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Adaptive Combined Space-Time Receiver Structures for DS-CDMA Systems

by

Abdelgader M. Legnain, B.Sc., M.Sc.

A Thesis submitted to the Faculty of Graduate
Studies and Research in partial fulfillment of the
requirements for the degree of Doctor of Philosophy.

**Ottawa-Carleton Institute for Electrical and Computer Engineering
Faculty of Engineering
Department of Systems and Computer Engineering
Carleton University
Ottawa, Ontario, Canada
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Adaptive Combined Space-Time Receiver Structures for DS-CDMA Systems

submitted by

Abdelgader M. Legnain, B.Sc., M.Sc.

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

Chair, Department of Systems and Computer Engineering
Professor **John W. Chinneck**

Thesis Supervisor
Professor **David D. Falconer**

External Examiner
Professor **Ahmed K. Elhakeem**
Concordia University, Montreal

Carleton University
October 2000

Abstract

Direct-Sequence Spread-Spectrum (DS/SS) systems offer several attractive features such as interference rejection, multipath diversity, multiple access capability, and accurate ranging. Recently, a greater interest has been devoted to the use of DS/SS systems in many mobile radio applications including digital cellular systems and indoor wireless networks due to the expected increase in capacity and an increased demand for new services. This interest motivates growing research on SS systems as a result of the critical role that it plays in the operation of SS systems.

With the development of wireless and personal communication systems, there is a considerable interest in using multiuser detection techniques and adaptive array processing technology to improve the system capacity in both present and future generation wireless systems. This thesis presents novel design ideas for DS-CDMA systems which use a combination of adaptive multiuser detection and adaptive array processing.

Three novel adaptive combined space-time receiver structures are proposed in this thesis. These receiver structures jointly combine the spatial and temporal domain to improve the overall system performance. These structures are called: 1) the linear adaptive combined space-time receiver, 2) the decision feedback adaptive combined space-time receiver, and 3) the centralized decision feedback adaptive combined space-time receiver. Analytical and simulation results are presented and performances are compared with the time only adaptive multiuser structures. The analytical and simulation results show that a significant improvement in capacity and performance can be achieved by utilizing the adaptive combined space-time receivers.

The performance of the adaptive space-time receiver is also studied in frequency selective fading channels. Analytical and simulation results show that the space-time structure has the ability to perform the task of the RAKE receiver. It is found that the proposed space-time receivers combines the function of multiuser detection, adaptive array processing, ISI equalizer and RAKE reception in a single structure.

The normalized least mean squares (NLMS) algorithm is used to adapt the filter coefficient. It is found that even though the adaptive space-time receiver has more coefficients to adapt, its training period is much less than that of the time only multiuser receiver and its training period less sensitive to the number and power of interferers. Also a study of the effect of time varying user populations and packet transmission shows the ability of the adaptive space-time structures to handle this kind of environment and makes them a very attractive solution for high capacity packet wireless systems.

Acknowledgments

I wish to express my sincere gratitude to my thesis supervisor, Professor David D. Falconer, for his wise advice, competent guidance, gentle encouragement and genuine friendliness throughout my thesis research. His fine examples of professional and personal conduct have left an indelible impression not only on me but on every body who has the opportunity to meet him.

I also want to express my sincere gratitude to Professor Asrar Shiek for his help during my first year in the Ph.D. program.

I thank Professor Roshdy Hafez for his help, valuable discussions, and cooperation during my graduate studies at the department of Systems and Computer Engineering at Carleton University.

I also would like to express my thanks to my friend, Dr. Mohamed G. Eltarhuni, for his patience while listening to my ideas and interesting discussions that follows. Also I would like to thank him for his help during my stay in Canada.

I thank all the student in the WCBS lab, previously called PCS lab, for putting up a nice working environment. Moreover, I am appreciative of the faculty and staff of Carleton University and the department of Systems and Computer Engineering who provided much support through the period of my study.

I am indebted to my parents, Murray Legnain and Salma Mobark, and my brothers and sisters, for their steadfast love, support and encouragement. I dedicate this work to my father and mother.

Finally and most importantly, I am also indebted to my wife, Hanan, and my children, Fatma, Asma, Murray, and Zakariya, for their love support and encouragement.

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List of Abbreviations

Abbreviation	Meaning
AAA	Adaptive Antenna Array
AAP	Adaptive Array Processing
AOA	Angle Of Arrival
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CMF	Chip Matched Filter
dB	decibel
DFE	Decision Feedback Equalizer
DS-CDMA	Direct Sequence - Code Division Multiple Access
DS/SS	Direct Sequence / Spread Spectrum
FDMA	Frequency Division Multiple Access
FH/SS	Frequency Hopping / Spread Spectrum
FIR	Finite Impulse Response
FPA	Full Power Access
ISI	Intersymbol Interference
LMS	Least Mean Square
MAI	Multiple Access Interference
MMSE	Minimum Mean Square Error
MSE	Mean Square Error

Abbreviation	Meaning
MUD	Multi-User Detection
NFP	Near Far Problem
NLMS	Normalized Least Mean Square
PG	Processing Gain
PIC	Parallel Interference Cancellation
PN	Pseudo-Random Noise
RPA	Ramp Power Access
SIC	Successive Interference Cancellation
SIR	Signal to Interference Ratio
SNR	Signal to Noise Ratio
SS	Spread Spectrum
TDMA	Time Division Multiple Access

Chapter 1

Introduction

The demand on wireless communication due to freedom in location and time has increased recently. Cochannel interference due to this rapid increase in demand on wireless communication becomes a major problem. As the demand on wireless communication continues to grow, and due to the limited available spectrum, the need for the development of an efficient transmission and multiple access techniques to efficiently utilize the spectrum, cancel cochannel interference, and increase the system capacity recently became a research challenge. Code division multiple access (CDMA), time division multiple access (TDMA), and frequency division multiple access (FDMA) are known multiple access techniques that allow many users to share the same wireless channel.

1.1 Background

In CDMA multiple users are allowed to share the same bandwidth over a common channel by using a pre-assigned code for each user. In TDMA each user is assigned a time slot to communicate through. In FDMA each user is given a certain frequency channel. TDMA and FDMA tend to be bandwidth limited techniques, while CDMA tends to be interference limited. Gilhousen et al prove in [23] that CDMA offers large capacity increase over the TDMA and FDMA by exploiting the multipath resolution, voice activity, antenna sectorization and robustness to interference.

Frequency hopping spread spectrum (FH-SS) and Direct sequence spread spectrum (DS-

SS) are the two main techniques used in CDMA. In direct sequence code division multiple access (DS-CDMA) the transmitted data is multiplied by a pre-assigned code to spread the transmitted energy over a wider bandwidth. This pre-assigned code has higher rate than the transmitted data. The same assigned code will be used at the receiver to recover the transmitted data. In frequency hopping code division multiple access (FH-CDMA) the transmitted carrier frequency is changed according to a specific code sequence. DS-CDMA is the most commonly used technique in CDMA systems.

Wireless communication channels suffer from many impairments which place fundamental limitations on the performance of the wireless systems. Fading, multipath, and cochannel interference are the main impairments in wireless channels. Multipath arises from scattering, reflection, and diffraction of the transmitted signal of objects that lie in the area between the transmitting and receiving antennas. Multipath causes intersymbol interference (ISI) in the received signal. The severity of the ISI depends on the delay spread of the channel. Fading describes the continuous change of the power of the received signal due to motion in combination with multipath - induced signal strength variation with location. The fading could be slow or fast depending on the Doppler spread of the channel, where the Doppler spread depends on the velocity of the mobile or reflecting objects. Cochannel interference in CDMA comes from users in the same cell and from adjacent cells who use the same bandwidth but different codes.

CDMA provides implicit diversity protection against frequency selective fading because different portions of the signal bandwidth fade independently. This protection is achieved by using the RAKE receiver to combine the resolvable multipath signal components.

In DS-CDMA, as we explained before, the transmitted data is multiplied by a preassigned code to spread the data over a wider bandwidth. A decoder which detects the signal by passing it through a matched filter, matched to the desired user code, and a decision device is known as the conventional single user detector or the conventional receiver.

A major problem with the conventional receiver is the near-far problem, where nearby strong users dominate the transmission. As a result the receiver fails to detect the signal from the far weak user. This problem is due to the multiple access interference (MAI)

where the conventional receiver ignores or makes no effort to estimate the MAI when detecting the desired user. A practical solution to the near far problem is the use of power control to keep all users with the same power at the receiver.

Multi-user detection is another solution to the near far problem. Recently interest in improving the DS-CDMA performance against the near far problem has increased. In multi-user detection the information of all user's MAI are used to detect each user. Verdu in [103] and [104] derives the optimum multiuser detector for DS-CDMA systems, and shows that the near far problem is not an inherent problem for DS-CDMA, but is due to the inability of the conventional receiver to exploit the MAI dimension. Other multiuser detectors are proposed in the literature which we will discuss in more detail in chapter 2.

Adaptive array processing and smart antennas, is another class of useful techniques to mitigate the cochannel interference, fading, and multipath in the wireless channel [70] [113]. The adaptive array can cancel the cochannel interference by placing nulls in the antenna beam pattern in the direction of the interference. It also can combine the multipath components of the desired user by placing beams in the antenna beam pattern in the direction of that paths. Results reported in [25] and [79] show that even a reduction in the effect of delay spread can be achieved by employing the adaptive array processing.

Adaptive antenna arrays may be combined with a multiuser detector or interference canceller to enhance the performance of the wireless communication system. An adaptive antenna array in combination with an interference canceller for CDMA systems is shown subsequently to have improved performance and increased capacity that can't be achieved by each technique alone. Problems of the conventional antenna array and the conventional receiver such as low signal to interference ratio, the near far problem, and interference with same angle of arrival (AOA) as the desired user can be solved by the combined techniques. In this thesis we focus on combined adaptive array antenna and equalization to increase the wireless CDMA systems capacity and improve the performance.

1.2 Thesis Contributions

We have made several contributions in this thesis to the body of digital communication literature. These contributions are:

- 1) The development of the adaptive combined linear space-time receiver for CDMA.
 - Analysis of the optimum tap weights and the MMSE in synchronous and asynchronous CDMA systems.
 - Closed form expressions for the auto-correlation matrix and the cross-correlation vector.
 - Comparison study between the linear space-time receiver and the time only receiver in synchronous and asynchronous CDMA systems.
- 2) The development of the adaptive combined decision feedback space-time receiver.
 - Analysis of the optimum tap weights and the MMSE in MAI and ISI channels.
 - Closed form expressions for the auto-correlation matrix and the cross-correlation vector.
 - Comparison study between the linear and decision feedback structures in MAI, ISI, and AWGN channels
- 3) The development of the adaptive combined centralized decision feedback receiver.
 - Analysis of the optimum tap weights and the MMSE in MAI and ISI channels.
 - Closed form expressions for the auto-correlation matrix and the cross-correlation vector.
 - Comparison study between the linear and decision feedback structures in MAI, ISI, and AWGN channels
- 4) Design and analysis of the linear space-time receiver in frequency selective fading channel.
 - Analysis of the optimum tap weights and the MMSE.
 - Closed form expressions for the auto-correlation matrix and the cross-correlation vector.
 - Comparison study between the linear space-time structure and the time only structure

in frequency selective fading channel.

5) Studying some practical issues related to the space-time structures in cellular wireless CDMA system

- Studying the transient behavior of the linear space-time receiver
- Studying the effect of time varying user population
- Studying the effect of packet transmission
- Studying the effect of out-off-cell interference with the same spreading code as the desired user
- Studying the effect of out-off-cell interference and shadowing on the outage probability

Several of the main ideas of this work have already been published in several papers. The Adaptive linear combined space-time receiver is published in [54]. The Adaptive decision feedback combined space-time structure is published in [50]. In [49] we present the Adaptive centralized decision feedback combined space-time receiver. The performance of the linear adaptive combined space-time receiver in frequency selective fading channel is published in [51]. The effect of time varying user population and packet transmission is presented in [50]. The transient behavior of the linear adaptive combined space-time receiver is published in [48]. An invited tutorial paper about space-time processing is published in [17].

1.3 Thesis Structure

Overview of recent research in the area of multiuser detection, adaptive array processing, and combined spatial and temporal techniques for DS-CDMA systems are given in chapter 2. In chapter 3 we develop the Adaptive linear combined space-time structure. Analysis of the MMSE and the optimum tap weights for the linear structure is also given in chapter 3. In chapter 4 we propose and analyze the adaptive decision feedback combined space-time receiver. A comparison study between the linear and the decision feedback structures is also given in chapter 4. The adaptive centralized decision feedback receiver is proposed in

chapter 5. Analysis of the optimum tap weights and the MMSE of the centralized structure is presented in chapter 5. A comparison study among the linear, decision feedback, and the centralized structures in MAI and ISI channels is also given in chapter 5.

Chapter 6 is devoted to the frequency selective fading channels. In chapter 6 we study the performance of the linear space-time structure in frequency selective fading channels. In chapter 7 we study some practical issues related to the space-time structures in cellular wireless CDMA systems.

Chapter 2

Spread Spectrum Multiple Access

For several decades spread spectrum communication was considered only for military applications. The reason is for its ability to deal with anti-jamming and low probability of intercept problems which have a major concern in military communication [92]. Recently, spread spectrum communication has been shown to have many interesting applications in civilian communication systems. Spread spectrum is one of the strongest candidates for cellular communication systems and third generation wireless communication [8], [76], [77], [108].

2.1 Related Research on Spread Spectrum Systems

Conventional Receiver

A bank of K conventional receivers for receiving each of K interfering DS-CDMA signals is shown in Fig-(2.1), and it consists of a bank of matched filters followed by decision devices. Due to the cross-correlation between the spreading codes and since the conventional receiver makes no effort to estimate the multiple access interference (MAI), cochannel interference will affect the performance of the conventional receiver. If the spreading gain is N , and there are K equal power interfering CDMA signals with different codes, the signal to total interference ratio at the input is roughly N/K . Moreover, if the received power of the different users are not the same, the strongest user will dominate the transmission, and the conventional receiver will fail to detect the signal for the weakest users. This is known as the near-far problem. The only practical solution to this problem is the

use of power control. Also by designing spreading codes with good cross-correlation properties and the use of powerful forward error correction codes the problem of near-far reception can be minimized.

Optimum Multi-User Detector

Verdu shows that the near far problem is not an inherent problem for the CDMA systems, but is due to the inability of the conventional receiver to exploit the MAI dimension. In [104], and [105] he developed the multiuser maximum likelihood detector, or simply the optimum multiuser detector. It is optimum in the sense that it minimizes the probability of error. The optimum receiver is shown in Fig-(2.2) and it consists of a bank of matched filters followed by a multi-user Viterbi processor. Verdu shows that there is no performance degradation due to the MAI. Unfortunately the optimum multiuser detector has complexity that grows exponentially with the number of users and it is not practical for cellular systems where the number of users is high. Another problem of the optimum multiuser detectors is that it requires the knowledge of the received signals powers, delays, and the spreading codes for all users.

Suboptimum Multi-User Detector

Due to the complexity of the optimum receiver and the near far problem of the conventional receiver many researchers sought a suboptimal receiver that has performance comparable to the optimum receiver and complexity does not depend on the number of users or grows linearly with the number of users. In the following paragraphs we will survey some of the suboptimal multiuser detectors found in the literature.

Linear Multi-User Detector

One of the important multiuser detectors is the decorrelating receiver which is shown in Fig-(2.3). It was proposed in [59] and [60]. The decorrelating receiver applies the inverse of the correlation matrix $\mathbf{R}$ of the spreading codes to the output of the bank of matched filters,

Fig-(2.1) The block diagram of the conventional receiver.

Fig-(2.2) The block diagram of the optimum multiuser receiver.

where in the case of synchronous interference,

$$\mathbf{R} = \begin{bmatrix} 1 & \rho_{2,1} & \dots & \rho_{N,1} \\ \rho_{1,2} & 1 & \dots & \rho_{N,2} \\ \dots & \dots & \dots & \dots \\ \rho_{1,N} & \rho_{2,N} & \dots & 1 \end{bmatrix} \quad (2.1)$$

and

$$\rho_{i,j} = \begin{cases} 1 & i=j \\ \frac{1}{T_b} \int_{T_b} c_i(t) c_j(t) dt & i \neq j \end{cases} \quad (2.2)$$

where T_b is the symbol period, N is the number of users, $c_i(t)$ is the spreading code of the i^{th} user.

The decorrelating receiver completely eliminates the MAI and it is analogous to the zero forcing equalizer used to eliminate the intersymbol interference (ISI). It is found that the decorrelating receiver has many interesting properties such as: 1) significant capacity gain over the conventional receiver; 2) it is not required to estimate the energy of the users; 3) its complexity is linear with the number of users, so it is less complex than the optimum multiuser receiver. The drawback of the decorrelating receiver is that there is a noise enhancement at the output in a similar way as the zero forcing equalizer does.

The minimum mean square error (MMSE) multiuser detector is another common approach which takes into account the background noise. This type of detector was proposed in [61], [62], and [114]. This structure applies the linear transformation, T , to the output of a bank of matched filters, see Fig-(2.4), where in the synchronous case T is equal to

$$\mathbf{T} = \left[\mathbf{R} + \left(\frac{N_o}{2} \right) \mathbf{A}^{-2} \right]^{-1} \quad (2.3)$$

Fig-(2.3) The block diagram of the decorrelating receiver.

