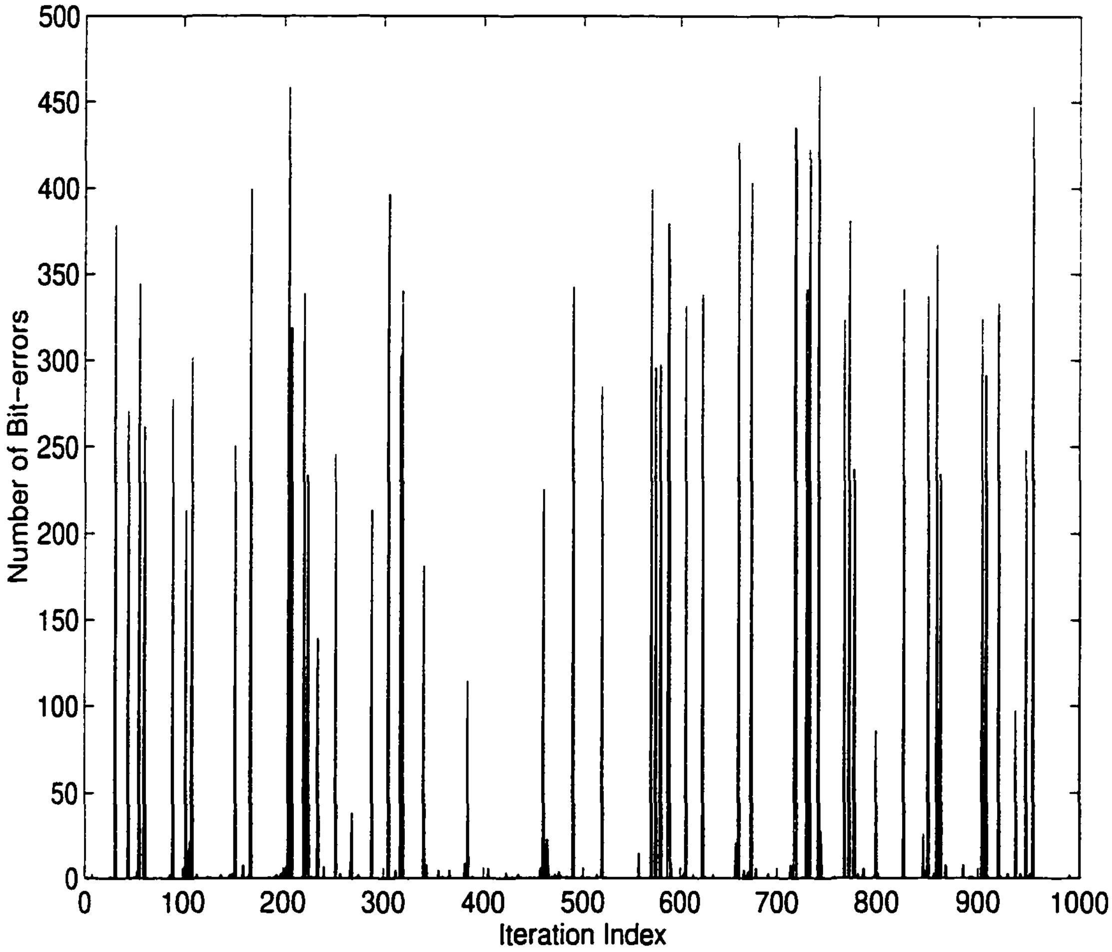

Figure 5.13 Number of bit errors in each iteration for a 1-antenna system without the near-far condition.

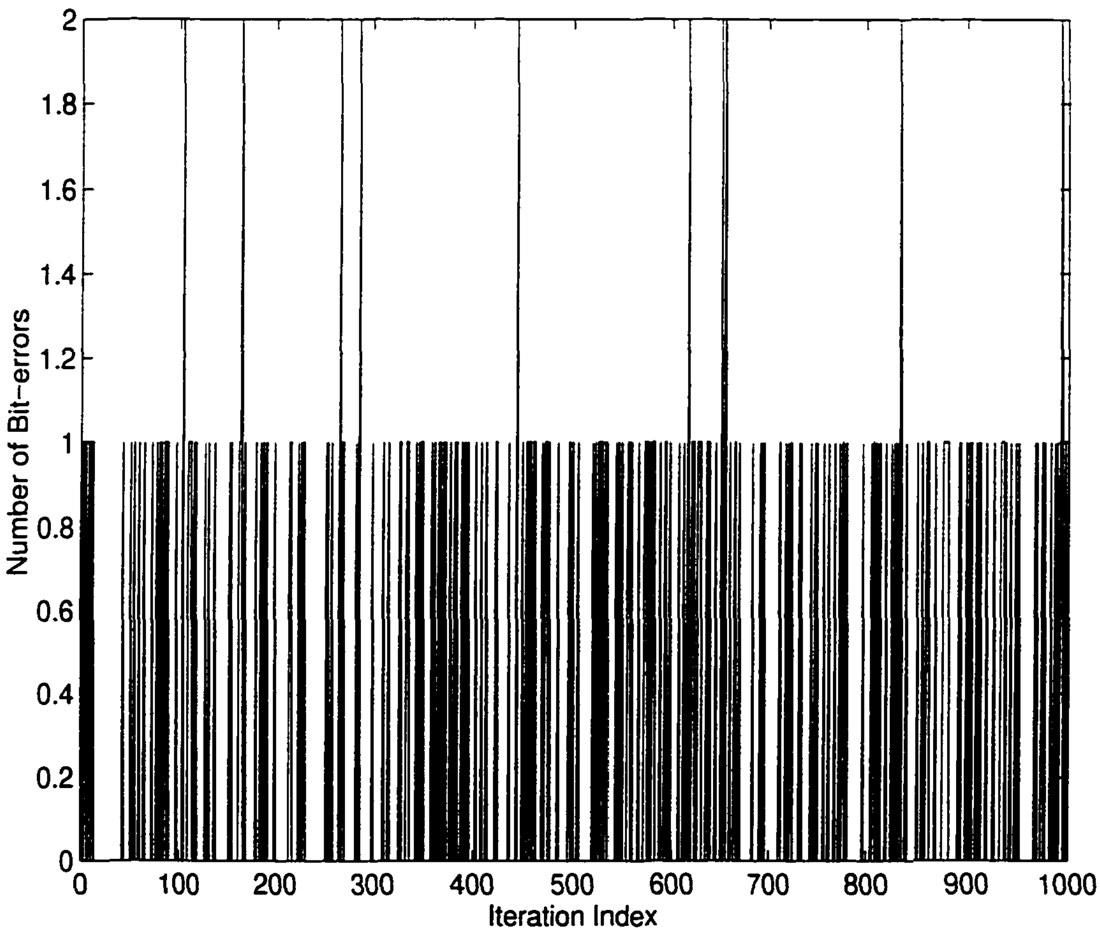

Figure 5.14 Number of bit errors in each iteration for a 2-antenna system with near-far condition.

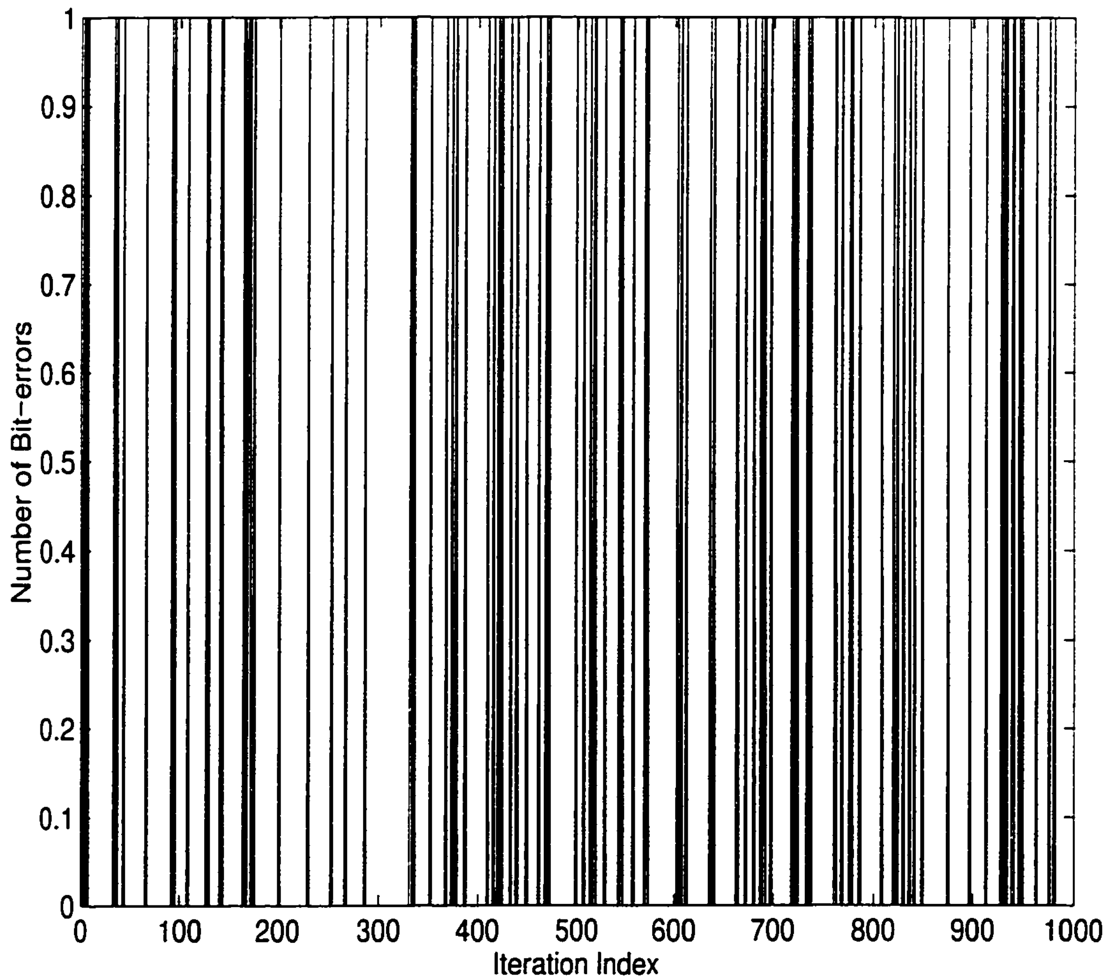

Figure 5.15 Number of bit errors in each iteration for a 3-antenna system with near-far conditions.

nature of the MAME system and its superior interference suppression capability result in a small number of bit errors. The total number of bit errors for the 3 systems is given in Table 5.1

System type	Total number of bit errors without near-far condition	Total number of bit errors with near-far condition
1-antenna system	17011	52892
2-antenna system	0	242
3-antenna system	0	100

Table 5.1. Effect of near-far condition on the number of bit errors for 3 MAME systems.

These results illustrate that the MAME system has the potential to be an effective solution to the near-far problem. We have seen that for the cases considered here, a small number of bit errors occurs due to the onset of the near-far condition for the two multiple-antenna systems. Such errors can be corrected by using techniques of error-correction coding. Hence, the MAME system can offer an important advantage in tackling a crucial problem in many wireless systems.

5.5.4 Birth of interferers

We have assumed so far that all users start transmitting at the same time instant but, in practice, users should be able to switch on and off randomly. When users switch on randomly, the condition is called the birth of interferers [16]. To simulate such a condition, only the desired user was assumed to be transmitting for a duration of 64 symbol periods in the training mode after which DDE was used. Then, the interferers were introduced one-by-one into the CDMA system. The first interferer was simulated to start transmission after 100 symbol periods and, subsequently, an extra interferer was simulated to take "birth" 100 symbol periods after the previous birth. This birthing process was continued till all eight users were transmitting in the CDMA system.

The effect of birth of interferers on the MSE performance for a 1-, 2- and 3-antenna system with chip-rate FSEs and 27, 26, and 27 total taps, respectively, is shown in Figs. 5.16-5.18. The plots clearly show the advantages that are possible by using the MAME system instead of a single FSE. As discussed earlier, the MAME system can achieve enhanced interference suppression performance as compared with a single FSE. This can be seen from the plots where the degradation in performance as the number of interferers is increased is more severe for the 1-antenna system than the two multiple-antenna systems. Moreover, the 3-antenna system experienced the least amount of degradation because of its superior interference suppression capability. The spikes in the MSE curves indicate that the MSE increases abruptly when an interferer takes birth. The tap coefficients need to adapt to the birth at these points. Such a situation would also arise when a user switches off transmission. The plots can also be interpreted as a study of the influence of the number of interferers on performance.

The effect of the birth of interferers condition on the bit-error performance was also examined. The total number of bit errors observed with the three MAME systems is given in table 5.2. For comparison, results when all users start transmitting at the same time (called the standard case) is also shown. In both cases, the number of bit errors observed with the 1-antenna system is much higher than with the other two systems. There were no bit errors observed with the 2- and 3-antenna systems in the standard case. However, with the 2-antenna system, there is a significant number of bit-errors with the birth of interferers condition. Very few bit errors were observed with the 3-antenna system as indicated in Table 5.2.

System type	Total number of bit errors in the standard case	Total number of bit errors with birth of interferers
1-antenna system	17954	18175
2-antenna system	0	392
3-antenna system	0	5

Table 5.2. Effect of birth of interferers condition on the number of bit errors for 3 MAME systems.