Fig-(2.4) The block diagram of the MMSE receiver.

where $\mathbf{R}$ is the cross-correlation matrix given in Eq.(2.1), $\mathbf{A}$ is a diagonal matrix containing the received amplitudes of the users, and $\left(\frac{N_o}{2}\right)$ is the two sided power spectral density of the background noise. As can be seen, the MMSE detector takes into account the background noise. If the background noise goes to zero the MMSE detector will converge to the decorrelating receiver. The MMSE multiuser detector is analogous to the MMSE equalizer used to combat the ISI. From the linear transformation $\mathbf{T}$ the MMSE multiuser detector requires estimation of the received amplitudes of the all users. Also its performance depends on the power of the MAI. Therefore, compared to the decorrelating receiver there is some loss in the resistance to the near far problem. However the important advantages of the MMSE multiuser detector is the adaptive implementation of this detector.

Subtractive Interference Cancellation

Subtractive interference multiuser detectors are another important group of multiuser detectors. They are classified as successive interference cancellation and parallel interference cancellation.

Successive Interference Cancellation (SIC)

In successive interference cancellation techniques [46], a conventional receiver detects the strongest interference, makes hard data decisions, respreads the data, and cancels it from the received signal. This process is repeated until all interferers are cancelled. The problems with this multiuser detector are: 1) the strongest user will not benefit from the MAI cancellation; 2) The signals should be ordered in a descending order according to their received powers, so any change in the MAI power profile requires reordering the signals again; 3) one bit delay is required per stage; 4) if the first stage estimate is not reliable, then the power of the interference will quadruple.

Parallel interference cancellation (PIC)

Parallel interference cancellation (PIC) was proposed in [45], [46], [100] and [101] where all the MAI for each user are estimated and subtracted in parallel. The first stage of the PIC

Fig-(2.5) The block diagram of the parallel interference cancellation receiver.

Fig-(2.6) Multistage parallel interference cancellation receiver.

multiuser detector is shown in Fig-(2.5) and Fig-(2.6). The outputs of a bank of matched filters are passed through a hard decision device to get an estimate of the detected bits, these bits are multiplied by the estimate of the amplitude of the received signals, respread by the spreading codes for each user, and subtracted from the received signal. A good review of the multiuser detection can be found in [14], [47], [71], [105] and [107].

Adaptive Multi-User Detector

The optimum and the suboptimum multiuser detectors discussed above generally require side information such as the spreading codes, powers, and delays for each user, which increase the complexity of the multiuser detectors. Furthermore, if they operate in multipath channels the knowledge of each path gain and delay is also required.

Adaptive structures for multiuser detection which do not require explicit knowledge of any of the variables mentioned above are proposed in [1], [64], and [87]. Even the spreading code for the desired user is not required. The only requirement is that the spreading code for each user should be repeated each transmitted bit. The adaptive nature for these structures requires overhead bits to train the coefficients. These detectors have many interesting features besides not requiring side information. They have much better performance than the conventional receiver, and are much less complex than the optimum receiver. Their complexity does not depend on the number of users. Even more, [1] and [64] showed that these structures combine the function of RAKE reception and MAI cancellation. Also these detectors are found to be near far resistant, so they do not require strict power control. The simplicity of these structures make them attractive not only for the base station but for the mobile too. The structure in Fig-(2.7) is called adaptive linear multiuser detector, and the structure in Fig-(2.8) is called adaptive decision feedback multiuser detector. These detectors are proposed in [1] and [64]. Another structure proposed in [87] is called centralized adaptive decision feedback multiuser detector, where the receiver has access to the detected symbols of all users.

The adaptive multiuser detectors discussed above require transmission of a sequence of training bits to adapt the receiver coefficients, and the spreading code should be repeated each bit (short code).

Fig-(2.7) The block diagram of the adaptive linear multiuser receiver.

Fig-(2.8) The block diagram of the decision feedback multiuser receiver.

Since in CDMA users start and end their transmission randomly, the training operation of the adaptive multiuser detection may be a difficult task in such a environment, because the detector needs to be continuously trained as new interferers enter and old interferers leave the system at random times. Honig et al [32] propose a blind multiuser detector that does not require a training sequence. Study of the convergence behavior of the LMS adaptive multiuser detector is done in [65] and [55]. Review of recent research on adaptive multiuser detection could be found in [106] and the references therein.

Adaptive Antenna Array (AAA)

All the adaptive and non adaptive structures mentioned above can be considered as temporal filtering. Further increase in the ability of any receiver to cancel cochannel interference can be achieved by the exploitation of the spatial domain. Adaptive array processing can discriminate among users according to their geometrical location or their angle of arrival (AOA) to the receiving antenna. Adaptive array processing is useful in canceling cochannel interference by placing nulls in the antenna beam pattern in the direction of that interference. [25], [26], [29], [37], [70] and [79] are good references in adaptive array processing. The conventional adaptive antenna array structure is shown in Fig-(2.9).

Adaptive Antenna Array in wireless Systems

In [112] Winters studies the use of adaptive antenna array (with optimum combining) to increase the capacity of radio communication systems with multiple users. In [112] Winters used space diversity not only to combat Rayleigh fading of the desired signal but also to reduce the power of the cochannel interference at the receiver. By optimum combining, the received signal at the antennas are weighted and combined to maximize the output signal to interference plus noise ratio. In [109] Winters studies the use of optimum combining for indoor radio systems with multiple users. Results show that the system with a L-element adaptive receiving antenna can achieve up to a L-fold increase in the number of users. [42] studys the capacity improvement using antenna array in third generation CDMA wireless systems.

θ is angle of arrival (AOA) of $s(t)$

Fig-(2.9) The conventional adaptive antenna array.

Combined Techniques

Combination of the spatial domain (adaptive array processing) and the temporal domain (multiuser detection) can further increase the capacity of the CDMA cellular system and enhance the interference cancellation capabilities of the CDMA multiuser detectors.

Combined Diversity & Equalization

For non CDMA systems the work in [67], [68], [69], [99] and [58] combine diversity (spatial) and equalization to combat cochannel interference and fading. Falconer et al in [18] survey recent advances in equalization and diversity combining in digital portable wireless systems. For CDMA systems the combination of diversity and DFE equalization is proposed in [96].

Combined AAA & Conventional CDMA Receiver

In CDMA systems the total power of interference and noise is much larger than the desired user's power at the chip level. The problem with conventional beam forming (adaptive antenna array) is that it can't converge in a situation where the signal to interference plus noise ratio is small. Kohno in [44] combined the adaptive array processing and the conventional receiver. He uses the inherent processing gain for the CDMA system to update the weights of the adaptive antenna array. The structure gives some improvement in capacity but has many disadvantages. Due to the use of a conventional receiver this structure is still not near-far resistant. Also if there is a high interference level and many users have the same angle of arrival (AOA) as the desired user, the adaptive antenna array will not be effective in separating interferers.

Combined AAA & Subtractive Interference Cancellation

To solve these problems Kohno proposed in [46] a combination of an adaptive array and a multiuser interference canceller. Kohno found that this system can achieve high performance and stable acquisition in heavy traffic or when many users have the same AOA as the desired user, where the conventional antenna array can't. However performance of both structures, [44] and [46], can be degraded by the delay in the feedback control loop. Also the structure proposed in [46] requires many adaptations and the canceller needs to

be adapted first before the array adapts. Moreover, in wireless cellular systems where the number of interferers is in the order of 60 or more the Kohno structure is not useful. Because the antenna array can cancel only $L-1$ interferers in non multipath and fading channels and even fewer than $L-1$ in multipath and fading, where L is the number of antenna elements. A review of his work can be found in [47].

2.2 The Proposed Structures

From the above survey of recent research in Multi-User Detection, AAA, and Combined Space-Time filtering, we introduce novel structures that jointly combine the spatial and the temporal domains to cancel cochannel interference and increase the overall capacity of the CDMA system. The proposed structures can be seen as extensions of the structures proposed in [1], [64], and [87] to the spatial domain.

In this thesis we propose a joint combination of AAA and adaptive multi-user structure. AAA is used in this thesis to steer beams toward the desired user and his multipath components, and place nulls in the antenna beam pattern in the directions of interference to reduce or eliminate their effects.

In this thesis we introduce three novel structures for CDMA systems. The first structure is called the linear adaptive combined space-time receiver, the second structure is called the decision feedback adaptive combined space-time receiver, and the third structure is called the centralized decision feedback adaptive combined space-time receiver. In all structures a L -element linear array is used. Each element is followed by a chip matched filter and a FIR filter processing samples at the chip rate. Where in the decision feedback adaptive space-time receiver another FIR filter is used to feed back the detected symbols for the desired user to improve the performance. In the centralized structure the detected symbols from all users are fed back through a FIR filter to improve the performance. Detailed description and analysis of all structures are the subject of the thesis.

The proposed structures have many interesting features as follows: (1) Large increase in capacity compared to the conventional receiver and the detectors proposed in [1] and [64]; (2) Near-far resistance with no need for strict power control; (3) No side information is

required such as delays, powers, spreading codes, and channel impulse responses. Even the code for the desired user is not needed. The only information needed is the delay of the desired user and a training sequence; (4) Complexity does not depend on the number of users, so it is much less complex than the optimum multi-user detector; (5) It can adapt in heavy traffic conditions with several users having the same angle of arrival (AOA) as the desired user, while the conventional adaptive array can't; (6) It jointly adapts the array and the detector. So, it solves the problem of adapting the array and the canceller separately, which is mentioned in [46]; (7) Combines the function of multiuser detection, adaptive antenna array, RAKE reception, and ISI equalizer in a single structure.

Also considering the complexity of our proposed structures we found that it is comparable to that of the conventional receiver with antenna array. Considering only the forward tap coefficients, and assuming the length of each forward filter is N (the spreading gain) we see that the total number of multiplications per output bit is $L*N$, which is the same as that of a coherent conventional receiver in which there is a correlator at the output of each of the L elements. The main difference is that the multiplications in our receiver are complex, while those of the conventional receiver involve multiplying element outputs by chip values (± 1), and our receiver requires an adaptation algorithm.

Chapter 3

Linear Adaptive Combined Space-Time Detector for CDMA Systems

In this chapter the linear adaptive combined space-time detector for CDMA systems are described and discussed in more detail. First Section 3.1 describes the received signal and channel model for the proposed structure. In section 3.1 the signal and channel model for DS-CDMA system is described. In section 3.2 the block diagram of the Linear Space-Time Receiver is given and described. The analysis of the optimum tap weights and the MMSE in synchronous and asynchronous CDMA systems is given in sections 3.2.1 and 3.2.2. In sections 3.3 to 3.7 we evaluate the performance of the linear space-time structure in synchronous and asynchronous CDMA systems. Finally section 3.8 concludes the chapter.

3.1 Signal and Channel Model

Consider a CDMA base-station receiver with K users as shown in Fig-(3.1). The signal transmitted by the k^{th} user is denoted by $S_k(t)$, where $k = 1, 2, \dots, K$. Assume that $S_1(t)$ is the signal for the desired user, and $S_k(t)$, $k = 2, 3, \dots, K$ are considered as co-channel interference with respect to the desired user. Each received signal comes from a certain direction depending on the location of each user, see Fig-(3.2). We assume that the direction of arrival (θ_k) is uniformly distributed in $[-\pi/2, \pi/2]$. In this analysis we assume two cases, the synchronous and the asynchronous multiuser channel to see the resistance of our structures against the MAI and near-far problem.

The receiver uses a L -element linear uniform array with inter-element distance separation

d. The received signal by the l^{th} antenna element is

$$x_l(t) = \sum_{k=1}^K r_k(t) A_l(\theta_k) + N_l(t) \quad (3.1)$$

where the complex baseband received signal from the k^{th} user is

$$r_k(t) = \sqrt{p_k} \sum_i b_k^i c_k(t - iT_b - \tau_k) \quad (3.2)$$

In these equations, T_b is the symbol period, b_k^i is the data symbol transmitted by user k in the i^{th} interval, p_k is the received power of the k^{th} user, $N_l(t)$ is a zero mean complex gaussian random variable with power spectral density N_o at the l^{th} antenna element, τ_k is the delay for the k^{th} user, we assumed that $\tau_1 = 0$ for the desired user, $c_k(t)$ is the code sequence of the k^{th} user, where

$$c_k(t) = \sum_{m=0}^{N-1} a_k(m) \Pi(t - mT_c) \quad (3.3)$$

$a_k(m) \in (1, -1)$ is the m^{th} chip of the k^{th} user, and T_c is the chip period. $\Pi(t)$ is a unit rectangular pulse of duration T_c , $T_c = T_b/N$ is the chip period, N is the processing gain, $A_l(\theta_k)$ is the steering coefficient of the k^{th} user at the l^{th} antenna element, where

$$A_l(\theta_k) = e^{-j2\pi \frac{d}{\lambda} \left(l - \frac{1+L}{2} \right) \sin \theta_k} \quad (3.4)$$

Fig-(3.1) CDMA Cell Site.

Fig-(3.2) DS-CDMA transmitter and antenna elements structure.

Where L is number of elements, λ is the wave length, l is the element number. θ_k is the angle of arrival (AOA) of the k^{th} user with respect to the array normal.

3.2 Analysis of the Tap weights and the MMSE

The receiver structure is shown in Fig-(3.3). The structure utilizes a L -element linear uniform array antenna with element separation d . Each element is followed by a chip matched filter (CMF) whose output is sampled at the chip rate, and is passed through a FIR filter which has a delay for each tap equal to the chip period and the number of taps equal to the processing gain N . All the L -adaptive FIR filter outputs are summed and sampled at the bit rate to form a soft decision output which is passed through a decision device to form an estimate of the transmitted bits. The structure in Fig-(3.3) is called linear adaptive combined space-time multi-user detector. The analysis of this structure is given in the next section.

3.2.1 In Synchronous CDMA Systems

In synchronous CDMA systems where all the spreading codes are synchronous $\tau_k = 0$ for all users. The signal received by the l^{th} antenna element, $x_l(t)$, is passed through a CMF and sampled at the chip rate. Then the output from the CMF from the l^{th} antenna element is,

$$u_l(t) = \frac{1}{T_c} \int_{cT_c} x_l(t) dt \quad (3.5)$$

(a) Implemented with FIR filters

(b) Implemented with correlator

Fig-(3.3) Linear Adaptive Space-Time Receiver.

Substitute Eq.(3.1) and Eq.(3.2) into Eq.(3.5) then

$$u_l(t) = \frac{1}{T} \int_{cT_c}^c \left(\sum_{k=1}^K \sqrt{p_k} \sum_i b_k^i c_k(t - iT_b - \tau_k) A_l(\theta_k) + N_l(t) \right) dt \quad (3.6)$$

$\tau_k = 0$ for all k in the synchronous CDMA system. Also we assume that there is no multipath or fading. If we sample $u_l(t)$ at the chip rate and take N samples each symbol interval then at the i^{th} symbol interval the content of the equalizer at the l^{th} antenna element is

$$u_l^i = \sum_{k=1}^K \sqrt{p_k} b_k^i c_k A_l(\theta_k) + N_l^i \quad (3.7)$$

where c_k is the code vector for the k^{th} user, where

$$c_k = [a_k(0) \ a_k(1) \ \dots a_k(N-1)]^T \quad k = 1, 2, \dots, K \quad (3.8)$$

and the superscript T denotes transposition. Now we can do the analysis in matrix and vector format. We will drop the superscript i from our equations, since it will not affect our analysis, and defining,

$$r = [r_1 \ r_2 \ \dots r_K] \quad (3.9)$$

where r is a $K \times N$ matrix, and r_k for $k = 1, 2, \dots, K$ is the received N -dimensional signal vector from the k^{th} user and is equal to

$$r_k = \sqrt{p_k} b_k c_k \quad (3.10)$$

Let

$$A_l = \begin{bmatrix} e^{-j2\pi\frac{d}{\lambda}\left(l-\frac{L+1}{2}\right)\sin\theta_1} & e^{-j2\pi\frac{d}{\lambda}\left(l-\frac{L+1}{2}\right)\sin\theta_2} & \dots \\ & e^{-j2\pi\frac{d}{\lambda}\left(l-\frac{L+1}{2}\right)\sin\theta_K} & \\ & \dots e & \end{bmatrix}^T \quad (3.11)$$

be a K -dimensional vector containing the steering coefficients for the K users at the l^{th} element. Then the content of the FIR filter of the l^{th} antenna element in vector form is

$$u_l = A_l^T r + N_l \quad (3.12)$$

Let

$$w_l = [w_{l,1} \ w_{l,2} \ \dots w_{l,N}]^T, \quad l = 1, 2, \dots, L \quad (3.13)$$

where w_l is the N -dimensional weight vector for the FIR filter of the l^{th} antenna element. Now we can define the contents of all the FIR filters and their tap weights in a vector form.

Let

$$W = [w_1^T \ w_2^T \ \dots w_L^T]^T \quad (3.14)$$

where W is a LN -dimensional vector which contains all the FIR filters coefficients. Let

$$U = [u_1^T \ u_2^T \ \dots u_L^T]^T \quad (3.15)$$

be a LN -dimensional vector containing the contents of all the FIR filters.