These results demonstrate the advantages of the MAME system. By using the 3-

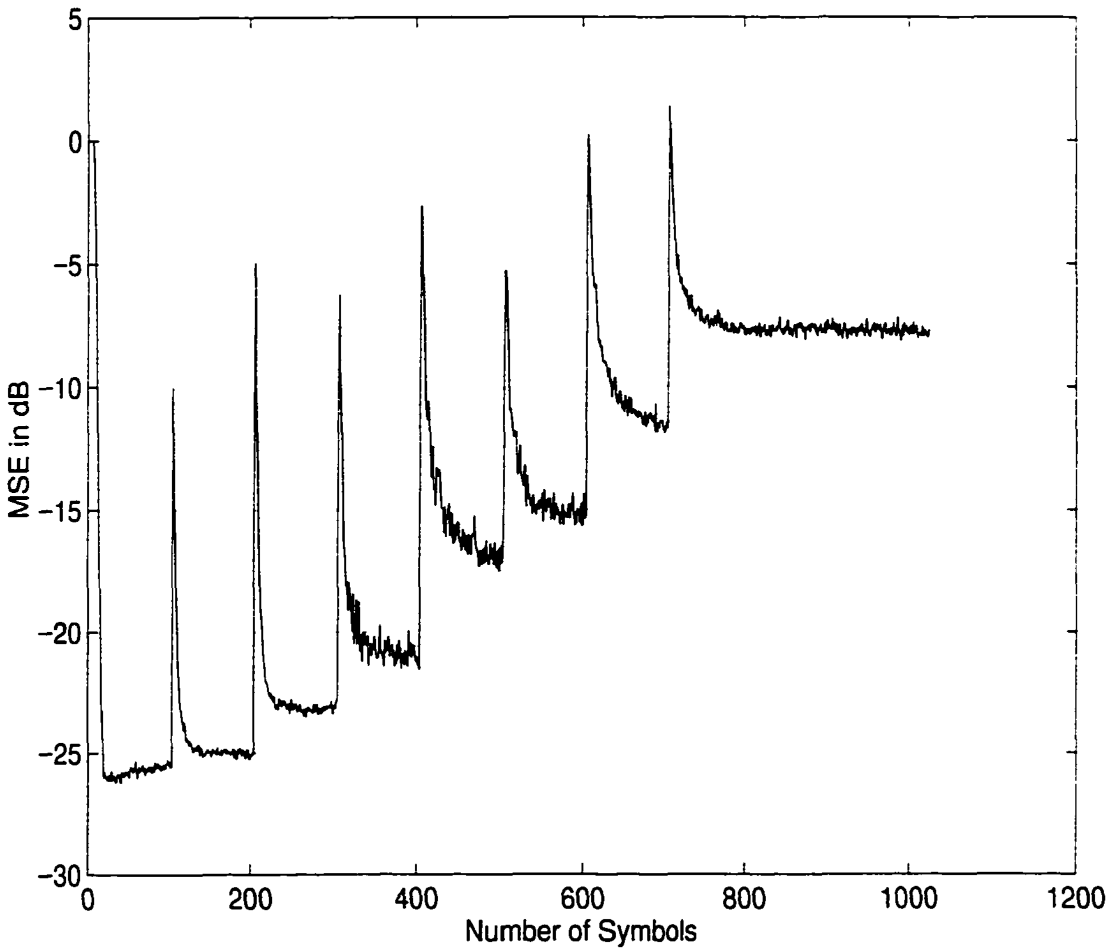

Figure 5.16 Effect of birth of interferers on MSE performance of a 1-antenna system.

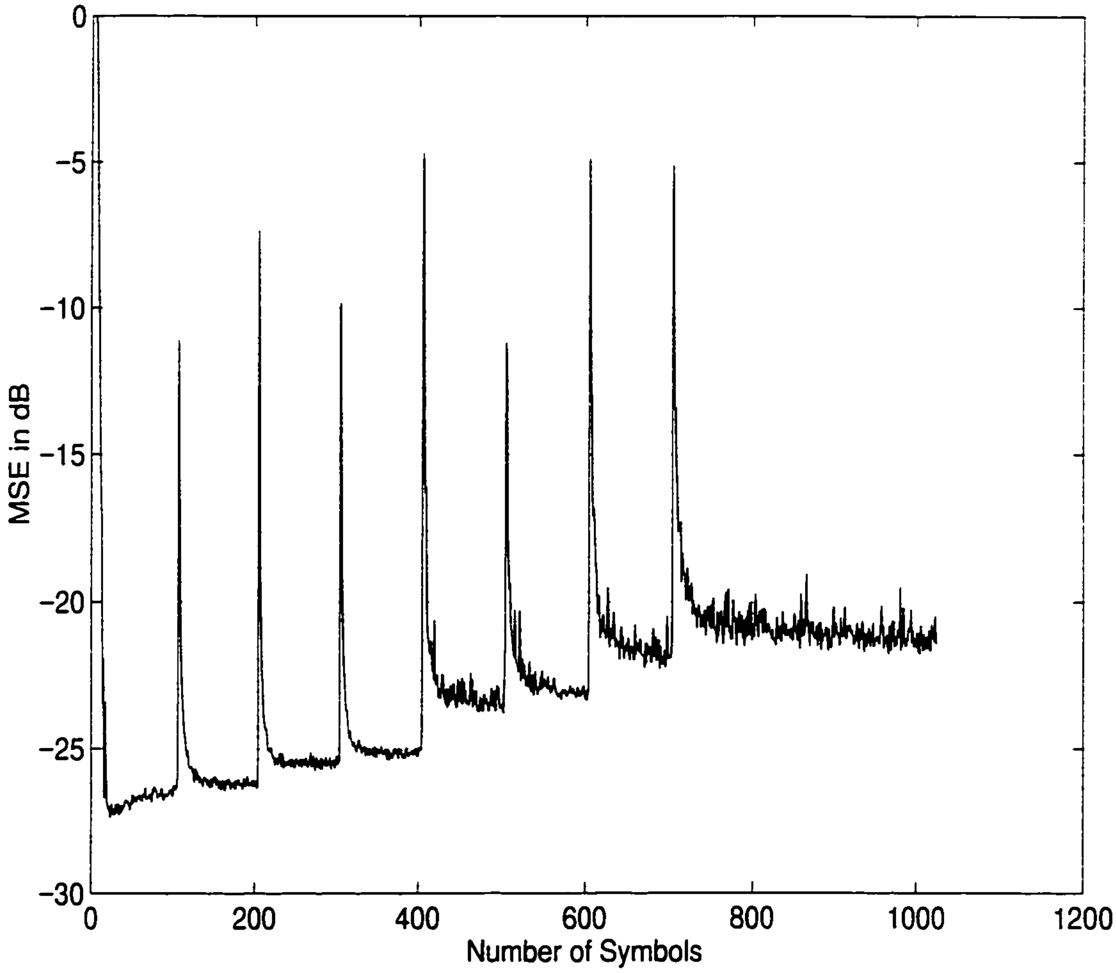

Figure 5.17 Effect of birth of interferers on MSE performance of a 2-antenna system.