Now after defining the vectors W and U we can calculate the optimum tap weights and the minimum mean square error (MMSE) of our structures.

The output of the structure shown in Fig-(3.3) is

$$y = W^H U \quad (3.16)$$

The mean square error is

$$MSE = 1 - W^H P - P^H W + W^H R W \quad (3.17)$$

where the superscript H denotes the Hermitian transposition, R is the autocorrelation matrix of the input vector U and is equal to,

$$R = E(UU^H) \quad (3.18)$$

and P is the cross-correlation vector between the input vector U and the desired output b^1 , where b^1 denotes the data from the first user,

$$P = E(Ub^1) \quad (3.19)$$

To find the optimum coefficients, W_{opt} , from the Weiner-Hopf solution

$$W_{opt} = R^{-1} P \quad (3.20)$$

substitute W_{opt} into Eq.(3.17) to find the minimum MSE (MMSE), then

$$MMSE = 1 - P^H W_{opt} = 1 - P^H R^{-1} P \quad (3.21)$$

In order to find W_{opt} and the MMSE we need to calculate R and P which are shown

below.

$$R = E[UU^H] = E \left[\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_L \end{bmatrix} \begin{bmatrix} u_1^* & u_2^* & \dots & u_L^* \end{bmatrix} \right] \quad (3.22)$$

$$R = \begin{bmatrix} Ru_1u_1 & Ru_1u_2 & \dots & \dots & Ru_1u_L \\ R^*u_1u_2 & Ru_2u_2 & \dots & \dots & Ru_2u_L \\ \dots & \dots & \dots & \dots & \dots \\ R^*u_1u_L & R^*u_2u_L & \dots & \dots & Ru_Lu_L \end{bmatrix} \quad (3.23)$$

where, assuming the noise sequence is uncorrelated,

$$Ru_lu_l = E(u_lu_l^H) = \sum_{k=1}^K p_k \{c_k c_k^T\} + \sigma^2 I_{N \times N} \quad (3.24)$$

and

$$Ru_lu_n = \sum_{k=1}^K p_k c_k c_k^T A_l(\theta_k) A_n^*(\theta_k) \quad (3.25)$$

and P is equal to

$$\mathbf{P} = E \begin{bmatrix} u_1 b^1 \\ u_2 b^1 \\ \dots \\ \dots \\ u_L b^1 \end{bmatrix} = \begin{bmatrix} E(u_1 b^1) \\ E(u_2 b^1) \\ \dots \\ \dots \\ E(u_L b^1) \end{bmatrix} \quad (3.26)$$

where

$$E\{u_l b^1\} = \sqrt{p_1} c_1 A_l(\theta_1) \quad (3.27)$$

In the above analysis we here found the MMSE and the optimum taps, $\mathbf{W}_{opt}$, for a linear space-time receiver as a function of $\mathbf{R}$ and $\mathbf{P}$ in synchronous CDMA system, where $\mathbf{R}$ and $\mathbf{P}$ depend on the number of users, and antenna elements. From these results we will see later in this chapter the effect of the number of users, and number of antenna elements on the performance of our proposed structure in synchronous CDMA system. We will repeat the same analysis in asynchronous CDMA system in the next section.

3.2.2 In Asynchronous CDMA Systems

In asynchronous CDMA systems all users have different time delay where $\tau_k \neq 0$ for $k = 2, 3, \dots, K$. We assume that $\tau_1 = 0$ for the desired user. If we sample $u_l(t)$, Eq.(3.6), at the chip rate and take N samples each symbol interval, then at the i^{th} symbol interval the content of the equalizer at the l^{th} antenna element is

$$u_l^i = \sqrt{p_1} b_1^i c_1 A_l(\theta_1) + \sum_{k=2}^K \sqrt{p_k} b_k^i C_k^j A_l(\theta_k) + N_l^i \quad (3.28)$$

where the code vector C_k^i for the k^{th} user is

$$\mathbf{C}_k^i = \begin{cases} \frac{\varepsilon_k}{T_c} \mathbf{D}_k(\rho_k + 1) + \left(1 - \frac{\varepsilon_k}{T_c}\right) \mathbf{D}_k(\rho_k) & \text{if } b_k^{i-1} = b_k^i \\ \frac{\varepsilon_k}{T_c} \mathbf{B}_k(\rho_k + 1) + \left(1 - \frac{\varepsilon_k}{T_c}\right) \mathbf{B}_k(\rho_k) & \text{if } b_k^{i-1} = -b_k^i \end{cases} \quad (3.29)$$

where $\mathbf{C}_k^i$ is called the *rotated code*. Assuming $\tau_1 = 0$, then $\mathbf{C}_1 = \mathbf{c}_1$, where

$$\mathbf{D}_k(\rho_k) = \begin{bmatrix} a_k(N - \rho_k) & \dots & a_k(N - 1) & a_k(0) & a_k(1) \\ \dots & a_k(N - 1 - \rho_k) \end{bmatrix}^T \quad (3.30)$$

and

$$\mathbf{B}_k(\rho_k) = \begin{bmatrix} -a_k(N - \rho_k) & \dots & -a_k(N - 1) & a_k(0) & a_k(1) \\ \dots & a_k(N - 1 - \rho_k) \end{bmatrix}^T \quad (3.31)$$

where $\tau_k = \rho_k T_c + \varepsilon_k$, ρ_k is an integer number, $0 \leq \rho_k \leq N - 1$ and $0 \leq \varepsilon_k < T_c$.

Then as in the previous analysis we will drop the superscript i from our equations. Let

$$\mathbf{r} = [\mathbf{r}_1 \ \mathbf{r}_2 \ \dots \ \mathbf{r}_K] \quad (3.32)$$

be a $N \times K$ matrix that contains the received signal from all K users, where $\mathbf{r}_k$ for $k = 1, 2, \dots, K$ is the received signal from the k^{th} user in vector form

$$\mathbf{r}_k = \sqrt{p_k} b_k \mathbf{C}_k \quad (3.33)$$

Then the content of the FIR filter of the n^{th} antenna element in vector form is

$$u_l = A_l^T r + N_l \quad (3.34)$$

Let

$$w_l = [w_{l,1} \ w_{l,2} \ \dots w_{l,N}]^T, l = 1, 2, \dots, L \quad (3.35)$$

where w_l is the weight for the FIR filter of the l^{th} antenna element. Now we can define the contents of all the FIR filters and their tap weights in a vector form.

Let

$$W = [w_1^T \ w_2^T \ \dots w_L^T]^T \quad (3.36)$$

where W is a LN -dimensional vector which contains all the FIR filters coefficients, and let

$$U = [u_1^T \ u_2^T \ \dots u_L^T]^T \quad (3.37)$$

be a LN -dimensional vector containing the contents of the all FIR filters.

Now after defining the vectors W and U we can calculate the optimum tap weights and the minimum mean square error (MMSE) of our structures.

The output of the receiver shown in Fig-(3.3) is

$$y = W^H U \quad (3.38)$$

The mean square error is, [28]

$$MSE = 1 - \mathbf{W}^H \mathbf{P} - \mathbf{P}^H \mathbf{W} + \mathbf{W}^H \mathbf{R} \mathbf{W} \quad (3.39)$$

where the superscript H denotes the Hermitian transposition, and where $\mathbf{R}$ is the autocorrelation matrix of the input vector $\mathbf{U}$ and it is equal to,

$$\mathbf{R} = E(\mathbf{U}\mathbf{U}^H) \quad (3.40)$$

and $\mathbf{P}$ is the cross-correlation vector between the input vector $\mathbf{U}$ and the desired output b_1 , where b_1 denotes the data from the first user, then $\mathbf{P}$ is equal to,

$$\mathbf{P} = E(\mathbf{U}b_1) \quad (3.41)$$

To find the optimum coefficients, $\mathbf{W}_{opt}$, from the Weiner-Hopf solution,

$$\mathbf{W}_{opt} = \mathbf{R}^{-1} \mathbf{P} \quad (3.42)$$

substitute $\mathbf{W}_{opt}$ into Eq.(3.39) to find the minimum MSE (MMSE), then

$$MMSE = 1 - \mathbf{P}^H \mathbf{W}_{opt} = 1 - \mathbf{P}^H \mathbf{R}^{-1} \mathbf{P} \quad (3.43)$$

In order to find $\mathbf{W}_{opt}$ and the MMSE we need to calculate $\mathbf{R}$ and $\mathbf{P}$ which are shown below.

$$\mathbf{R} = E[\mathbf{U}\mathbf{U}^H] = E \left[\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_L \end{bmatrix} \begin{bmatrix} u_1^* & u_2^* & \dots & u_L^* \end{bmatrix} \right] \quad (3.44)$$

$$R = \begin{bmatrix} Ru_1u_1 & Ru_1u_2 & \dots & \dots & Ru_1u_L \\ R^*u_1u_2 & Ru_2u_2 & \dots & \dots & Ru_2u_L \\ \dots & \dots & \dots & \dots & \dots \\ R^*u_1u_L & R^*u_2u_L & \dots & \dots & Ru_Lu_L \end{bmatrix} \quad (3.45)$$

where, assuming the noise sequence is uncorrelated,

$$Ru_lu_l = E(u_lu_l^H) = p_1 (c_1 c_1^T) + \sum_{k=2}^K p_k E\{C_k C_k^T\} + \sigma^2 I_{N \times N} \quad (3.46)$$

and

$$Ru_lu_n = p_1 (c_1 c_1^T) A_l(\theta_1) A_n^*(\theta_1) + \sum_{k=2}^K p_k E\{C_k C_k^T\} A_l(\theta_k) A_n^*(\theta_k) \quad (3.47)$$

and P is equal to

$$P = E \begin{bmatrix} u_1 b^1 \\ u_2 b^1 \\ \dots \\ \dots \\ u_L b^1 \end{bmatrix} = \begin{bmatrix} E(u_1 b^1) \\ E(u_2 b^1) \\ \dots \\ \dots \\ E(u_L b^1) \end{bmatrix} \quad (3.48)$$

where

$$E\{u_l b^1\} = \sqrt{p_1} c_1 A_l(\theta_1) \quad (3.49)$$

In the above analysis we found the MMSE and the optimum taps, W_{opt} , for our proposed detector as a function of R and P in asynchronous CDMA systems, where R and P depend

on the number of users, and antenna elements. From these results we will see later in this chapter the effect of the number of users, and the number of antenna elements on the performance of our proposed structure.

3.3 Performance Evaluation of the Linear Adaptive Space-Time Structure

To evaluate our structures we calculate the MMSE using the analysis done in the last sections. In this chapter we show the performance of the Linear Space-Time Receiver using the MMSE criteria in synchronous and asynchronous CDMA systems.

3.3.1 Settings and System Parameters

For the evaluation we assumed that the system has the following parameters unless otherwise mentioned

- 1- Spreading Gain $N=8$
- 2- Synchronous and asynchronous DS-CDMA
- 3- Only AWGN and cochannel interference, i.e. no fading, multipath, or ISI.
- 4- The received $E_b/N_0=18$ dB for each user, so we assume perfect power control
- 5- The number of adaptive filter coefficients for each antenna element is equal to the processing gain.
- 6- The distance between the antenna elements $d=\lambda/2$.
- 7- Angle of arrival (AOA) is a random variable uniformly distributed in the interval $[\pi/2, -\pi/2]$ unless otherwise mentioned.
- 8- Random spreading codes.

Where in the following results the MMSE is averaged over all the random parameters: noise, data, AOA, spreading codes, and delays. 300 runs are used to get the average MMSE.

3.4 The effect of the number of antenna elements on the MMSE

The effect of the number of antenna elements on the MMSE performance is shown in Fig-(3.4). This figure is drawn by calculating the MMSE equation derived in previous sections as a function of the number of antenna elements used at the receiver. Fig-(3.4) also shows the effect of number of users accessing the wireless channel at the same time by drawing different curves, each curve represents certain number of users.

From Fig-(3.4) we see that an increase in the number of antenna elements increase the performance (minimize the MMSE) and the capacity without the need for extra bandwidth (bandwidth is kept fixed).

By adding more antenna elements the structure is able to cancel more interference. If the number of users is much less than $L \cdot P_G$ then interference effects are essentially eliminated, leaving only effects from noise. Then by further doubling the number of antenna elements we could reduce the MMSE by 3dB. Also increasing the number of users does not affect the MMSE if enough elements are used, which translate directly to more capacity. For a large number of users, doubling the number of antenna elements decreases the MMSE by more than 7dB.

Also comparing the synchronous and asynchronous results we see that there is some degradation in performance due to the asynchronous channels and this is because each user will give two interfering vectors.

(a) in asynchronous CDMA system

(b) in synchronous CDMA system

Fig-(3.4) The effect of antenna elements on the MMSE.

3.5 Capacity Comparison

In Fig-(3.5) we evaluate the capacity (number of simultaneous equal power users) of the proposed structure by calculating the MMSE as a function of number of users. In this figure we also compare the capacity of the proposed structures with the structures proposed in [64]. We did not compare it with the conventional receiver because the structures in [64] were found to outperform the conventional receiver.

We set $PG=8$ for all structures. Also we choose two sets of antennas for the proposed structure for comparison. These sets have 4 and 9 antenna elements respectively.

The curves are drawn by calculating the MMSE as a function of the number of users accessing the channel. For example, in synchronous CDMA system with 4 antenna elements we can let 30 users access the channel with a MMSE approximately equal to -15dB. For the structures in[64] only 3 users can access the channel with MMSE equal -15dB.

The significant increase in capacity by using the proposed structures is clear from the figure and we can accommodate more users than the processing gain.

For more antenna elements the structure outperform the time only linear MMSE receiver and become more robust against cochannel interference. For example with 9 antenna elements we can let 30 users access the channel with MMSE equal to -25dB, where for the time only linear MMSE receiver we can't get this level of performance even with one user (i.e. no interference at all).

Also comparing the synchronous and asynchronous results we see that there is some degradation in performance due to the asynchronous channels and this is because each user will give two interferers. For example the proposed structure with 4 antenna elements and 20 users can be used in the system with MMSE equal to -20dB in synchronous channel, but in asynchronous channel only 12 users with -20dB.

(a) in asynchronous CDMA system

(b) in synchronous CDMA system

Fig-(3.5) Capacity Comparison.

3.6 Near-Far Resistance

One of the common problems in wireless CDMA systems is the near-far problem, where the power of the received signals for different users are not the same. In consequence the conventional receiver will fail to detect the signal from weakest user, and the users with the highest power will dominate the transmission. As mentioned earlier in this thesis, the only practical remedy to this problem for the conventional receiver is the employment of strict power control [23].

One of the most desirable features of any CDMA receiver is to be near-far resistant, such that the performance of the receiver does not depend on the received powers of the different users. In this section we will evaluate the performance of the proposed structures in a near-far environment.

Fig-(3.6) shows the MMSE of the proposed structure as a function of the interference to desired signal ratio. Fig-(3.6) shows 3 different cases with different number of users accessing the channel. In this result we calculate the MMSE for 2, 16, and 20 users. We set the number of the forward FIR filter taps equal to the processing gain which is equal to 8, and the number of antenna elements equal to 4.

In the three cases we change the power of only one interferer keeping the other interference powers fixed at the same value as that of the desired signal and calculate the MMSE as a function of interference to desired user power ratio. The resistance of the proposed structure to the near-far resistance is clear from this figure and there is no need for strict power control, which will minimize the complexity of the receiver.

(a) in asynchronous CDMA system

(b) in synchronous CDMA system

Fig-(3.6) The effect of the Near-Far problem on the MMSE.

Also we see from Fig-(3.6) that the effect of M interferers with the same power as the desired user is worse than the effect of one interferer with power equal to M times the power of the desired user, which contradicts [64] due to the use of antenna array, and this is likely due to the fact that the antenna array can place a null in the direction of one interferer much easier than to place nulls in the directions of many interferers. So no matter what is the power of the interference, the structure will place a null in space and time to null out that interference.

3.7 The effect of AOA on the MMSE

Adaptive antenna arrays differentiate between users according to their AOA by placing nulls in the direction of interference and placing a beam towards the direction of the desired user. A common problem in AAA is that it can't differentiate between users with the same AOA or even can't converge toward the MMSE solution. This problem is usually found when the interference and the desired user are close to or at the same AOA. When the number of users is small the probability that two users have the same AOA is small. However in high traffic channels (i.e. large number of users) like cellular systems this probability will increase and will affect the performance of the AAA.

The structure proposed in this chapter combines the spatial and the temporal domains jointly to cancel cochannel interference and increase the capacity of the system. However if the interference has the same AOA as the desired user then these structures may cancel the interference only in the time domain. Also if the interference code has high crosscorrelation with the desired user then the structure may cancel the interference in the space domain only.

In this section we will show the effect of the AOA on the performance of the proposed structures. Fig-(3.7) shows the effect of one or many interferers having the same AOA as the desired user.

Fig-(3.7) The effect of interferences with same AOA as the desired user in synchronous CDMA system.

Fig-(3.7) Shows that there is some degradation in performance when interference has the same AOA as the desired user. However the structure can still work and give good performance compared to the AAA. This is because the structure has the ability to cancel interference in the spatial and temporal domains jointly, when ever interference has same AOA the structure will try to cancel this interference in the time domain.

3.8 Conclusion

The Linear space-time structure has been described in details. Also, the analysis of the optimum tap weights and the minimum mean square error in synchronous and asynchronous CDMA systems are given. A closed form for the correlation matrix R and the cross correlation vector P are derived. R and P found to be function in the number of antenna elements, number of users, spreading codes, AOA, and the noise power spectral density. The numerical evaluation of the structure based on these analyses is also given in this chapter. In the next chapter we will propose another novel structure which is called the adaptive decision feedback combined space-time detector.

Chapter 4

Decision Feedback Adaptive Combined Space-Time Detector for CDMA Systems

In this chapter we develop the decision feedback adaptive combined space-time detector. The structure uses the knowledge of the detected symbols of the desired user and feeds them back through a FIR filter with a tap delay equals to the bit duration. This detector does not require any side information except the detected symbols and the delay of the desired user. Even the code of the desired user is not required.

4.1 Introduction

In this chapter we propose a modified version of the linear adaptive combined space-time detector proposed in the previous chapter. The new detector uses the feedback equalizer structure. It feeds back the detected symbols to a FIR filter with tap delay equal to a bit duration and whose length depends on the channel delay spread. The output of the all feed forward FIR filters and the feed backward FIR filter is added and sampled at the bit rate to form a soft decision output, then passed through a decision device to form an estimate for the transmitted bits. Fig.(4.1) shows the block diagram of this receiver.

4.2 Signal and Channel Model

Consider a CDMA receiver with K users. The signal transmitted by the k^{th} user is denoted by $S_k(t)$, where $k = 1, 2, \dots, K$. Assume that $S_1(t)$ is the signal from the desired user,

and $S_k(t)$, $k = 2, 3, \dots, K$ are considered as co-channel interference with respect to the desired user. Each signal received comes from a certain direction. We assume that the direction of arrival (θ_k) is uniformly distributed in $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$. To see the resistance of our structure against co-channel interference and ISI, in this analysis we assume multiple users and inter symbol interference ISI (no fading) channel,.

The receiver uses a L-element uniform array with distance separation d.

The complex baseband transmitted signal from the k^{th} user is

$$S_k(t) = \sqrt{p_k} \sum_i b_k^i c_k(t - iT_b - \tau_k) \quad (4.1)$$

The channel impulse response at the l^{th} element is

$$\mathfrak{R}_{kl}(t) = \sum_{m=1}^M h_{km} A_l(\theta_{km}) \delta(t - t_{km}) \quad (4.2)$$

The received signal at the l^{th} element from the k^{th} user is then

$$x_{kl}(t) = \sqrt{p_k} \sum_i b_k^i \sum_{m=1}^M h_{km} A_l(\theta_{km}) c_k(t - iT_b - \tau_k - t_{km}) \quad (4.3)$$

The total received signal at the l^{th} element from all users including AWGN is

$$x_l(t) = \sum_{k=1}^K x_{kl}(t) + N_l(t) \quad (4.4)$$

In these equations, T_b is the symbol period, b_k^i is the data transmitted by user k in the i^{th} interval, h_{km} is the complex channel coefficient as seen by user k during the m^{th} path, p_k is the power transmitted by the k^{th} user, $N_l(t)$ is a zero mean complex gaussian random process with N_0 is the complex noise power spectrum at the l^{th} antenna element, τ_k is the delay for the k^{th} user, t_{km} of the m^{th} path of the k^{th} user, M is the number of the multipath components, and $c_k(t)$ is the code sequence of the k^{th} user, where

Fig.(4.1) Decision Feedback Adaptive Combined Space-Time Receiver.

$$c_k(t) = \sum_{m=0}^{N-1} a_k(m) \prod(t - mT_c) \quad (4.5)$$

$a_k(m) \in (1, -1)$ is the m -th chip of the k^{th} user, and T_c is the chip period. $\prod(t)$ is a unit rectangular pulse of duration T_c , $T_c = T_b/N$ is the chip period, N is the processing gain, $A_l(\theta_{km})$ is the steering coefficient of the k^{th} user in the m^{th} path at the l^{th} antenna element, where

$$A_l(\theta_{km}) = e^{-j2\pi \frac{d}{\lambda} \left(l - \frac{1+L}{2}\right) \sin \theta_{km}} \quad (4.6)$$

Where d is the distance between adjacent elements, L is number of elements, λ is the wave length, l is the element index. θ_{km} is the angle of arrival (AOA) of the k^{th} user in the m^{th} path with respect to the array normal.

4.3 The Proposed Structure

The new detector is shown in Fig.(4.1). It uses the decision feedback equalizer structure. the structure utilizes a L -elements array antenna. Each element is followed by a chip matched filter (CMF) whose output is sampled at the chip rate and passed through a fractionally spaced adaptive FIR filter which has a delay for each tap equal to the chip period and length equal to the processing gain. The detected symbols are fed back through a FIR filter with a tap delay equals to a bit duration and whose length depends on the delay spread of the channel. All the L -FIR filters output and the feed backward FIR filter are summed and sampled at the bit rate to form a soft decision output which is passed through a decision device to form an estimate of the transmitted bits. The structure in Fig.(4.1) is called an adaptive combined space-time decision feedback multiuser receiver. In the following analysis we will assume MAI and ISI channel only. Multipath fading will be considered in chapter 6.

The signal received by the l^{th} antenna element, $x_l(t)$, is passed through a chip matched filter and sampled at the chip rate, then at the i^{th} symbol interval the content of the FIR filter of the l^{th} element will be represented by an N -dimensional vector assuming the

number of the forward taps is equal to N for the analysis.

$$u_l^i = \sum_{k=1}^K \sqrt{p_k} \sum_{m=1}^M b_k^i h_{km}^i A_l(\theta_{km}) (\underline{C}_{km}^i)^T + N_l^i \quad (4.7)$$

In this analysis we assume that all the ISI components have the same gain, so $h_{km} = 1/M$ for all k and m , where the code vector $\underline{C}_{km}$, in the i^{th} sampling interval is,

$$\underline{C}_{km}^i = \begin{cases} \left(\frac{\epsilon_{km}}{T_c} D_k(\rho_{km} + 1) + \left(1 - \frac{\epsilon_{km}}{T_c}\right) \right) D_k(\rho_{km}) & \text{if } b_k^{i-1} = b_k^i \\ \left(\frac{\epsilon_{km}}{T_c} B_k(\rho_{km} + 1) + \left(1 - \frac{\epsilon_{km}}{T_c}\right) \right) B_k(\rho_{km}) & \text{if } b_k^{i-1} = -b_k^i \end{cases} \quad (4.8)$$

$$D_k(\rho_{km}) = [a_k(N - \rho_{km}) \dots a_k(N - 1) a_k(0) a_k(1) \dots a_k(N - 1 - \rho_{km})] \quad (4.9)$$

and

$$B_k(\rho_{km}) = \begin{bmatrix} -a_k(N - \rho_{km}) \dots -a_k(N - 1) a_k(0) a_k(1) \\ \dots a_k(N - 1 - \rho_{km}) \end{bmatrix} \quad (4.10)$$

and $\tau_k + t_{km} = \rho_{km} T_c + \epsilon_{km}$, where ρ_k is an integer number $0 \leq \rho_{km} \leq N - 1$ and $0 \leq \epsilon_{km} < T_c$

let

$$r_{km}^i = h_{km}^i S_k(iT_b - \tau_k - t_{km}) = \frac{1}{M} b_k^i (\underline{C}_{km}^i)^T \quad (4.11)$$

where the N -dimensional vector r_{km} is the received signal from the k^{th} user during the m^{th} path. Then the received signal from the k^{th} user from all paths is the matrix X_k of dimension $(N \times M)$ where X_k is equal to,

$$X_k = \begin{bmatrix} r_{k1} & r_{k2} & \dots & r_{kM} \end{bmatrix} \quad (4.12)$$

We dropped the superscript i from our equations, since it will not affect our analysis. Then the received signal from all users from the all M paths is the matrix X of dimension $(N \times KM)$ where X is equal to

$$X = [X_1 \ X_2 \ \dots X_K] \quad (4.13)$$

Let the steering vector of the of the k^{th} user for the all M paths at the l^{th} element be equal to

$$A_{lk} = \begin{bmatrix} A_l(\theta_{k1}) & A_l(\theta_{k2}) & \dots & A_l(\theta_{kM}) \end{bmatrix} \quad (4.14)$$

where A_{lk} a M -dimensional row vector. Let

$$A_l = \begin{bmatrix} A_{l1}^T & A_{l2}^T & \dots & A_{lK}^T \end{bmatrix}^T \quad (4.15)$$

be a KM -dimensional row vector containing the steering coefficients of all users for all paths, then the contents of the FIR filter of the l^{th} antenna element in vector form is

$$u_l = A_l^T X + N_l \quad (4.16)$$

Then let

$$u = \begin{bmatrix} u_1^T & u_2^T & \dots & u_L^T \end{bmatrix}^T \quad (4.17)$$

be LN - dimensional vector contains the content vectors for all the L forward FIR filters. and

$$w_l = [w_{l,1} \ w_{l,2} \ \dots w_{l,N}], \ l = 1, 2, \dots, L \quad (4.18)$$

be the taps weight for the FIR filter of the l^{th} element, then

$$\mathbf{w} = \begin{bmatrix} \mathbf{w}_1^T & \mathbf{w}_2^T & \dots & \mathbf{w}_L^T \end{bmatrix}^T \quad (4.19)$$

be a LN-dimensional vector containing the weights for the all FIR filters of the all antenna element.

Let the contents of the feedback FIR filter be

$$\mathbf{v} = \begin{bmatrix} b_{i-1}^k & b_{i-2}^k & \dots & b_{i-Q}^k \end{bmatrix}^T \quad (4.20)$$

where Q is the number of taps of the feed back filter. Let the tap weight vector for the feedback FIR filter be

$$\mathbf{z} = \begin{bmatrix} z_1^k & z_2^k & \dots & z_Q^k \end{bmatrix}^T \quad (4.21)$$

Now we can define the contents of the all FIR filters and their tap weights in two vectors.

Let

$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_1^T & \mathbf{w}_2^T & \dots & \mathbf{w}_L^T & \mathbf{z}^T \end{bmatrix}^T \quad (4.22)$$

where $\mathbf{W}$ is a (LN+Q)-dimensional vector containing the all FIR filters coefficients, and let

$$\mathbf{U} = \begin{bmatrix} \mathbf{u}_1^T & \mathbf{u}_2^T & \dots & \mathbf{u}_L^T & \mathbf{v}^T \end{bmatrix}^T \quad (4.23)$$

be a (LN+Q)-dimensional vector containing the contents of the all FIR filters.

Now after defining the vectors $\mathbf{W}$ and $\mathbf{U}$ we can calculate the optimum taps and the minimum mean square error (MMSE) of our structure.

The output of the structure shown in Figure 1 is equal to

$$y = \mathbf{W}^H \mathbf{U} \quad (4.24)$$

The mean square error is, [28]

$$MSE = 1 - W^H P - P^H W + W^H R W \quad (4.25)$$

where R is the autocorrelation matrix of the input vector U and it is equal to,

$$R = E(UU^H) \quad (4.26)$$

and P is the cross-reaction vector between the input vector U and the desired out b^1 , where b^1 denotes the data from the first user, then P is equal to,

$$P = E(Ub_1) \quad (4.27)$$

To find the optimum coefficients, W_{opt} , from the Weiner-Hopf solution, [28]

$$W_{opt} = R^{-1} P \quad (4.28)$$

substitute W_{opt} in Eq.(4.28) into Eq.(4.25) to find the MMSE,

$$MMSE = 1 - P^H W_{opt} = 1 - P^H R^{-1} P \quad (4.29)$$

In order to find W_{opt} and the MMSE we need to calculate Eq.(4.26) and Eq.(4.27) which is shown below.

$$R = E[UU^H] = \begin{bmatrix} R_1 & H \\ H^H & R_2 \end{bmatrix} \quad (4.30)$$

where

$$R_1 = E(uu^H) \quad (4.31)$$

and

$$R_2 = I_{Q \times Q} \quad (4.32)$$

and

$$H = E(uv^H) \quad (4.33)$$

and $\mathbf{P}$ is equal to

$$\mathbf{P} = E(\mathbf{U}\mathbf{b}_1) = \begin{bmatrix} \mathbf{P}_1 \\ \dots \\ \mathbf{0}_{Q \times 1} \end{bmatrix} \quad (4.34)$$

$$\mathbf{P}_1 = E \begin{bmatrix} u_1 b^1 \\ u_2 b^1 \\ \dots \\ \dots \\ u_L b^1 \end{bmatrix} = \begin{bmatrix} E(u_1 b^1) \\ E(u_2 b^1) \\ \dots \\ \dots \\ E(u_L b^1) \end{bmatrix} \quad (4.35)$$

where $\mathbf{0}_{Q \times 1}$ is a $Q \times 1$ vector with all its elements equal zeros.

In the above analysis we found the MMSE and the optimum tap weights for the proposed structure in a multipath fading channels as a function of $\mathbf{R}$ and $\mathbf{P}$, where $\mathbf{R}$ and $\mathbf{P}$ depend on the number of users, and the number of antenna elements. From these results we will see later the effect of the number of users, number of antenna elements, and the number of equalizer taps on the performance of the proposed structure.

4.4 Numerical Results

In this section we calculate the MMSE using the equations derived in the previous section as a function of the number of users and number of antenna elements. Here in these results we will see the effect of ISI on the performance of the centralized decision feedback space-time receiver. The impulse response of the channel is assumed to have three independent paths, and all the paths are assumed to have the same gain and there is no fading. The delay for each path are assumed to be uniformly distributed in the intervals $[0, T)$, $[2T, 3T)$, and $[3T, 4T)$ for the first, second, and third paths respectively.

The DS-CDMA signal used in the analysis has a processing gain(PG) equal to eight, and uses BPSK modulation. We use random codes for spreading our data with eight chips in each code. The sampling frequency of the received signal before the chip matched filter is

equal three times the chip rate, so there are three samples per chip. The angle of arrival (AOA) is modeled as a random process uniformly distributed in the interval $[-\pi/2, \pi/2]$. E_b/N_o is set to 18dB for all users unless otherwise mentioned, where $E_b = p_k T_b$. We also assume plane wave propagation, and the separation distance between antenna elements is set to $\lambda/2$. In these results 300 runs are used to average the MMSE around all the random parameters: noise, data, AOA, spreading codes, and channel impulse responses.

The effect of the number of antenna elements on the MMSE is shown in Fig.(4.2) for different numbers of users accessing the channel. We set the number of the forward taps equal to 8 and the number of backward taps equal to 5. From Figure 2 we see that by increasing the number of antenna element the structure becomes more robust against the co-channel interference, as a result the capacity is increased while the bandwidth is remains unchanged.

In Fig.(4.3) we evaluate the capacity (number of simultaneous equal power users) of the proposed structures. In this figure we also compare the capacity of the proposed structures with the structures proposed in [1]. We set PG=8 for all structures. The curves are drawn by calculating the MMSE as a function of the number of users accessing the channel. The significant increase in capacity by using the proposed structures is clear from the figure and we can accommodate more users than the processing gain.

For more antenna elements the structures outperform the structure in [1] and become more robust against cochannel interference.

In Fig.(4.4) we compared the structure proposed in this chapter with the linear space-time structure and the structures proposed in [1] and [64]. In this comparison we assume that the AOA for all paths of all users are uniformly distributed in $[-\pi/2, \pi/2]$. From Fig.(4.4) we see a huge increase in capacity for our structures compared to the one element structures proposed in [1] and [64]. Also comparing the decision feed back and the linear space-time structures there is no significant improvement in performance for the decision feed back structure compared to the linear space-time structure, i.e. there is no need for the decision feedback filter for the case where the angle of arrival of the various ISI components are

widely distributed. And this is due to the ability of the space time structure to reduce the ISI components in the space domain. From Fig.(4.4) we conclude that space-time structure can reduce the delay spread of the channel and cancel severe ISI by placing nulls in the direction of the late arrival paths. The ability of the proposed structures to suppress multipath components (which act like interference having the same spreading code as that of the desired signal), also extends to suppressing out of cell interferers which for short spreading code, may also have the same spreading codes as the desired signal. This will be seen later in chapter 7.

However if the all ISI components of the desired user have close or same AOA then we see significant gain in capacity and performance for the decision feed back structure proposed in this chapter compared to the linear space-time structure proposed in the previous chapter. Fig.(4.4) shows the effect if all the paths of the desired user have same AOA. Comparing Fig.(4.4) and Fig.(4.5) there is no degradation in performance for the decision feed back space-time structure, however there is significant degradation for the linear space-time structure. This results gives an advantage to the decision feed back over the linear space time receiver in situation where the angle spread is very small or zero, i.e. at the base station with the antenna is located high above the roof top.

4.5 Conclusion

In this chapter we propose the decision feedback combined space-time receiver. We developed a formula for the MMSE and the optimum taps. Analytical results based on the MMSE criteria showed that the decision feed back space-time structure has the ability to cancel cochannel interference and ISI. Also we found that in very small angle spreads the decision feed back structure out perform the linear space-time structure. However in large angle spreads there is no advantage of the decision feed back over the linear, the linear space-time receiver will be preferable for its simplicity.