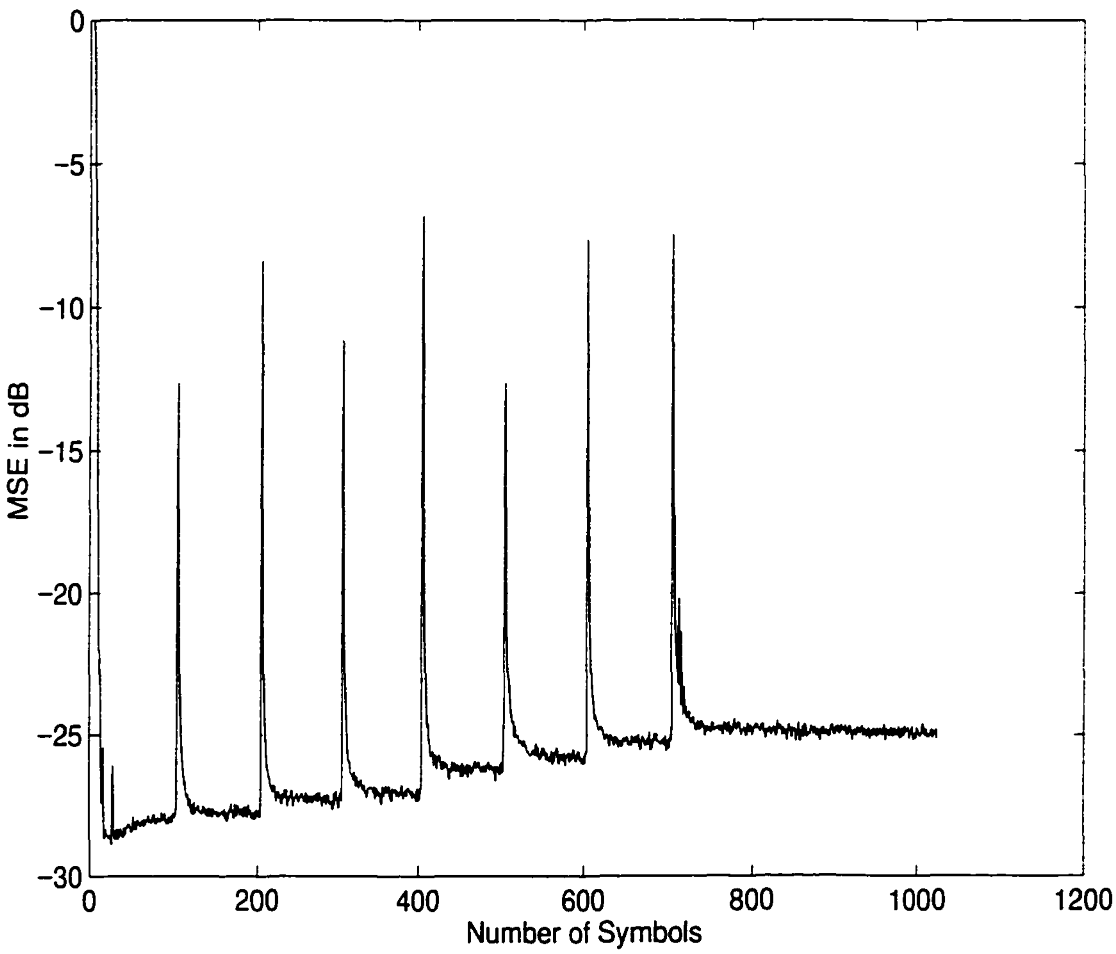

Figure 5.18 Effect of birth of interferers on MSE performance of a 3-antenna system.

antenna system in the above-mentioned experiment, very few bit errors ensued. Therefore, simple techniques to deal with such situations can be used. The adaptive nature of the system and the inherent interference suppression capability provide advantages to the designer for dealing with many situations.

5.6 Conclusions

The MSE and bit-error performance was examined under various conditions. Because of the ill-conditioning of the autocorrelation matrix, a QN algorithm which is well suited to the MAME system is recommended for adapting the tap coefficients. Simulation results presented confirm the advantages of using the QN algorithm as compared with the NLMS algorithm. The MSE performance with near-far condition demonstrates benefits of the adaptive nature of the MAME system.

The BER results of a representative MAME system indicate that the gains in MMSE performance will most likely translate into gains in BER. Investigations of the bit-error performance with near-far condition demonstrate the potential of the MAME system to overcome a crucial problem in CDMA systems. The effects of birth of interferers on performance was studied and results presented illustrate the advantages and flexibility due to the MAME system.

Chapter 6

An Indoor Wireless Network Strategy

6.1 Introduction

The effectiveness of the MAME system in overcoming CCI in CDMA systems has been demonstrated. The properties and advantages of the MAME system have also been discussed. In this chapter, an indoor wireless network strategy based on the MAME system is examined. Such a strategy is tailored to use the advantages due to the MAME system. The main benefits will be in the areas of receive filtering, choice of code sequences, and capacity. These benefits will be discussed and simulation results will be presented to support the discussion.

6.2 General Remarks

We focus on indoor wireless applications like WLANs since standardization activities in these fields are at a nascent stage. This means that these applications provide a fertile ground for testing new ideas and proposals. We propose a WLAN where the MAME system is used at each receiver to overcome cochannel interference (CCI). There are no specific data rates proposed for this network and the limits on data rates will be due to the technology and cost constraints for implementing the MAME system and other modules. However, with rapid advances in digital signal processing hardware technologies and associated fields, it is expected that this limit on data rates will improve rapidly.

Each user in the network will have a MAME system in the receiver section. The number of users who can share the WLAN will depend on the processing gain of the CDMA system, the number of antennas and tap spacing of the FSEs and performance requirements. Systems with small processing gain (10-20) are more suitable since the tap spacing of the FSEs has to be equal to the chip period for the best interference suppression performance with the MAME system. It is expected that the data rates will increase rapidly in indoor wireless systems in the near future, and hence, there will be technological and cost limitations on achieving the best performance using the MAME system for systems with high processing gains. We assume that all users use the same carrier frequency. This means that CCI is the only mutual user interference which is considered. However, the network could be expanded by using adjacent channels, in which case, adjacent channel interference (ACI) will also have to be considered. Note that the MAME system can be used to overcome in general ACI in addition to the CCI. However, in general, it is expected that the performance degradation with ACI from a certain number of interferers will be less than with an equivalent amount of CCI.

The mobility of the networked elements is an important issue since the performance of the network can vary depending on the mobility of the users. The focus is on applications where the important reason for choosing a wireless medium for communications is because of problems which might be encountered when installing a wired network. Such applications could arise in buildings with wiring difficulties, in temporary offices, and laboratories among many other cases. In such cases, the mobility of the users in the network is usually restricted to a limited space, and mobility outside this limited space is not a crucial requirement. This is an important difference from outdoor cellular wireless systems, where rapid mobility of users over a wide area is an important requirement. Note that the MAME system can be used in such an outdoor system. However, several other issues which are not considered need to be addressed. The adaptive nature of the MAME system means that mobility and the associated near-far problems can be dealt with effectively.

6.3 System Issues

The main purpose of using the MAME system is to overcome CCI so that several user signals can share the same frequency band without the need for any frequency allocation schemes or synchronization. This is an important advantage of CDMA systems as compared with TDMA and FDMA systems [53]. Moreover, in a world where spectral resources are becoming scarce in all ranges, it is possible that the efficient use of such resources will become a significant issue. Thus far, we have focussed on the interference suppression capability of the MAME system. Here, we focus on other advantages which are also applicable to the development of a network strategy.

6.3.1 Receiver

An important difference between most CDMA systems and the proposed strategy is the use of an LPF as the RXF instead of the conventional despreading operation. Results have been presented that illustrate the better performance with the LPF than with a filter matched to the desired user's code sequence. The use of an LPF is possible because the interference suppression capability of the MAME system does not crucially depend only on the crosscorrelation properties of the code sequences.