Fig.(4.2) The effect of the No. of antenna elements and the No. of users on the MMSE.

Fig.(4.3) Capacity curve for the decision feed back combined space-time structure

Fig.(4.4) Capacity comparison between the proposed structures where AOA of the various ISI components are assumed to be widely distributed.

Fig.(4.5) Capacity comparison between the proposed structures where AOA of the various ISI components are assumed to be the same.

Chapter 5

Centralized Decision Feedback Adaptive Combined Space-Time Detector for CDMA Systems

In previous chapters in this thesis we propose and analyze the linear and decision feedback adaptive space-time detectors. We assumed that the receiver has no knowledge of the detected symbols of all users in the case of the linear space-time receiver, and we assumed that the receiver has knowledge only about the desired user symbols and feed them back through a FIR filter to enhance the performance as in the decision feedback space-time detector. As a natural extension to these two cases we propose a receiver which we assume has access to the detected symbols of all users, so that we can feed them to the detector through a FIR filter. This receiver is called the centralized decision feedback adaptive combined space-time detector

5.1 Introduction

Until this point of the thesis we considered two structures only. In the linear space-time structure we assume that the receiver has no knowledge of the detected symbols of all users, whereas in the decision feedback space-time receiver we assume that the receiver feeds back the detected symbols of the desired user only. The centralized structure which we will present in this chapter can be seen as an extension of the previous structures. In the centralized structure we assume that the receiver has access to the detected symbols of all users and can feed them back through FIR filters to improve the performance of the overall

CDMA system. This kind of information are only available at the base-station, so the practical application of the centralized detector is at the base-station. The complexity of the centralized detector is linear with the number of users and it is more complex than the linear and the decision feedback detectors. But because it's application is limited only at the base-station, so extra complexity can be acceptable.

The centralized idea is not new in the multiuser detection literature. Different detectors proposed in the literature used similar ideas of centralized decision feedback, but under different names. However, it is worth mentioning here before we start discussing these detectors that the major difference between them and our structure is the joint utilization of the spatial and temporal domains.

In [12] Duel Hallen proposed the decorrelating decision feedback multiuser detector, see Fig.(5.1). In [12], forward and feedback filters are chosen to eliminate all multiuser interference provided that the feedback data are correct. Decisions of users are made in the order of decreasing received powers. The receiver for each user linearly combines sampled outputs of the matrix matched filter with decisions of all strongest interfering users. Thus the receiver for the strongest user does not benefit from the interference cancellation property and it is equivalent to the decorrelating receiver. In [13] Duel Hallen extended the same idea to other multiuser detectors and compared them.

Another receiver was proposed by Rapajic et. al. in [87] called adaptive centralized decision feedback detector, see Fig.(5.2). In this receiver all symbols from all users are assumed to be known. The adaptive centralized decision feedback detector consists of a linear fractionally spaced adaptive filter, a centralized feedback filter, and a decision device as shown in Fig.(5.2). It was shown in [87] that this detector has the same timing recovery, near-far resistance and multipath combined properties as the adaptive linear multiuser detector proposed in [64] and [87] whereas MAI cancellation is significantly improved. However the complexity of the adaptive centralized decision feedback receiver increases linearly with number of users.

Subtractive interference cancellation is another technique that uses the decision feedback

Fig.(5.1) Decorrelating Decision Feedback Multiuser Detector [12].

Fig.(5.2) Adaptive Centralized Decision Feedback Multiuser Detector, [87].

idea to cancel the MAI [45],[100]. There are two types of subtractive interference cancellation. The first is called successive interference cancellation and the second is called the parallel interference cancellation. We discussed these detectors in chapter 2.

In this chapter we propose another novel structure for DS-CDMA systems which is called the centralized decision feedback space-time receiver. This structure is more complex than the structures proposed in the previous chapters. The difference between this structure and the other structures are; 1) no need to order users according to their received powers, 2) all users will benefit from the MAI cancellation, 3) jointly combine the antenna array (spatial domain) and the multiuser detector (temporal domain) to reduce the effect of MAI, ISI, and near-far problem, 4) no need to respread the detected symbols of the users. In this chapter we will discuss and analyze the centralized decision feedback receiver.

5.2 Signal and Channel Model

It is the same signal and channel model discussed previously but we include it here for clarity. Consider a CDMA receiver with K users. The signal transmitted by the k^{th} user is denoted by $S_k(t)$, where $k = 1, 2, \dots, K$. Assume that $S_1(t)$ is the signal from the desired user, and $S_k(t)$, $k = 2, 3, \dots, K$ are considered as co-channel interference with respect to the desired user. Each signal received comes from a certain direction. We assume that the direction of arrival (θ_k) is uniformly distributed in $\left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$. In this analysis we assume a multiuser and inter symbol interference ISI from multipath (no fading) channel, to see the resistance of our structure against co-channel interference and ISI.

The receiver uses a L -element uniform array with distance separation d .

The complex baseband transmitted signal from the k^{th} user is

$$S_k(t) = \sqrt{p_k} \sum_i b_k^i c_k(t - iT_b - \tau_k) \quad (5.1)$$

The channel impulse response at the l^{th} element is

$$\mathcal{R}_{kl}(t) = \sum_{m=1}^M h_{km} A_l(\theta_{km}) \delta(t - t_{km}) \quad (5.2)$$

The received signal at the l^{th} element from the k^{th} user is then

$$x_{kl}(t) = \sqrt{p_k} \sum_i b_k^i \sum_{m=1}^M h_{km} A_l(\theta_{km}) c_k(t - iT_b - \tau_k - t_{km}) \quad (5.3)$$

The total received signal at the n^{th} element from all users including AWGN is

$$x_l(t) = \sum_{k=1}^K x_{kl}(t) + N_l(t) \quad (5.4)$$

In these equations, T_b is the symbol period, b_k^i is the data transmitted by user k in the i^{th} interval, h_{km} is the complex channel coefficient as seen by user k during the m^{th} path, p_k is the power transmitted by the k^{th} user, $N_l(t)$ is a zero mean complex gaussian random process with N_0 is the complex noise power spectrum at the l^{th} antenna element, τ_k is the delay for the k^{th} user, t_{km} of the m^{th} path of the k^{th} user, M is the number of the multipath components, and $c_k(t)$ is the code sequence of the k^{th} user, where

$$c_k(t) = \sum_{m=0}^{N-1} a_k(m) \prod(t - mT_c) \quad (5.5)$$

$a_k(m) \in (1, -1)$ is the m -th chip of the k^{th} user, and T_c is the chip period. $\prod(t)$ is a unit rectangular pulse of duration T_c , $T_c = T_b/N$ is the chip period, N is the processing gain, $A_l(\theta_{km})$ is the steering coefficient of the k^{th} user in the m^{th} path at the l^{th} antenna element, where

$$A_l(\theta_{km}) = e^{-j2\pi \frac{d}{\lambda} \left(l - \frac{1+L}{2} \right) \sin \theta_{km}} \quad (5.6)$$

Where d is the distance between adjacent elements, L is number of elements, λ is the wave length, l is the element index. θ_{km} is the angle of arrival (AOA) of the k^{th} user in the m^{th} path with respect to the array normal.

Fig.(5.3) Centralized Decision Feedback Adaptive Combined Space-Time Receiver.

5.3 The Proposed Structure

The new detector is shown in Fig.(5.3). The structure utilizes a L-element array antenna. Each element is followed by a chip matched filter (CMF) whose output is sampled at the chip rate and passed through a fractionally spaced adaptive FIR filter which has a delay for each tap equal to the chip period and length equal to the processing gain. The detected symbols of all users are fed back through FIR filters with tap delay equal to a bit duration and with length depending on the delay spread of the channel. All the L-FIR filter outputs and all the feedback FIR filters outputs are summed and sampled at the bit rate to form a soft decision output which is passed through a decision device to form an estimate of the transmitted bits. The structure in Fig.(5.3) is called the adaptive centralized decision feedback space-time receiver. In the following analysis we will assume MAI and ISI only. The frequency selective fading channel will be discussed in chapter 6.

The signal received by the l^{th} antenna element, $x_l(t)$, is passed through a chip matched filter and sampled at the chip rate, then at the i^{th} symbol interval the content of the FIR filter of the l^{th} element will be represented by an N-dimensional vector assuming the number of the forward taps is equal to N for the analysis.

$$u_l^i = \sum_{k=1}^K \sqrt{P_k} \sum_{m=1}^M b_k^i h_{km}^i A_l(\theta_{km}) (C_{km}^i)^T + N_l^i \quad (5.7)$$

in this analysis we assume that there is no fading and all paths have same gain because we want to see the effect of ISI, so $h_{km} = 1/M$ for all k and m, the superscript T denotes transposition, where the code vector C_{km} in the i^{th} sampling interval is,

$$C_{km}^i = \begin{cases} \left(\frac{e_{km}}{T_c} D_k(\rho_{km} + 1) + \left(1 - \frac{e_{km}}{T_c} \right) D_k(\rho_{km}) \right) & \text{if } b_k^{i-1} = b_k^i \\ \left(\frac{e_{km}}{T_c} B_k(\rho_{km} + 1) + \left(1 - \frac{e_{km}}{T_c} \right) B_k(\rho_{km}) \right) & \text{if } b_k^{i-1} = -b_k^i \end{cases} \quad (5.8)$$

$$D_k(\rho_{km}) = \begin{bmatrix} a_k(N-\rho_{km}) \dots a_k(N-1) a_k(0) a_k(1) \\ \dots a_k(N-1-\rho_{km}) \end{bmatrix} \quad (5.9)$$

and

$$B_k(\rho_{km}) = \begin{bmatrix} -a_k(N-\rho_{km}) \dots -a_k(N-1) a_k(0) a_k(1) \\ \dots a_k(N-1-\rho_{km}) \end{bmatrix} \quad (5.10)$$

and $\tau_k + t_{km} = \rho_{km} T_c + \varepsilon_{km}$, where $0 \leq \rho_{km} \leq N-1$ and $0 \leq \varepsilon_{km} < T_c$,
let

$$r_{km}^i = h_{km}^i S_k(iT_b - \tau_k - t_{km}) = \frac{1}{M} b_k^i(C_{km}^i) \quad (5.11)$$

where the N -dimensional vector r_{km} is the received signal from the k^{th} user during the m^{th} path. Then the received signal from the k^{th} user from all paths is the matrix X_k of dimension $(N \times M)$ where X_k is equal to,

$$X_k = \begin{bmatrix} r_{k1} & r_{k2} & \dots & r_{kM} \end{bmatrix} \quad (5.12)$$

We dropped the superscript i from our equations, since it will not affect our analysis. Then the received signal from all users from the all M paths is the matrix X of dimension $(N \times KM)$ where X is equal to

$$X = [X_1 \ X_2 \ \dots X_K] \quad (5.13)$$

Let the steering vector of the of the k^{th} user for the all M paths at the l^{th} element is equal to

$$A_{lk} = \begin{bmatrix} A_l(\theta_{k1}) & A_l(\theta_{k2}) & \dots & A_l(\theta_{kM}) \end{bmatrix} \quad (5.14)$$

where A_{lk} is a M -dimensional row vector. Let

$$A_l = \begin{bmatrix} A_{l1}^T & A_{l2}^T & \dots & A_{lK}^T \end{bmatrix}^T \quad (5.15)$$

be a KM -dimensional row vector containing the steering coefficients of all users for all paths, then the contents of the FIR filter of the l^{th} antenna element in vector form is

$$u_l = A_l^T X + N_l \quad (5.16)$$

Then let

$$u = \begin{bmatrix} u_1^T & u_2^T & \dots & u_L^T \end{bmatrix}^T \quad (5.17)$$

be a LN - dimensional vector contains the content vectors for all the L forward FIR filters. and

$$w_l = [w_{l,1} \ w_{l,2} \ \dots w_{l,N}], \ l = 1, 2, \dots, L \quad (5.18)$$

be the taps weight for the FIR filter of the l^{th} element, then

$$w = \begin{bmatrix} w_1^T & w_2^T & \dots & w_L^T \end{bmatrix}^T \quad (5.19)$$

is a LN -dimensional vector containing the weights for the all FIR filters of the all antenna element.

Let the content of the k^{th} feedback FIR filter be

$$v_k = [b_{i-1}^k \ b_{i-2}^k \ \dots b_{i-Q}^k]^T \quad (5.20)$$

where Q is the number of taps of each feed back filter. Let

$$V = \begin{bmatrix} v_1^T & v_2^T & \dots & v_K^T \end{bmatrix}^T \quad (5.21)$$

and let the tap weight vector for the feedback FIR filter be

$$z_k = \begin{bmatrix} z_1^k & z_2^k & \dots & z_Q^k \end{bmatrix}^T \quad (5.22)$$

Then the tap weight vector of the feedback FIR filters is

$$Z = \begin{bmatrix} z_1^T & z_2^T & \dots & z_K^T \end{bmatrix}^T \quad (5.23)$$

Now we can define the contents of all the FIR filters and their tap weights in the proposed structure as two vectors.

Let

$$U = \begin{bmatrix} u_1^T & u_2^T & \dots & u_L^T & v^T \end{bmatrix}^T \quad (5.24)$$

be a $(LN+Q)$ -dimensional vector containing the contents of all FIR filters, and let

$$W = \begin{bmatrix} w_1^T & w_2^T & \dots & w_L^T & z^T \end{bmatrix}^T \quad (5.25)$$

where W is a $(LN+Q)$ -dimensional vector containing the FIR filters coefficients.

Now after defining the vectors W and U we can calculate the optimum taps and the minimum mean square error (MMSE) of our structure.

The output of the structure shown in Fig.(5.3) is equal to

$$y = W^H U \quad (5.26)$$

The mean square error is, [28]

$$MSE = 1 - W^H P - P^H W + W^H R W \quad (5.27)$$

where the superscript H denotes the Hermitian transposition, and where R is the autocorrelation matrix of the input vector U and it is equal to,

$$R = E(UU^H) \quad (5.28)$$

and P is the cross-reaction vector between the input vector U and the desired out b^1 , where

b_1 denotes the data from the first user, then P is equal to,

$$P = E(Ub_1) \quad (5.29)$$

To find the optimum coefficients, W_{opt} , from the Wiener-Hopf solution, [28]

$$W_{opt} = R^{-1}P \quad (5.30)$$

substitute W_{opt} in Eq.(5.30) into Eq.(5.27) to find the MMSE,

$$MMSE = 1 - P^H W_{opt} = 1 - P^H R^{-1}P \quad (5.31)$$

In order to find W_{opt} and the MMSE we need to calculate Eq.(5.28) and Eq.(5.29) which is shown below.

$$R = E[UU^H] = \begin{bmatrix} R_1 & H \\ H^H & R_2 \end{bmatrix} \quad (5.32)$$

where

$$R_1 = E(uu^H) \quad (5.33)$$

and

$$R_2 = \begin{bmatrix} \Phi_1 & 0 & 0 \\ 0 & \Phi_2 & 0 \\ \dots & \dots & \dots \\ 0 & 0 & \Phi_K \end{bmatrix} = I_{QK \times QK} \quad (5.34)$$

where

$$\Phi_1 = \Phi_2 = \dots = \Phi_K = I_{Q \times Q} \quad (5.35)$$

where I is the identity matrix, and

$$\mathbf{H} = E(\mathbf{u}\mathbf{V}^H) \quad (5.36)$$

and $\mathbf{P}$ is equal to

$$\mathbf{P} = E(\mathbf{U}\mathbf{b}_1) = \begin{bmatrix} P_1 \\ \dots \\ \mathbf{0}_{QK \times 1} \end{bmatrix} \quad (5.37)$$

$$\mathbf{P}_1 = E \begin{bmatrix} u_1 b^1 \\ u_2 b^1 \\ \dots \\ \dots \\ u_L b^1 \end{bmatrix} = \begin{bmatrix} E(u_1 b^1) \\ E(u_2 b^1) \\ \dots \\ \dots \\ E(u_L b^1) \end{bmatrix} \quad (5.38)$$

where $\mathbf{0}_{QK \times 1}$ is a vector with zeros.

In the above analysis we found the MMSE and the optimum tap weights for the proposed structure in multipath channels as a function of $\mathbf{R}$ and $\mathbf{P}$, where $\mathbf{R}$ and $\mathbf{P}$ depend on the number of users, and the number of antenna elements. From these results we will see later the effect of the number of users and the number of antenna elements on the performance of the proposed structure.

5.4 Numerical Results

In this section we calculate the MMSE using the equations derived in the previous section as a function of the number of users and number of antenna elements. Here in these results we will see the effect of ISI on the performance of the centralized decision feedback space-time receiver. The impulse response of the channel is assumed to have three independent paths, and all the paths are assumed to have the same gain and there is no fading. The delay for each path are assumed to be uniformly distributed in the intervals $[0, T)$, $[2T, 3T)$, and $[3T, 4T)$ for the first, second, and third paths respectively.

The DS-CDMA signal used in the analysis has a processing gain(PG) equal to eight, and uses BPSK modulation. We use random codes for spreading our data with eight chips in each code. The sampling frequency of the received signal before the chip matched filter is

three times the chip rate, so there are three input samples per chip. The angle of arrival (AOA) is modeled as a random process uniformly distributed in the interval $[-\pi/2, \pi/2]$. E_b/N_o is set to 18dB for all users unless otherwise mentioned, where $E_b = P_k T_b$. We also assume plane wave propagation, and the separation distance between antenna elements is set to $\lambda/2$. In these results the MMSE is averaged around all the random parameters: noise, data, AOA, spreading codes, and channel impulse responses.

The effect of the number of antenna elements on the MMSE is shown in Fig.(5.4) for different number of users accessing the channel. We set the number of the forward taps equal to 8 and the number of backward taps equal to 5. From Fig.(5.4) we see that by increasing the number of antenna elements the structure becomes more robust against the co-channel interference, as a result the capacity is increased and the bandwidth remains unchanged.

In Fig.(5.5) we calculate the effect of number of users on the MMSE for different number of users. From Fig.(5.5) we see the ability of the proposed structure to totally cancel the cochannel interference and ISI by adding more elements.

Comparison with the structures proposed in [2], [64], [87], and the space-time structures proposed in previous chapters are given in Fig.(5.6). We can see the significant increase in performance and capacity of the proposed structure compared to the others. Comparing the all structures we see the superior ability of the centralized decision feedback space-time receiver to cancel MAI and ISI, which result in much higher capacity without adding extra bandwidth.

Fig.(5.4) The effect of the No. of antenna elements and the No. of users on the MMSE.

Fig.(5.5) Capacity curve for the proposed structure.

Fig.(5.6) Capacity comparison between the proposed structures.

5.5 Conclusion

In this chapter we proposed the centralized decision feedback combined space-time receiver. We developed a formula for the MMSE and the optimum taps. Analytical results based on the MMSE criterion showed that the centralized structure has the ability to cancel cochannel interference and ISI. The complexity of the centralized structure is linear with number of users and can only be applied at the base-station, so extra complexity will not be a problem at the base-station. In this chapter we also compare the centralized receiver with the previously proposed receivers. It is found that the centralized structure outperforms the linear space-time structure and the decision feedback space-time structure.

In the next chapter we will begin a new stage of the thesis where we will see the effect of the wireless channel on the proposed structure. The linear space-time receiver will be only tested because of its simplicity and performance and we can use it as a bench mark for the other structures.

Performance of the Adaptive Linear Space-Time Structure in Frequency Selective Fading Channels

In all our previous analysis and simulation we assume that AWGN and cochannel interference are the only impairments in the channel. Applying the proposed structures to cellular systems gives rise to other impairments due to the wireless channel. Wireless communication channels suffer from many impairments which place fundamental limitations on the performance of any wireless system. The focus in this chapter is on the performance of the adaptive linear combined space-time structure in frequency selective fading channels.

6.1 Introduction

In a wireless communication channel, the received signal strength for a certain user is affected by the physical channel in several ways. In this section we will explain the channel model which will be used in the performance analysis of the adaptive linear space-time receiver.

The transmitted signal from a wireless system arrives at its destination along a number of different paths referred to as multipath. These multipath components arise from scattering, reflection, and diffraction of the transmitted signal off objects that lie in the area between the transmitting and receiving antennas in the wireless environment, Fig.(6.1).

The received signal strength for a given user is affected by path loss, multipath fading, and shadowing. Path loss is a function of the distance between the transmitting and receiving antennas, which is defined as the ratio between the received power P_r and the transmitting power P_t .

$$PL = \frac{P_t}{P_r} \quad (6.1)$$

Fig.(6.1) Multipath Propagation in cellular systems.

where PL is the path loss. The inverse path loss for the free space model is given by

$$Ld = \frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi d} \right)^2 G_t G_r, \quad (6.2)$$

Where λ is the wavelength, G_t, G_r are the power gain of the transmit and receive antennas, respectively, and d is the distance between the transmit and receive antennas.

The main path is usually accompanied by a surface reflected path that may destructively interfere with the main path. This is called the ground reflection model or the 2-ray model. The inverse path loss for this model can be approximated by

$$Ld = \left(\frac{h_r h_t}{d^2} \right)^2 G_t G_r, \quad (6.3)$$

where h_r, h_t are the effective heights of the transmit and receive antennas respectively. The effective path loss follows the inverse fourth power law (exponent equal to four) that results in a loss of 40dB/decade. In real wireless environment the path loss exponent varies from 2.5 to 5.

In addition to deterministic path loss due to distance, there is a random component due to the location dependent, spatial distribution of objects relative to the mobile. That is, the path loss experienced by the mobile depends on both the separation from the transmitter and on the particular placement of the surrounding objects that may prevent line-of-sight communication. This latter effect is called shadowing. From measurements, the random variation in path loss around the distance dependent mean can be modeled as a log normal random variable. The path loss and shadowing is called slow fading or large scale path loss [86].

In addition to path loss and shadowing the received signal has another component which will cause its power to fluctuate with small spatial changes of the transmitter, receiver, or scattering objects in the environment. This component is called fast fading or small scale fading, [86].

The fast fading is caused by the multiple signal reflections arriving at the base-station each with its own phase. This multiple signal reflection is caused by scattering of the signal off objects near the moving mobile. When the number of multipath components is large, each with random ampli-

tude and angle of arrival arrive at the receiver with phases uniformly distributed in the interval $[0, 2\pi)$, then the in-phase and quadrature component of the received signal level will be an independent Gaussian process. The envelope of the received signal is then a Rayleigh distributed random variable which probability density function given by

$$p(x) = \begin{cases} \frac{x}{\sigma^2} \exp\left\{-\frac{x^2}{2\sigma^2}\right\} & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (6.4)$$

If there is a direct path, then the envelop of the received signal will be a Rician random variable, which has a probability density function as follows

$$p(x) = \begin{cases} \frac{x}{\sigma^2} \exp\left\{-\frac{(x^2 + s^2)}{2\sigma^2}\right\} I_0\left(\frac{xs}{\sigma^2}\right) & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (6.5)$$

where s^2 is the mean power of the direct path and I_0 is the modified zero order Bessel function of the first kind.

Multipath fast fading is described by its Doppler spread (time-selective fading), delay spread (frequency selective fading) and angle spread (space selective fading).

Doppler spread is due to the movement of the mobile user or due to moving objects in the wireless system environment. Doppler spread causes variation in the received signal amplitude with time. The Doppler spread is inversely proportional to the channel coherence time, where the coherence time represents the time separation for which the channel impulse response remains strongly correlated, and is a measure of how fast the channel changes in time.

Doppler spread and coherence time are parameters which describe the time varying nature of the wireless channel. However they do not offer information about the time dispersive nature of the wireless channel. Delay spread and coherence bandwidth are parameters which describe the time dispersive nature of the channel. Coherence bandwidth is a statistical measure of the range of frequencies over which the channel can be considered flat. The coherence bandwidth is inversely

proportional to the delay spread and is a measure of the channel's frequency selectivity.

In a CDMA system, we spread the data signal over a much wider bandwidth. The bandwidth of the transmitted signal is usually much greater than the coherence bandwidth of the channel, and frequency selective fading channel model is usually applied. So in this chapter we will use the frequency selective fading channel model in the analysis and the evaluation of the proposed structure.

Angle spread refers to the spread of angles of the arrival of the multipaths at the antenna array. Angle spread causes space selective fading, which means that the received signal level at different antennas will have low or high correlation depending on coherence distance. As for the coherence time and the coherence bandwidth, the coherence distance represents the maximum spatial separation for which the channel responses at two antennas remain strongly correlated. The larger the angle spread the shorter the coherence distance.

At a high base-station antenna (above roof level) the angle spread is usually very small and the signal envelope remains strongly correlated between two antennas separated by several λ , however at the mobile or at the base-station for indoor wireless systems the angle spread is usually 360° which causes the signal envelope to be uncorrelated for distances greater than $\lambda/2$. So, In the channel model which we used in this thesis we will assume zero angle spread for each path, so the signal level of the received signal at different antenna will be totally correlated for each path, however the total angle spread of the channel (all resolvable paths) depends on the antenna location and heights and system type, i.e. outdoor or indoor.

6.2 Channel model including AOA

The channel impulse response for the k^{th} user at the l^{th} antenna element which will be used in this chapter is given by, [75],

$$\mathcal{R}_{kl}(t) = \sum_{m=1}^M h_{km} A_l(\theta_{km}) \delta(t - t_{km}) \quad (6.6)$$

In the above equations, h_{km} is the complex channel coefficient as seen by user k during the m^{th} path, t_{km} is the delay of the m^{th} path of the k^{th} user, where h_{km} has a complex gaussian distribution, M is the number of resolvable multipath component, $A_l(\theta_{km})$ is the steering coefficient of

the k^{th} user in the m^{th} path at the l^{th} antenna element, where

$$A_l(\theta_{km}) = e^{-\left(2j\pi\frac{d}{\lambda}\left(l - \frac{1+L}{2}\right)\sin\theta_{km}\right)} \quad (6.7)$$

where d is the distance between adjacent elements, L is number of elements, λ is the wave length, l is the element number. θ_{km} is the angle of arrival (AOA) of the k^{th} user in the m^{th} path with respect to the array normal, where θ_{km} is a uniformly distributed in the interval $[\pi/2, -\pi/2]$. In the above equations for the channel model including AOA we made the following assumptions:

- 1) The bandwidth of the transmitted CDMA signal is much greater than the coherence bandwidth. So, we assume a frequency selective fading channel with M resolvable paths.
- 2) Each path of the M resolvable paths consists of many unresolvable paths that are approximately of the same length and are not resolvable at the receiver. Thus, they are combined into a single path.
- 3) Each of the unresolvable paths mentioned above has its own time delay, and their time delays are approximately the same. Then they combined into a single path with time delay t_{km} .
- 4) Each of the unresolvable paths also has its own angle of arrival, and their angles of arrival are uniformly distributed in the interval $\left[-\frac{\Delta}{2} + \theta_{km}, \frac{\Delta}{2} + \theta_{km}\right]$, where Δ and θ_{km} are the angle spread and AOA of the resolvable paths, respectively. We assume that the angle spread Δ is negligible and h_{km} is totally correlated at each antenna element.
- 5) Each of the resolvable paths consists of large number of unresolvable paths where each has its own amplitude. So the in-phase and quadrature components of each of the resolvable paths will be an independent gaussian random process. Then the envelope of each of the resolvable paths will be a Rayleigh random variable.
- 6) We assume a finite number of resolvable paths, where M is usually between 3 and 6 each with its own angle of arrival, AOA. In the numerical results and simulations M will be equal to 3 each with its own AOA.
- 7) We assume that the frequency response of each antenna is approximately flat over the signal bandwidth.
- 8) We also assume that the mobile is in the far field of the base-station antenna (point source), and

the mobile and the base-station array are in the same plane. So plane wave propagation is used.

Fig.(6.2) is an illustration of the channel model described by the above equations.

6.3 Received signal model

Consider a CDMA receiver with K users. The signal transmitted by the k^{th} user is denoted by $S_k(t)$, where $k = 1, 2, \dots, K$. Assume that $S_1(t)$ is the signal from the desired user, and $S_k(t)$, $k = 2, 3, \dots, K$ are considered as co-channel interference with respect to the desired user. Each signal received comes from a certain direction. The complex baseband transmitted signal is

$$S_k(t) = \sqrt{p_k} \sum_i b_k^i c_k(t - iT_b - \tau_k) \quad (6.8)$$

From (6.6) the channel impulse response for the k^{th} user at the l^{th} element is repeated here for clarity

$$\mathfrak{R}_{kl}(t) = \sum_{m=1}^M h_{km} A_l(\theta_{km}) \delta(t - t_{km}) \quad (6.9)$$

From (6.8) and (6.9) the received signal at the l^{th} from the k^{th} user is

$$r_{kl}(t) = \sqrt{p_k} \sum_i b_k^i \sum_{m=1}^M h_{km} A_l(\theta_{km}) c_k(t - iT_b - t_{km}) \quad (6.10)$$

Then the total received signal at the l^{th} element due to all users including the AWGN is

$$x_l(t) = \sum_{k=1}^K r_{kl}(t) + N_l(t) \quad (6.11)$$

where all of the variables above are defined before in this thesis.

Fig.(6.2) Multipath Propagation Model.

6.4 Analysis of the Linear Structure in Frequency Selective Fading Channel

After defining the channel model, the transmitted signal model, and the received signal model, now we can analyze the optimum coefficient vectors and the MMSE for the Adaptive Linear Combined Space-Time structure. In this section we will define the tap vector model and the coefficient vector for the linear structure by using the same idea of representing the codes used in chapter 3, which is called the *rotated code vector*. In this chapter we will change the *rotated code vector*, the tap vector, and the coefficient vector to include the frequency selective channel model described in this chapter.

First let us recall from chapter 3 that the signal received by the l^{th} antenna element, $x_l(t)$, is passed through a chip matched filter and sampled at the chip rate, then at the i^{th} symbol interval the contents of the FIR filter of the l^{th} element will be represented by an N -dimensional vector assuming the number of the forward taps is equal to N for the analysis.

$$u_l^i = \sum_{k=1}^K \sqrt{p_k} b_k^i \sum_{m=1}^M h_{km}^i A_l(\theta_{km}) C_{km}^i + N_n^i \quad (6.12)$$

where the code vector C_{km}^i in the i^{th} sampling interval is,

$$C_{km}^i = \begin{cases} \left(\frac{\varepsilon_{km}}{T_c} D_k(\rho_{km} + 1) + \left(1 - \frac{\varepsilon_{km}}{T_c} \right) D_k(\rho_{km}) \right) & \text{if } b_k^{i-1} = b_k^i \\ \left(\frac{\varepsilon_{km}}{T_c} B_k(\rho_{km} + 1) + \left(1 - \frac{\varepsilon_{km}}{T_c} \right) B_k(\rho_{km}) \right) & \text{if } b_k^{i-1} = -b_k^i \end{cases} \quad (6.13)$$

$$D_k(\rho_{km}) = [a_k(N - \rho_{km}) \dots a_k(N - 1) a_k(0) a_k(1) \dots a_k(N - 1 - \rho_{km})]^T \quad (6.14)$$

and

$$\begin{aligned} \mathbf{B}_k(\rho_{km}) = & [-a_k(N-\rho_{km}) \dots -a_k(N-1) \ a_k(0) \ a_k(1) \\ & \dots \ a_k(N-1-\rho_{km})]^T \end{aligned} \quad (6.15)$$

where $t_{km} = \rho_{km}T_c + \varepsilon_{km}$, where ρ_{km} is an integer number, and $0 \leq \varepsilon_{km} < T_c$.

Let

$$r_{km}^i = h_{km}^i S_k(iTb - t_{km}) = \sqrt{P_k} h_{km}^i b_k^i C_{km} \quad (6.16)$$

be the vector the received signal from the k^{th} user over the m^{th} fading path. Then the received signal from the k^{th} user from all paths is the matrix X_k of dimension $(N \times M)$ where X_k is equal to,

$$X_k = [r_{k1} \ r_{k2} \ \dots \ r_{kM}] \quad (6.17)$$

We dropped the superscript i from our equations, since it will not effect our analysis. Then the received signal from all users from all M paths is the matrix $\mathbf{X}$ of dimension $(N \times KM)$ where $\mathbf{X}$ is equal to

$$X = [X_1 \ X_2 \ ...X_K]^T \quad (6.18)$$

Let the steering vector of the of the k^{th} user for all M paths at the l^{th} element is equal to

$$A_{lk} = \begin{bmatrix} A_l(\theta_{k1}) & A_l(\theta_{k2}) & \dots & A_l(\theta_{kM}) \end{bmatrix} \quad (6.19)$$

where A_{lk} is a M -dimensional vector. Let

$$A_l = \begin{bmatrix} A_{l1}^T & A_{l2}^T & \dots & A_{lK}^T \end{bmatrix}^T \quad (6.20)$$

be a KM -dimensional vector containing the steering coefficients of all users for all paths, then the contents of the FIR filter of the l^{th} antenna element in vector form is

$$u_l = A_l^T X + N_l \quad (6.21)$$

Let

$$w_l = [w_{l,1} \ w_{l,2} \ \dots w_{l,N}]^T \quad l = 1, 2, \dots, L \quad (6.22)$$

be a N -dimensional vector containing the weights for the FIR filter of the l^{th} antenna element.

Now we can define the contents of the all FIR filters and their tap weights in vector form.

Let

$$W = [w_1^T \ w_2^T \ \dots w_L^T]^T \quad (6.23)$$

where W is a LN -dimensional vector containing the all FIR filters coefficients, and let

$$U = [u_1^T \ u_2^T \ \dots u_L^T]^T \quad (6.24)$$

be a LN -dimensional vector containing the contents of the all FIR filters.

Now after defining the vectors W and U we can calculate the optimum taps and the minimum mean square error (MMSE) of our structure.