There are several advantages that are possible when a LPF is used. There is no need for any code acquisition or tracking at the receiver. This can be important since in many CDMA systems, special schemes are designed to acquire and track the codes. In this indoor wireless network, no such schemes are necessary as no information about the code sequences is needed at the receiver. There is another important advantage which is realizable by implementing a fixed analog LPF as the RXF. We have seen, that in the MAME system, FSEs which have a tap spacing greater than the chip period can be used to achieve comparable performance with systems where chip-rate FSEs are used. Hence, by using an analog LPF and FSEs which have a tap spacing greater than the chip period, the speed of the A/D converter used before the FSE can be reduced depending on the tap spacing of the FSE. This can be an important factor in high data-rate applications which are envisaged for indoor WLANs where considerable savings in the speed and cost of the A/D converter are possible.

The above discussion highlights the flexibility available to the designer due to the MAME system. In situations where the capacity of the system is the crucial objective, chip-rate FSEs should be used to achieve maximum interference suppression. However, in cases where technology and cost constraints become the crucial factors, FSEs slower than the chip rate can be used while still satisfying performance objectives.

6.3.2 Influence of code sequences

One of the main reasons for proposing the MAME system for CDMA systems is because of the spread bandwidth of the transmitted signal as compared with the data symbol rate. Moreover, CCI is the most important impediment which needs to be overcome for improving the capacity and efficiency of CDMA systems. Hence, a combination of FSEs and multiple antennas is a effective and relevant method to improve performance in CDMA systems.

Unlike in many CDMA systems, we have not discussed the issues and influences associated with the choice of code sequences. This is because, the MAME system does not explicitly use the crosscorrelation properties of the code sequences to achieve interference suppression. Distinctness between users is assured by the use of code sequences even in pathological conditions when the multipath responses associated with different users are identical. We have used Walsh-Hadamard codes based on the system investigated in [16]. Note that many discussions on code sequences for CDMA systems are usually based on large processing gain systems and these might not be relevant to small processing gain systems which are more conducive to the MAME system. However, in situations where multipath impulse responses of different users can be assumed to be independent, as in our simulation model, the need for well-designed code sequences can be examined.

In most CDMA systems, a code sequence is assigned to a user before transmission. A central monitor or base station is necessary to ascertain that no two cochannel users are assigned the same code. This is because of the crucial dependence on the code sequences to effect CCI suppression. We have seen that in the proposed network information about code sequences is not needed at the receiver. This means that the main role of code sequences is to spread the signal at the transmitters. Hence, simple code sequences which need not satisfy particular crosscorrelation conditions can be used. For example, random code sequences can be considered for use at the transmitters. A further extreme measure is to consider identical codes for all users. Both schemes are not relevant to most CDMA systems but are possible due to the MAME system. When either of these schemes is used, the communication system can be viewed as a spread-spectrum system rather than as a CDMA system. This is because, codes are not the distinguishing factor facilitating multiple access in such a case. The independent multipath impulse responses and the training sequence associated with the desired user is the main factor used to distinguish among the users.

We have investigated the performance of the same 2- and 3-antenna systems as in Chapter 4. The curves in Figs. 6.1and 6.2 illustrate the influence of code sequences on MMSE performance. It can be seen that there is no significant performance degradation by using random code sequences when compared with the assigned Walsh codes case. There is a degradation when the same code is used especially for higher filter orders. The same code case can be considered as a worst-case scenario for the random codes. The MSE results illustrated in Fig. 6.3 is further proof of the viability of using random code sequences.

The results demonstrate that it is possible to consider simple code sequence allocation schemes in the proposed network. For instance, users can generate their code sequences before transmission. This obviates the need for a central monitor to keep

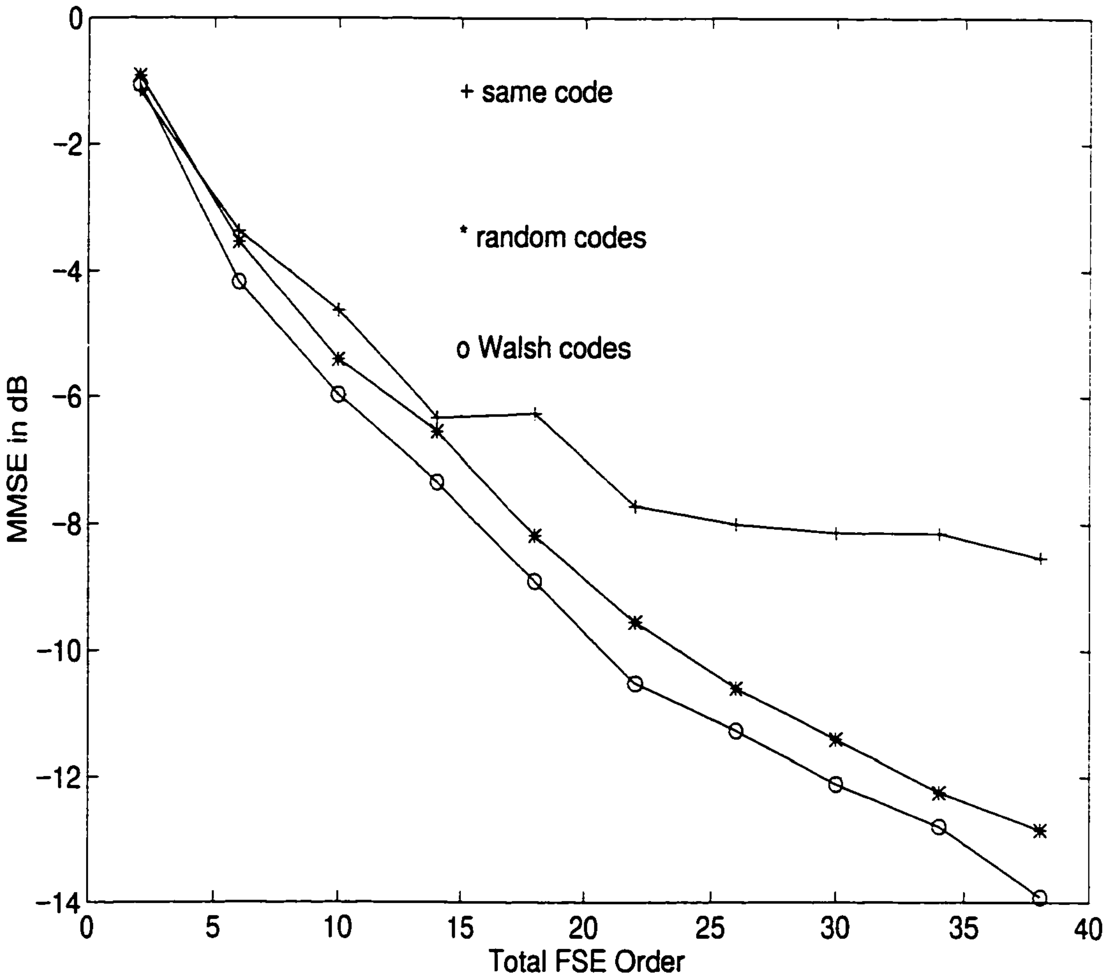

Figure 6.1 Performance of a 2-antenna system with different code sequences.