The output of the linear structure is equal to

$$y = \mathbf{W}^H \mathbf{U} \quad (6.25)$$

The mean square error is

$$MSE = 1 - \mathbf{W}^H \mathbf{P} - \mathbf{P}^H \mathbf{W} + \mathbf{W}^H \mathbf{R} \mathbf{W} \quad (6.26)$$

where $\mathbf{R}$ is the autocorrelation matrix of the input vector $\mathbf{U}$ and it is equal to,

$$\mathbf{R} = E(\mathbf{U}\mathbf{U}^H) \quad (6.27)$$

and $\mathbf{P}$ is the cross-correlation vector between the input vector $\mathbf{U}$ and the desired output b^1 , where b^1 denotes the data from the first user, then $\mathbf{P}$ is equal to,

$$\mathbf{P} = E(\mathbf{U}b^1) \quad (6.28)$$

To find the optimum coefficients, $\mathbf{W}_{opt}$, from the Weiner-Hopf solution

$$\mathbf{W}_{opt} = \mathbf{R}^{-1} \mathbf{P} \quad (6.29)$$

substitute $\mathbf{W}_{opt}$ in Eq.(6.29) into Eq.(6.26) to find the MMSE,

$$MMSE = 1 - \mathbf{P}^H \mathbf{W}_{opt} = 1 - \mathbf{P}^H \mathbf{R}^{-1} \mathbf{P} \quad (6.30)$$

In order to find $\mathbf{W}_{opt}$ and the MMSE we need to calculate Eq.(6.27) and Eq.(6.28) which is shown below.

$$R = E[UU^H] = E \left[\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_L \end{bmatrix} \begin{bmatrix} u_1^* & u_2^* & \dots & u_L^* \end{bmatrix} \right] \quad (6.31)$$

$$R = \begin{bmatrix} Ru_1u_1 & Ru_1u_2 & \dots & Ru_1u_L \\ R^*u_1u_2 & Ru_2u_2 & \dots & Ru_2u_L \\ \dots & \dots & \dots & \dots \\ R^*u_1u_L & R^*u_2u_L & \dots & Ru_Lu_L \end{bmatrix} \quad (6.32)$$

where, assuming the noise and data sequences are independent then,

$$Ru_lu_l = E(u_lu_l^*) = \sum_{k=1}^K p_k \sum_{m=1}^M |h_{km}|^2 E(C_{km}C_{km}^T) + \sigma^2 I_{N \times N} \quad (6.33)$$

and

$$Ru_lu_n = E(u_lu_n^*) = \sum_{k=1}^K p_k \sum_{m=1}^M |h_{km}|^2 E(C_{km}C_{km}^T) A_l^*(\theta_{km}) A_n(\theta_{km}) \quad (6.34)$$

and P is equal to

$$P = E \begin{bmatrix} u_1b^1 \\ u_2b^1 \\ \dots \\ \dots \\ u_Lb^1 \end{bmatrix} \quad (6.35)$$

where

$$\mathbf{P} = \begin{bmatrix} E(u_1 b^1) \\ E(u_2 b^1) \\ \vdots \\ E(u_L b^1) \end{bmatrix} \quad (6.36)$$

and

$$E(u_l b^1) = \sqrt{p_l} \sum_{m=1}^M h_{lm} A_l(\theta_{lm}) C_{lm} \quad (6.37)$$

In the above analysis we found the MMSE and the optimum tap weights for the proposed structure in a multipath frequency selective fading channels as a function of $\mathbf{R}$ and $\mathbf{P}$, where $\mathbf{R}$ and $\mathbf{P}$ depend on the number of users, and the number of antenna elements. From these results we will see later the effect of the number of users, number of antenna elements, and the number of forward taps on the performance of the proposed structure.

6.5 Channel Model and System Parameters

In the following sections we will evaluate the proposed structure in a frequency selective fading channel. The numerical evaluation is based on the analysis in section 5.4 where we will see the effect of many parameters on the MMSE criteria. In the next subsections the channel model and the system parameters used in the evaluation will be described in detail. These results are also used to show the advantages of the proposed space-time structures compared to other adaptive multiuser structures. The simulation model used for the frequency selective fading channel which includes the AOA parameter is shown in Fig.(6.3).

6.5.1 Channel Model Parameters

In this section the channel parameters will be explained. These channel parameters will be used to evaluate the performance of the space-time structure.

Equation (6.6) shows the channel impulse response model for the frequency selective fading including angle of arrival. In the evaluation process we have chosen the number of the resolvable multipath components M for each user to be equal to 3, and the total received average power for each mobile (user) is same for all mobiles. Only in near-far resistance measurements will this assumption will be changed to see the performance of the proposed structure in a near-far environment. Each path is modeled as a single planar wavefront with zero angle spread. The three paths are uniformly distributed within the first 6 chips of a bit period. So the delay spread of the channel will be $6T_c$, where T_c is the chip period.

h_{km} was chosen to be a complex Gaussian random variable. The in-phase and quadrature component of h_{km} are then a Gaussian random variable with equal variance and zero mean. So the magnitude of h_{km} will be a Rayleigh random variable. Also we assume that θ_{km} is a uniform random variable in the interval $[-\pi/2, +\pi/2]$. All 3 independent resolvable paths for each user have the same variance. This model is an extreme scenario of frequency selective fading channel where all the paths have the same variance. However, this channel model will help in evaluating the performance of the space-time structure in worst-case channel scenarios. The multipath components and delays of all interfering received signals are independent.

Fig.(6.3) Channel model used in the simulation.

6.5.2 System Parameters

For the evaluation of the performance of the space-time structures, we consider the following system setting unless otherwise mentioned.

- 1) We assume a base-station with uniform linear array of one to nine omni-directional antennas.
- 2) Antenna spacing equal to $\lambda/2$.
- 3) We assume a DS-CDMA system where the data and the spreading codes are with BPSK modulation.
- 4) All users have the same data rate and the spreading gain PG is equal to 8; i.e. 8 chips per code. Longer spreading codes could be used, also the complexity of the structure depends on the length of the spreading codes.
- 5) The codes used are random spreading codes. Later in the next chapter we will compare different spreading codes.
- 6) The received E_b/N_o for each user is equal to 18dB. So we assume perfect power control, where N_o is the power spectral density of the additive noise.
- 7) The number of adaptive forward filter taps for each antenna is equal to the processing gain.
- 8) We average the MMSE over 300 runs. Where in each run we select different codes, delays, fading coefficients for each user.
- 9) One equalizer input sample per chip and the data symbols have a variance of unity.

6.6 The effect of the number of forward taps

Because we are applying the proposed structure in a frequency selective fading channel, then the structure needs to cancel cochannel interference, cancel ISI, and combine multipath components. In Fig.(6.4) we display the calculated MMSE averaged over 300 runs, as a function of the number of forward taps per element, and 4 antenna elements are used. This calculation is based on the analytical results derived in section 6.4. Fig.(6.4) displays the results for different number of users accessing the channel. From Fig.(6.4) it is clear that the MMSE is improved by increasing the number of forward taps up to roughly 14, i.e. the sum of the delay spread and the number of chips per symbol. This is reasonable because the length of the forward filter should be enough to collect the energy in all the 3 paths.

Fig.(6.4) The effect of number of forward taps on the MMSE

However a lower number of forward taps can be used with good performance and reduced structure complexity. For example with number of forward taps equal to 4 (half the processing gain) the MMSE is less than -7.5dB for 6 users which is still a very good performance result compared to [64].

In the following results the number of forward taps is set to 8 unless otherwise mentioned. From Fig.(6.4) the degradation in performance between the 2 users case and the 18 users case is approximately 7dB with the number of forward taps equal to 14. This degradation can be further reduced by using more antenna elements as we will see in the next sections. Table 6.1 shows some particular results at different number of taps and different number of users to show the significant capacity increase of the space-time structures. Outage probability of the MMSE is calculated in section 6.11.

	4 taps	6 taps	8 taps	10 taps
2 users	-11 dB	-15 dB	-17.5 dB	-19 dB
4 users	-10 dB	-14 dB	-17 dB	-18 dB
6 users	-8 dB	-12.5 dB	-16.5 dB	-17.5 dB
8 users	6.5 dB	-12 dB	-16 dB	-16.5 dB

Table 6.1: Some selected values from Fig.(6.4).

6.7 The effect of the number of resolvable paths

To see the ability of the space-time structure to perform the job of a RAKE receiver we conducted the following test. In these results we set the number of interferers equal to 4 and the number of antenna elements equal to 4. From Fig.(6.5) it is clear that the space-time structure has the ability to collect the energy in the resolvable multipath component. Hence it performs the function of RAKE reception. This is because the adaptive forward filter is a tapped delay line with delay equal to the chip period, so any paths that are separated by more than a chip can be resolved by the filter and their energy can be collected. We conclude from these results that the space-time structure performs the function of multiuser detection and RAKE reception in one structure.

From Fig.(6.5) there is approximately 6dB improvement in the MMSE between the one and two resolvable path cases, and the improvement is approximately 9dB between the one and three resolvable path cases.

Fig.(6.5) The effect of number of resolvable paths on the MMSE.

6.8 The effect of the number of antenna elements

It was shown in [64] that the adaptive linear multiuser detector with a number of taps equal to the processing gain (PG) has the ability to cancel up to $K=PG-1$ interferers. By using an antenna array with L elements one can increase the capacity of the system by L fold without adding extra bandwidth.

The proposed adaptive space-time structure jointly adapts the spatial and temporal domains. By using L antenna elements, the number degrees of freedom of the adaptive multiuser detection is increased from PG to $L*PG$.

Fig.(6.6) shows the effect of the number of antenna elements on the MMSE in frequency selective fading channel. Comparing these results with the results in chapter 3, we see that in frequency selective fading channels the number of degrees of freedom is reduced due to the multipath components since the forward filter length only spans one symbol. In Fig.(6.6) we set the number of forward taps equal to 14. From Fig.(6.6) we see that by adding more elements the structure is able to cancel more interference. If the number of interference is less than $L*PG$ then interference effects can be essentially eliminated leaving the effects from noise only. Then by further doubling the number of elements we can reduce the MMSE by roughly 3dB. Also the space-time structure makes performance less sensitive to the number of interferers. If the number of users is greater than the degrees of freedom then doubling the number of elements decreases the MMSE by more than 7dB. For example, with two antenna elements and 16 users the MMSE is equal approximately -6dB, but for 4 antenna elements the MMSE is approximately -14.5dB with the same number of users which is a gain of 8.8dB.

Fig.(6.6) The effect of number of elements on the MMSE.

6.9 The effect of number of users.

In this experiment we compare the proposed space time structure with the non-array structures proposed in [64]. The comparison will be based on the MMSE criteria. In this experiment we will see how the proposed space-time receiver improves the capacity of the DS-CDMA system without adding extra bandwidth. Capacity here means the number of users with the same power that can access the CDMA wireless channel in a one cell system. So, here we assume only one cell system. Out-of-cell interference will be considered in the next chapter. In this test we set the number of forward taps equal to 14 for all structures in comparison.

Fig.(6.7) compares the proposed space-time structure capacity with the structures proposed in [64]. A significant increase in the number of interfering signals which can be tolerated in frequency selective channel for the space-time receiver without the need for extra bandwidth is clear from the figure. For example with 4 elements we can let 16 users access the channel with MMSE approximately equal to -14.5dB, however with the structure in [64] with same spreading gain only 2 users can access the channel with MMSE equal to -13.5dB. For more antenna elements the structure outperforms the time-only receiver and become more robust against interference. For example with 9 elements we can let 16 users access the channel with MMSE less than -20dB, where for the structure in [64] we can't get this performance even with one user, i.e. no interference at all. From this test we see the power of the space-time structure to accommodate more interference to enhance the capacity without adding extra bandwidth.

6.10 Near-Far resistance

As discussed earlier, one of the common problems for the conventional CDMA receiver is the near-far problem. One of the most desirable features of any CDMA receiver is to be near-far resistant, such that the performance of the receiver does not depend on the received powers of different users. In the following numerical results we evaluate the performance of the proposed structure in near-far environment.

Fig.(6.7) Capacity comparison.

Fig.(6.8) The effect of near-far problem.

Fig.(6.8) shows the MMSE of the linear adaptive combined space-time receiver as a function of the interference to desired signal ratio. In this figure we assume only 2 users in the systems (i.e. only one interference). We change the power of the interference and calculate the MMSE at each time. In the figure we plot the results for 4 antenna elements. The resistance of the proposed receiver to the near-far problem is clear from the figure and there is no need for strict power control, which will minimize the complexity of the receiver.

6.11 The Outage probability of the MMSE

As mentioned before the MMSE was calculated by averaging over 300 runs. In each run we randomly pick the spreading codes, delays, AOA, and the Rayleigh fading coefficients for each user. To get more insights on the behavior of the space-time receiver, one should look at the outage probability of the MMSE. Outage probability here means the number of runs the MMSE is below a certain level out of the total runs.

From Fig.(6.9) to Fig.(6.12) we compare the outage probability for the adaptive linear space-time receiver with 2, 4, and 8 elements with the outage probability of the structure proposed in [64] for different outage criteria (-6 dB, -10 dB, -14 dB, and -18 dB).

These figures were drawn for different number of users and different number of elements to see the performance of the space-time receiver compared to time only receiver.

In Fig.(6.9) we draw the outage probability of the MMSE below -6dB. Comparing the different structures it is clear that the more elements we add the lower outage we get. For example with 4 - elements the probability of an outage is almost zero up to 16 users.

Figures from (6.13) to (6.15) compare the cumulative distribution functions (CDF) of the MMSE for the space time detector with 2, 4, and 8 elements and the time only receiver. It is very clear from the figures that the CDF for the space-time structure is less sensitive to number of users than the time only detector and it becomes less sensitive by adding more elements.

6.12 Conclusion

Chapter 6 is devoted to study the performance of the linear space-time receiver in frequency selective fading channels, where multipath and fading can degrade the performance of any system. The analysis of the optimum tap weights and the MMSE of the linear space-time structure in frequency selective fading channels are given in chapter 6. Analytical results are also presented in

this chapter. From the results we found that the linear space-time receiver is not only capable of canceling MAI and ISI but also has the ability to collect the energy of the different multipath components. We found that these structures combine the function of multiuser detection, antenna arrays, ISI equalizer, and RAKE reception in one single structure. Also from the comparison study between the linear MMSE multiuser receiver (temporal only) and the linear space-time receiver we conclude that the space-time receiver has the ability to improve the performance of the CDMA system significantly.

Fig.(6.9) Outage probability on the MMSE $P(\text{MMSE} > -6 \text{ dB})$.

Fig.(6.10) Outage probability on the MMSE $P(\text{MMSE} > -10 \text{ dB})$.

Fig.(6.11) Outage probability on the MMSE $P(\text{MMSE} > -14 \text{ dB})$.

Fig.(6.12) Outage probability on the MMSE $P(\text{MMSE} > -18 \text{ dB})$.

Fig.(6.13) Cumulative distribution function of the MMSE with 2 users.

Fig.(6.14) Cumulative distribution function of the MMSE with 4 users.

Fig.(6.15) Cumulative distribution function of the MMSE with 14 users.

Practical Issues Related to the Space-Time Structures in Cellular CDMA Systems

7.1 Introduction

In this thesis we propose several space-time structures for DS-CDMA systems. In previous chapters we demonstrate their advantages compared to other structures. From these results we see that these structures have the ability to combine multipath components, cancel multiuser interference, and cancel intersymbol interference. We found that these space-time receivers provide a significant improvement of the performance of the CDMA system compared to other structures.

In this chapter we consider some practical issues. The linear adaptive space-time receiver will be tested in this chapter to give some insights into the potential advantages of the space-time structure in cellular CDMA systems.

In this chapter we run many simulations. The adaptive algorithm technique used in these simulation is the normalized LMS for its simplicity. But before we present these simulations we study the transient behavior of the linear space-time structure.

In section 7.2 the transient behavior of the linear space-time receiver will be analyzed and discussed. The effect of time varying user population and packet transmission will be discussed and

simulated in section 7.3. In section 7.4 we consider the effect of the spreading codes. Out-of cell interference is considered in section 7.5. Section 7.6 studies the capacity improvement offered by the linear space-time receiver including the effect of shadowing and distance related attenuation BER results is discussed in section 7.7. Finally the conclusion is in section 7.8.

7.2 Transient behavior

Many adaptive algorithm techniques are well established and their properties are well known in the literature, [28]. Our concern in this thesis is not on the adaptive technique itself but on the performance of the linear space-time detector in cellular systems and the study of some related aspects that reveal the advantages of the receiver. So the normalized least mean square algorithm will be adopted in this thesis for its simplicity. However, finding the best suitable adaptation algorithm that fits the linear space-time structure is an interesting area of research and it is outside the scope of this thesis. Before simulating the linear space-time detector using the NLMS algorithm we will study first its transient behavior using the LMS algorithm.

In [65], Miller studies the transient behavior of the adaptive MMSE receiver for DS-CDMA systems. Miller examines the length of the training period as a function of the number of interfering users and the effect of the near-far problem. Results in [65] show that as the number of users is increased, the eigen-value spread of the autocorrelation matrix is increased, thus requiring longer training period. Also results in [65] state that as the strength of the interfering users increases, the length of the training period is also significantly increased.

In this section we will study the transient behavior of the linear space-time receiver. Also a comparison study between the adaptive MMSE time only receiver and the adaptive combined space-time receiver is carried in this section.