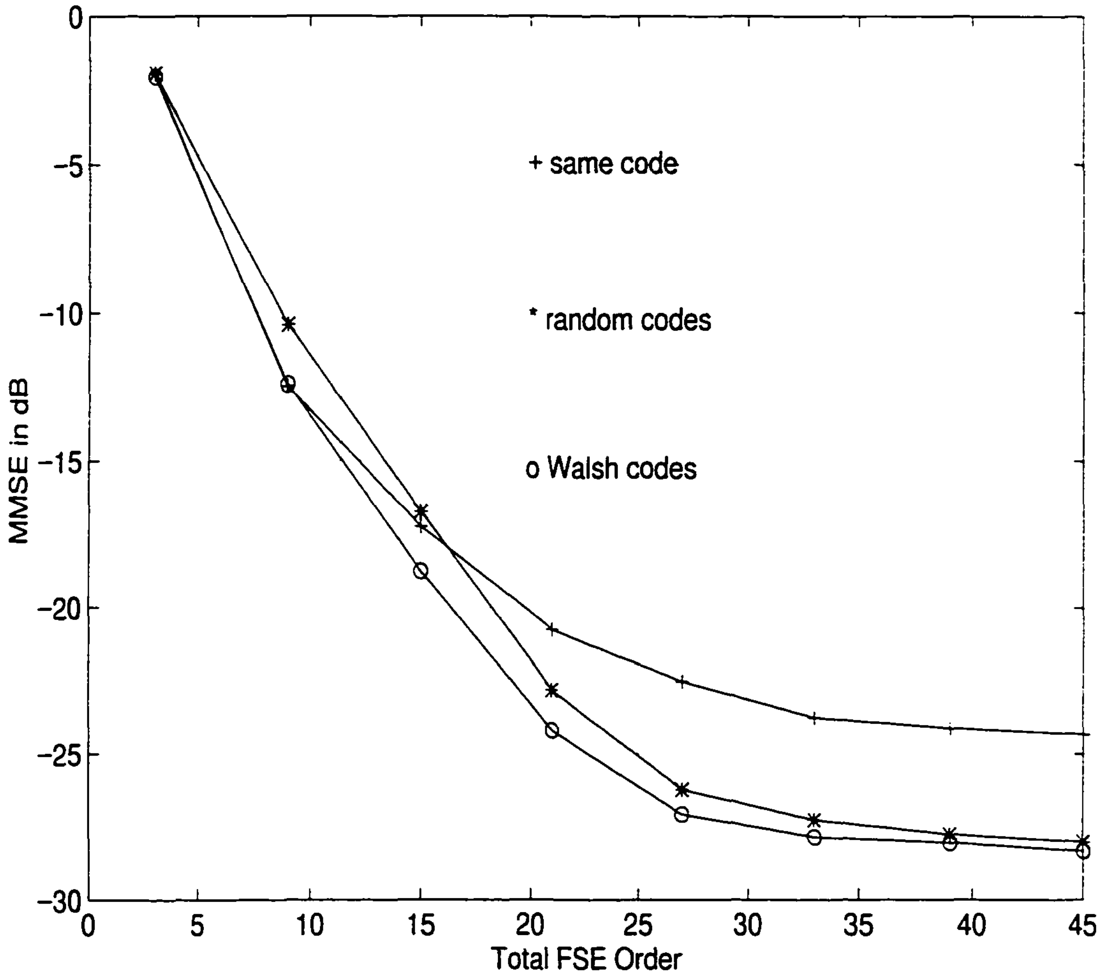

Figure 6.2 Performance of a 3-antenna system with different code sequences.

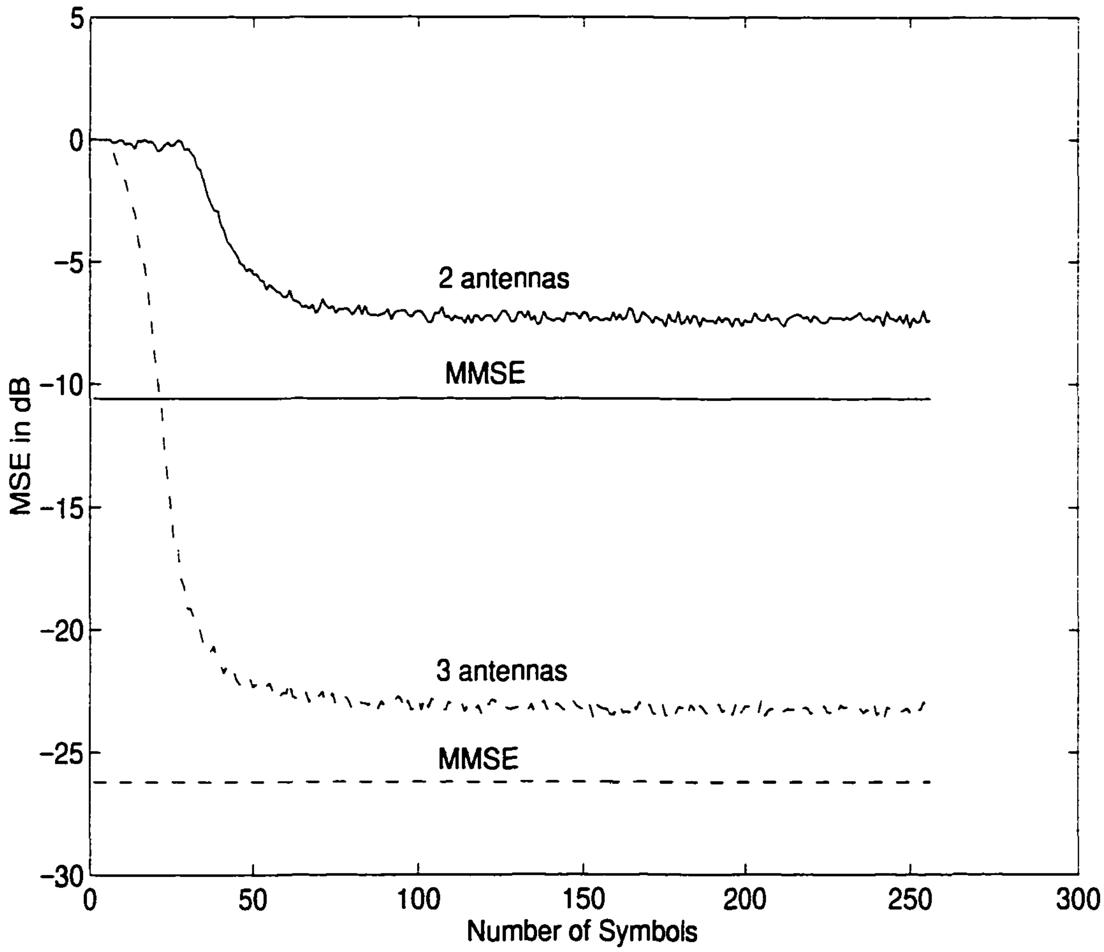

Figure 6.3 MSE performance with random codes.

track of the various users and their code sequences. However, training sequences are necessary to separate the users.

6.3.3 Capacity

It is clear from the results in the previous section that well-designed code sequences are not *necessary* in the proposed network. Hence, the number of cochannel users is not limited by the availability of good code sequences. Traditionally, the capacity of a CDMA system is given by the ratio of number of cochannel users to the processing gain. Many CCI suppression measures are designed to increase capacity as in the system proposed in [16], where 50% capacity is achieved. We have seen that by using the MAME system, in theory, the number of cochannel interferers that can be suppressed is greater than the processing gain, i.e., more than 100% capacity can be achieved. We have investigated the influence of the number of users on the performance of a 3-antenna system with chip-rate FSEs which can, in theory, suppress 23 interferers. Random code sequences were simulated for spreading the user signals. Results illustrated in Fig. 6.4 show that a -11 dB MMSE can be achieved even when there are 16 users. The MSE results illustrated in Fig. 6.5 are a confirmation of the gains. These results indicate that the capacity of the indoor wireless network can be significantly higher than 100%. Moreover, by appropriately choosing the number of antennas and the tap spacing of the FSEs, and by studying the multipath responses in the environment where the network will be deployed, variable numbers of users can be accommodated. Thus, the designer has inherent flexibility in controlling the capacity of the WLAN depending on specific needs and requirements. A case by case approach is recommended for choosing the parameters in the MAME system so that requirements can be met efficiently.

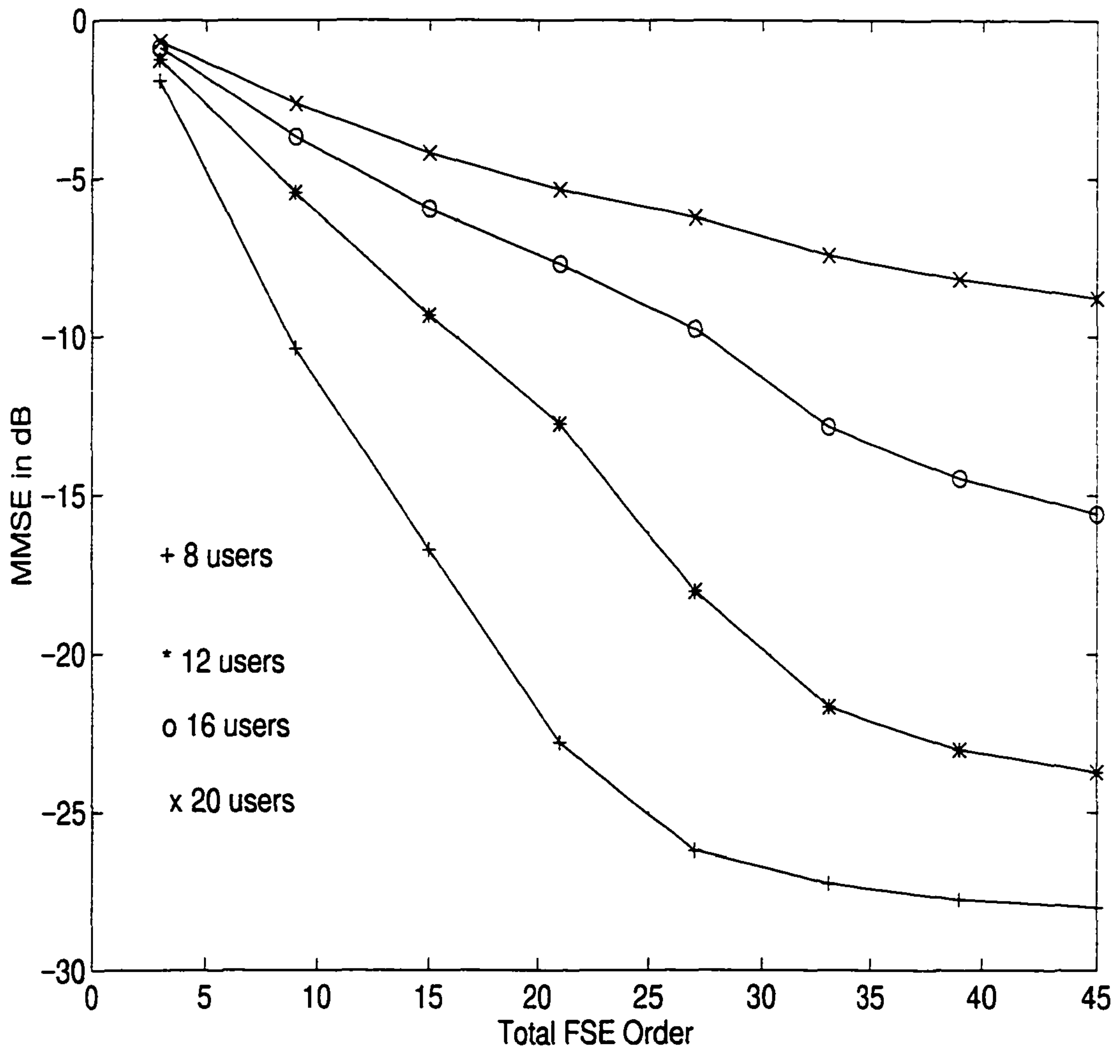

Figure 6.4 Performance of a 3-antenna system for different numbers of users.

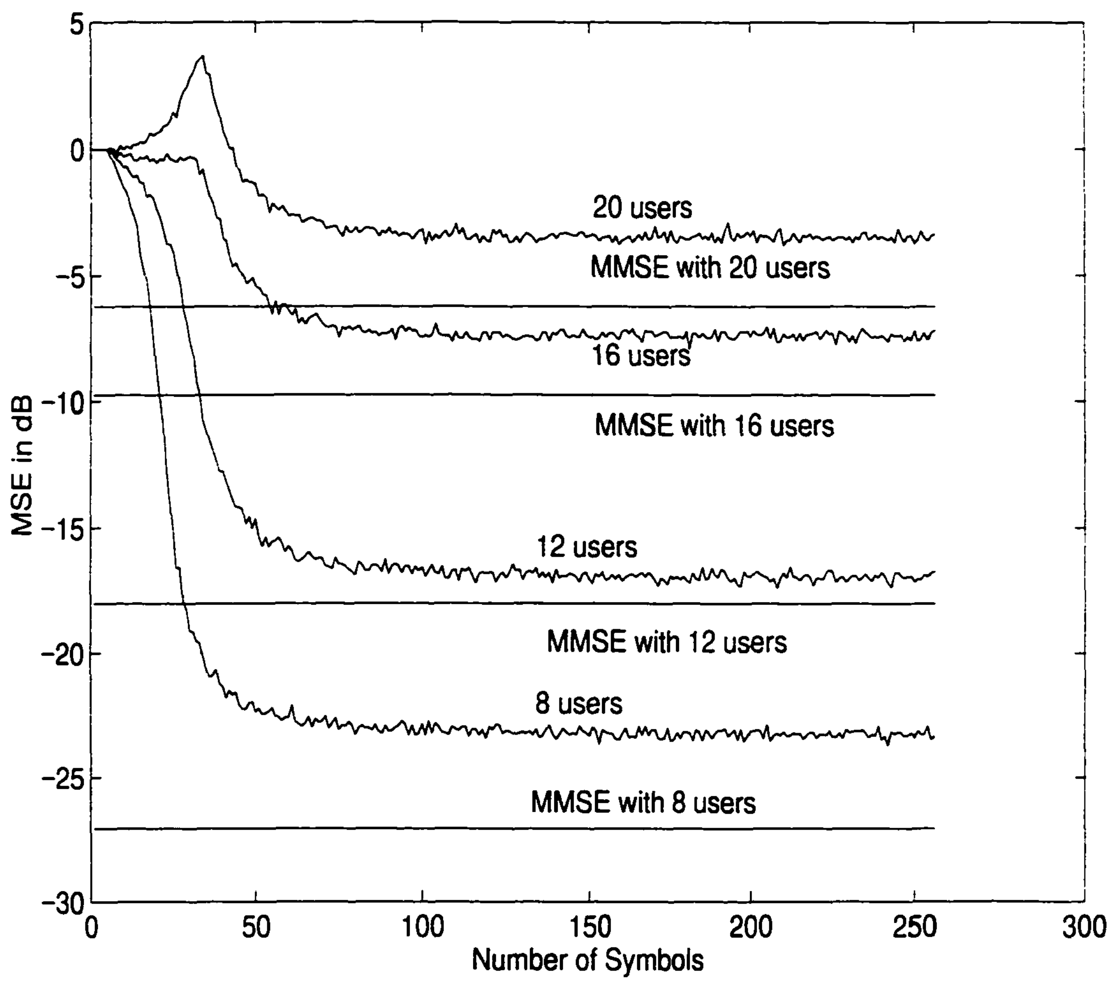

Figure 6.5 MSE performance of a 3-antenna system with different numbers of users.

6.4 Conclusions

An indoor wireless network strategy based around the MAME system has been examined. A WLAN which is primarily used because of difficulties in installing wired networks is the main envisaged application. No information about code sequences is needed at the receiver and it is argued that advantages in the implementation of the receive filter and A/D converter can be achieved. The influence of code sequences on performance was examined and it was demonstrated that simple code sequence allocation schemes can be used. This also obviates the need for a central monitor to track the code sequences of the users. The capacity of the network can be significantly higher than 100% and results are presented to support the discussion. The inherent flexibility available to the designer to accommodate variable numbers of users is also an advantage of this network. The performance with near-far conditions which was investigated in the previous chapter is also a feature of the network.

In effect, the proposed network can offer advantages in many areas and the main features can be summarized as follows:

1. The number of cochannel users can exceed the processing gain of the CDMA system.

2. No information about code sequences is needed at the receiver.

3. Simple code sequence allocation schemes can be used at the transmitter.

4. Variable numbers of users can be accommodated.

5. Simple power control and error-correction coding schemes can be used.

Chapter 7

Conclusions

7.1 Introduction

We have presented a signal processing scheme which can be used to achieve efficient, high-capacity, and flexible indoor wireless systems. This chapter summarizes the conclusions of the thesis and outlines a number of issues that could be pursued further.

7.2 Summary

In Chapters 1 and 2, ideas relevant to interference suppression using a combination of FSEs and multiple antennas were reviewed. The generalized zero-forcing condition for complete ISI and CCI suppression was discussed. The relevance of this concept to interference suppression in CDMA systems was then examined.

The MAME system was proposed for CCI suppression in CDMA indoor wireless systems in Chapter 3. The differences with existing multiple-antenna strategies were explained. It was shown that the inherent spectral correlation present in user signals is the reason for the superior interference suppression capability achieved. The MAME system was also interpreted as a dual-domain diversity combiner. The spectral correlation and diversity concepts enable clear understanding of the operation of the MAME system from different viewpoints. It was also shown that the near-far condition which can severely affect performance in CDMA systems will not, in theory, affect the interference suppression capability of the MAME system. A detailed mathematical model was then presented and was used in the calculation of the MMSE.

In Chapter 4, the MMSE performance of the MAME system was examined. The simulation model used to obtain the results was outlined. The MMSE performance under various conditions was then presented and discussed. The effects of number of antennas, tap spacing, receive filtering, noise power, spectral correlation, diversity domains, and the near-far condition were investigated. Results and discussions presented give a clear idea of the properties and advantages of the MAME system.

The focus in Chapter 5 was on the MSE and bit-error performance under various conditions. Because of the ill-conditioning of the autocorrelation matrix, a QN algorithm which is well suited to the MAME system was recommended for adapting the tap coefficients. Simulation results presented confirmed the advantages of using this algorithm as compared with the NLMS algorithm. The MSE performance with near-far condition demonstrated benefits of the adaptive nature of the MAME system.

The BER results of a representative MAME system indicated that the gains in MMSE performance will most likely translate into gains in BER. Investigations of the bit-error performance with near-far condition demonstrated the potential of the MAME system to overcome a crucial problem in CDMA systems. The effects of birth of interferers on performance was studied and results presented illustrate the advantages and flexibility due to the MAME system.

In Chapter 6, an indoor wireless network strategy based around the MAME system was examined. A WLAN which is primarily used because of difficulties in installing wired networks was the main envisaged application. No information about code sequences is needed at the receiver and it is argued that advantages in the implementation of the receive filter and A/D converter can be achieved. The influence of code sequences on performance was examined and it was demonstrated that simple code sequence allocation schemes can be used. This also obviates the need for a central monitor to track the code sequences of the users. The capacity of the network can be significantly higher than 100% and results were presented to support the discussion. The inherent flexibility available to the designer to accommodate variable numbers of users is also an advantage of this network. The features of the network were also summarized.

7.3 Ideas for Further Work

We have demonstrated the inherent interference suppression capabilities of the MAME system by simulation. An important issue which needs to be examined before practical realization of the MAME system is the hardware complexity of a practical implementation. It can be seen from Fig. 3.1 that the FSEs in the MAME system are inherently conducive to implementation using parallel hardware. However, when a second-order adaptation algorithm like the QN algorithm is used there is a need for communication among the parallel paths. Such a problem does not arise if first-order adaptation algorithms like the LMS are used. However, in either case, filtering of the signals and adaptation of the FSEs can still take place in parallel at different antennas. Such an approach can result in increased speeds of these operations as compared to a non-parallel approach. Many DSP manufacturers have systems which emphasize parallel processing approaches. Such resources can be used as a starting point for the investigation of parallel processing strategies in the MAME system. Hence, a detailed study of the hardware issues in the implementation can be a significant contribution towards the practical realization of the MAME system.

We have used established simulation models for the multipath channels and any variations in these models can crucially affect performance. Sophisticated tools are available at present for predicting the multipath environment in specific indoor sites [54]. Such tools are expected to become more accurate and might form an important part of the evaluation of indoor wireless systems. For example, using these tools, one could calculate the capacity for a specific indoor environment. In particular, for a designer using the MAME system, the tools can help decide the tap spacing of the FSEs and the number of antennas needed to achieve performance objectives. A study of system performance using such tools in different environments will also contribute towards the examination of the practical applicability of the MAME system.

The BER performance has been investigated using a symbol-by-symbol approach for a representative MAME system. It would be preferable if an analytical approach were available to calculate approximate values since BER performance is one of the most crucial aspects and such an approach can save simulation time. Practical situations with the near-far condition need to be investigated in different environments so that measures to detect and counter them can be improved. This can be studied along with mobility considerations in different environments. These investigations can help one to better understand the limitations of the MAME system and suitable measures can then be designed.

The suitability of the MAME system for applications other than those envisaged in this thesis can be investigated. For example, an underwater network for various remotely operated devices in an ocean environment using a spread-spectrum system has been proposed in [55]. The use of the MAME system to suppress interference in such a network could be an interesting topic for investigation.

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