7.2.1 Transient behavior analysis of the MSE

The analytical presentation of the transient behavior of the MSE of the linear space-time structure proposed in this thesis is presented in this section. Using the analysis given in [28] and assuming the independence assumption used in [28], the MSE at time n is defined as

$$J(n) = J_{ex}(n) + J_{min} \quad (7.1)$$

where J_{ex} is the excess mean-squared error, and J_{min} is the MMSE value, where

$$J_{ex}(n) = \sum_{i=1}^{NL} \lambda_i x_i(n) \quad (7.2)$$

where $\lambda_i, i = 1, 2, \dots, NL$ is the eigen-value of the correlation matrix R defined in the previous chapter, and $x_i(n), i = 1, 2, \dots, NL$ are the diagonal elements of the matrix $X(n)$, where $x(n)$ is calculated using the iterative equation:

$$x(n+1) = BX(n) + \mu^2 J_{min} \underline{\lambda} \quad (7.3)$$

where B is an NL -by- NL matrix with elements

$$b_{ij} = \begin{cases} (1 - \mu \lambda_i)^2 & i = j \\ \mu^2 \lambda_i \lambda_j & i \neq j \end{cases} \quad (7.4)$$

and μ is the step size of the adaptation algorithm. An initial setting corresponding to all tap coefficients at zero is needed for the vector $X(n)$ to calculate J_{ex} . This was found to be equal to

$$x(0) = V^H W_{opt} W_{opt}^H V \quad (7.5)$$

where V is the matrix of eigen-vectors and W_{opt} is the optimum tap weights which are given in chapter 6. The MSE at time n could now be calculated using the above equations to observe analytically its behavior in frequency selective fading channels.

7.2.2 Analytical results

In this section we calculate the MSE using the equations derived in the previous section as a function of the number of users and number of antenna elements. The impulse response of the channel is same as in chapter 6 and it is assumed to have three independent paths, and all the paths are assumed to be Rayleigh distributed with the same variance. The path delays are distributed uni-

formly within the first six chips of a bit interval; i.e. the delay spread is equal to six chip periods. The DS-CDMA signal used in the analysis has a processing gain(PG) equal to eight, and uses BPSK modulation. We use random codes for spreading our data with eight chips in each code. The sampling frequency of the received signal before the chip matched filter is equal to three times the chip rate, so there are three input samples per chip. The angle of arrival (AOA) is modeled as a random process uniformly distributed in the interval $[-\pi/2, \pi/2]$. E_b/N_o is set to 18dB for all users unless otherwise mentioned, where $E_b = p_k T_b$, and N_o is the PSD of the background thermal noise. We also assume plane wave propagation, and the separation distance between antenna elements is set to $\lambda/2$. In these results 300 runs are used to get the average MSE over all the random parameters: noise, data, AOA, spreading codes, and channel impulse responses (fading and multipath).

In Fig-(7.1) we compare the MSE curves for the adaptive linear space-time receiver with the adaptive linear time only receiver. We set the step-size equal to 0.0007, number of forward taps equal to 8, and the number of elements for the space-time receiver equal to 4. From Fig-(7.1) we see that the space time receiver converges faster than the time only receiver, for example with a four element space-time receiver the MSE reaches -10 dB level after 55 training bits while the time only receiver reaches the same level after 230 training bits, as a result it will require a shorter training period. Moreover, with more users the space-time structure becomes even faster than the time only structure. The convergence time is less sensitive to the number of users and the steady state MSE is much lower for the space-time structure than for the time only structure. The most likely explanation of the results is that the space-time structure reduces the correlation among codes by exploiting their spatial characteristic (their angle of arrival). So even though the space-time receiver has more coefficients to adapt, its training period is much less than that of the time only receiver.

In Fig-(7.1) we compare both structures with the same step-size. But because the maximum stable step-size should be inversely proportional to the number of the adapted parameters [28], we repeat the analysis in Fig-(7.2) with different step-sizes to see the effect on the MSE transient curve. Fig-(7.2) shows the transient curve for the adaptive time only receiver with two different step-sizes, (0.0007, 0.0028), and compares these two curves with the adaptive space-time receiver with step-

Fig-(7.1) Transient behavior curves of the space-time and time only receivers.

Fig-(7.2) Effect of the step-size on the training curve.

Fig-(7.3) Comparing the space-time receiver with the time only receiver with different processing gain.

size equal to 0.0007. We assume that there are 4 users in the system and a space-time receiver with 4 antenna elements. From Fig-(7.2) we see that even with the smaller step-size the adaptive space-time receiver still converges faster. For example with four elements space-time receiver the MSE reaches -8 dB level after 50 iterations while the time only receiver with smaller step size reaches the same level after 600 iterations.

In the final result we compare both structures with different chip rates. The reason for this is to keep the total number of taps for both structures the same, so both structure will have the same number of multiplications per bit. In the following results we assume that the space-time receiver has processing gain equal to eight and has 4 antenna elements. The time only structure has processing gain equal to 32, where both structures have the same bit rate and step size is set to 0.0007. We plot the curves for 1 and 4 users case. Fig-(7.3) shows that the space-time structure has better convergence time and less steady state MSE with less bandwidth required.

7.2.3 The adaptive NLMS algorithm

Many adaptive algorithm techniques are well established and their properties are well known in the literature. Our concern in this thesis is not on the adaptive technique itself but on the performance of the structure in a time varying user population. So the normalized least mean square algorithm, NLMS, will be adopted in this work for its simplicity. However, finding the best adaptive algorithm which fits the adaptive combined space-time detector is outside the scope of this thesis.

The NLMS adaptive algorithm is as follows [28],

$$e(n) = b(n) - \hat{W}^H(n)U(n) \quad (7.6)$$

$$\hat{W}(n+1) = \hat{W}(n) + \frac{\mu}{\alpha + \|U(n)\|^2} U(n)e^*(n), \quad (7.7)$$

where in the above equations, α is a positive constant, μ is adaptation constant where $0 < \mu < 2$, $e(n)$ is the error signal, and n is the iteration number.

7.2.4 Remarks on the transient behavior

In this section we conducted some experiments to see the transient behavior of the linear space-time structure and compared it with the time only receiver. From the results we conclude that the adaptive space-time structure improves the performance and reduces the training period length of the CDMA system compared to the time only receiver. Also the results show that with much less bandwidth the space-time receiver still has better convergence and steady state MSE than the time only receiver. The most likely explanation to these results is because the space-time structure has more degrees of freedom than that of the time only structure and it reduces the correlations among the spreading codes by exploiting not only the temporal characteristics but also their spatial characteristics too. In conclusion, even though the space-time receiver has more coefficients to adapt, its training period is much less than that of the time only receiver. These results make the proposed adaptive space-time structure more attractive for CDMA systems.

7.3 Effect of time varying user population and packet transmission

MMSE multiuser detection (time only) is one of the multiuser techniques proposed in the literature [64], [114]. One of the important features of the MMSE detector is that it can be implemented using a fractionally spaced equalizer [64], [2] and can be adapted using any of the popular adaptive algorithms [28]. In [64] and [2] it is shown that the adaptive MMSE detector is near-far resistance and has higher capacity than the conventional receiver. Although the adaptive MMSE detector has many interesting properties it has some problems.

One of problems of the adaptive MMSE multiuser detector is the effect of time varying user population (effect of sudden death and birth). In cellular systems carrying voice, packet data, multimedia etc., users start transmitting and terminate their transmission at different times, as shown in Fig-(7.4). Also in packet transmission users start and terminate their transmission many times during one session. Packet transmission in cellular systems cause transient problems for the adaptive MMSE detector due to the arrival and departure of interferers' packets; an adaptive MMSE receiver needs to readapt each time a new interfering packet arrive.

In [2], Abdulrahman et al. found that the sudden birth of interference can degrade the MSE by

more than 10 dB. The BER will be high at that time, and the detector may have to be retrained. But the detector performance doesn't degrade due to sudden death, instead [2] found the performance improve when interferer leaves. In [35], Honig proposed a rescue algorithm that detects the appearance of new interferers; if a new interferer is detected then the decision-directed mode is suspended and a blind algorithm, similar to the one proposed in [32], is used to readapt the filter coefficient.

In this section we study the effect of the sudden birth and death of interferers on the performance of the proposed linear adaptive space-time multiuser detector, for a frequency selective fading channel. The effect of packet transmission will be studied too.

7.3.1 Simulation Results

In this section we simulate the adaptive combined space-time detector in a frequency selective fading channel to study the effect of sudden death and birth. The NLMS algorithm with $\alpha = 1$ and $\mu = 0.25$ to update the filter coefficients. The impulse response of the channel is assumed to have three independent resolvable paths, and the gain of all resolvable paths are assumed to be Rayleigh distributed random variables with the same variance. The path delays are independent and distributed uniformly within the first six chips of a bit interval. So, the delay spread of the channel is equal to six chip periods.

The DS-CDMA signal used in the simulation has a processing gain (PG) equal to eight, and uses BPSK modulation. Random codes with eight chips are used to spread the data. The sampling rate of the received signal before the chip matched filter is equal three times the chip rate, so there are three samples per chip. The AOA of each resolvable path is modeled as a random process uniformly distributed in the interval $[-\pi, \pi]$. $E_b/N_o = 18dB$ for all users. We assume plane wave propagation and the distance between elements, d , is set to $\lambda/2$. In these results the *mse* is averaged over 100 runs.

Fig-(7.5) shows the effect of the sudden birth of interferers on the MSE. In Fig-(7.5) we assume that the system starts with six users and a new user is added every 300 bits until the total number of users reaches ten users. Fig-(7.5) is drawn for systems with one and four antenna elements. Three conclusions are drawn from this figure. The first conclusion is that the steady state response

after each new user of the adaptive linear MMSE detector is degraded severely, while for the adaptive space-time detector this degradation is very small and it can be reduced by adding more elements. So with the space-time detector the steady state MSE is less sensitive to number of users. The second conclusion is that it is not critical for the adaptive space-time detector to be retrained after each new user, and this is because the MSE does not rise above below -10 dB, which is still a very low value. The final conclusion is that the space-time detector converge faster than the adaptive linear MMSE detector which reduces the overhead bits required to train the filter coefficients. From Fig-(7.5) it is clear that the MSE reacts faster to lower values after each new interferer. For example with four antenna elements the MSE reaches -10 dB, which is a very good threshold to start the decision directed mode, with a training sequence four times shorter than the adaptive linear MMSE detector. Also note that with PG equal to 8 we can accommodate more than 10 users with very low MSE which is more than the processing gain. This results make this space-time detector suitable for high capacity wireless network with packet transmission.

Fig-(7.6) shows the effect of packet transmission. In Fig-(7.6) we assume that the system starts with three users. These three users are assumed to transmit continuously. A new user is added to the system which is assumed to transmit two packet of length 200 bits at the iteration numbers 400 and 1200, remaining silent at other times. From Fig-(7.6) we see that the space-time detector does not deteriorate at the second packet like the adaptive linear MMSE detector. From this figure it is clear that the space time structure better retains some memory of departed interferers, probably as a result of a larger number of degree of freedom than the linear MMSE detector. Also from Fig-(7.6) we see that sudden death does not affect the MSE, but it may enhance the performance for systems with fewer degrees of freedom.

From Fig-(7.6) we conclude that what we have to care about is the first packet of any new interferer. So we consider a RAMP POWER ACCESS technique to further reduce the effect of the sudden birth of interferers. This technique increases the over head bits required in each packet, but with the space time detector the RAMP POWER ACCESS technique will be used only in the first packet of each user, or after long periods of inactivity.

Fig-(7.7) compares the RAMP POWER ACCESS technique with the full power access for Four antenna elements. In the RAMP POWER ACCESS technique the interferers increase their power

linearly over 200 bits until they get full power. From Fig-(7.7) the RAMP POWER ACCESS technique reduces the degradation in the MSE due to new interferer by around 5 dB sometimes by more than 7 dB. From this result, by using the RAMP POWER ACCESS technique we make sure that the MSE does not jump above the -16 dB level.

7.3.2 Remarks on sudden birth and death

Adaptive MMSE time only multiuser detectors proposed in [2] and [64] have large capacity and performance compared to the conventional receiver. Their complexity except for the complex multiplications and the adaptive algorithm is similar to the conventional receiver. Sudden births degrade the performance of the adaptive MMSE detector, the BER will be high at that time, and we may need to retrain the filter coefficients again. In this section we studied the effect of time varying user population and packet transmission (sudden birth and death) on the performance of the combined space-time multiuser detector proposed in this thesis. From the results we made three important points. The first point is that the combined space-time structure alleviates the effect of sudden birth and there is no need to retrain the detector because the detected symbols are still reliable and the MSE is still low. The second point, at start-up or after a new interferer arrives the filter coefficients converge faster than that of the adaptive MMSE detector, thus reducing the required training period. Finally, the space-time structure has some memory of the packets of departed interferers, so new packets of the same interferers will cause less harm to the performance. Also we use the RAMP POWER ACCESS techniques with the space-time structure to further reduce the effect of the appearance of the first packet of the new interferers. As a result, this detector is an attractive solution for high capacity wireless systems with packet transmission.

Fig-(7.4) Packet transmission in cellular systems.

Fig-(7.5) Effect of sudden birth of interference.

Fig-(7.6) Effect of packet transmission.

Fig-(7.7) Ramp power access technique vs. full power access for the linear space-time receiver.

7.4 Effect of spreading codes on the performance

In all our previous results we have assumed that random codes were used for spreading the data sequence of the CDMA users. We don't claim that random codes are the best suitable codes for the space-time receivers proposed in this thesis. However random codes give us many codes that we can support more users than the processing gain. Previous results show that space-time structures can support many more users than the processing gain.

Finding the best spreading code sequence for the space-time structures is an interesting area of research, but it is out of the scope of this thesis. However in this section we show some simulation results to see the effect of the spreading code set on the performance of the linear space-time receiver. Random codes and Hadamard code are selected for the comparison. The effect of using the same spreading code will be discussed in the next section. The following simulations are conducted in frequency selective fading channel described in chapter 6.

Fig-(7.8) shows a comparison between the performance of the linear MMSE receiver (time only) with random and Hadamard codes. It is found that Hadamard codes gives somewhat better results on the average than random codes, which shows the effect of spreading codes selection of the performance of the linear MMSE multiuser detection receiver (time only). This result is in consistent with the results in [2].

Fig-(7.9) shows that with the space time receiver there is no difference in performance between the different code sets. This is because the space-time structure does not depend on the correlation between codes only to separate the interference, but on differences among their spatial signatures too. So this important feature of the space-time receiver can reduce the complexity associated with spreading codes planning and assignment.

From Fig-(7.9) we see that there is no difference in the performance of the space time receiver with random codes or Hadamard codes. To look more closely at these results we plot the outage probability of the MSE for the space-time structure with Hadamard and random codes. Fig-(7.10) shows the outages probability of the linear space-time structure with Hadamard and random codes. The results show no difference in outage between the Hadamard and the random codes.

Fig-(7.8) Effect of the spreading codes on the performance of the linear MMSE receiver (time only receiver).

Fig-(7.9) Effect of the spreading codes on the performance of the linear space-time receiver.

Fig-(7.10) Effect of spreading code selection on the outage probability of the linear space-time receiver.

7.5 Out-off-cell interference

Until this point, we have assumed that all interference came from the same cell as the desired user. Since we consider the space-time structure for cellular CDMA systems, it is necessary to look at the effect of out of cell interference (inter-cell interference) and the interference from the same cell (intra-cell interference) on the performance.

There are two types of out of cell interference. The first one is interference from spreading codes different from the desired user code, and the second type is interference with the same spreading code as the desired user. The first type of interference has a similar effect as the interference from the same cell as the desired user, but with less power due to distance separation. This type of interference was considered in previous chapters of this thesis.

The second type of interference, which is the subject of this section is the inter-cell interference with the same code as the desired user. One of the important feature of the CDMA system is that the same frequency bandwidth could be reused in the adjacent cells. So if we consider hexagonal cells, then there could be up to six adjacent-cell interferers with the same code as the desired user. In [2], Abdulrahman studied the effect of the time only structure with decision feedback filter. He found that one interferer with same code as the desired user could degrade the performance severely, specially if it is located on the cell boundary. Abdulrahman did not study the case where more than one interference with the same code as the desired user, but it is clear that it will be worst. He concluded from his study that neighboring cells should not assigned the same spreading codes over the same carrier frequency. The same spreading codes could be assigned over the same carrier frequency in cells that are further apart. He also came with a plan for the spreading bandwidth and spreading code assignments of neighboring cells.

In Fig-(7.11) to Fig-(7.20) we examine the effect of out-of-cell interference having the same spreading code as the desired user within the cell of interest on the performance of the linear space-time receiver. In the following simulations the out-of-cell interferer will be considered as the interferer who has the same code as the desired user.

In Fig-(7.11) and Fig-(7.13) we assume that there are 4 users in the system. Two cases are considered, in the first case we assume all users have different spreading codes and in the second case we assume that the fourth user has the same spreading code as the desired user, this fourth user is

considered as interferer from the adjacent-cell. In these simulations we assume that the impulse response of the channel is same as in chapter 6 and it is assumed to have three independent paths, and all the paths are assumed to be Rayleigh distributed with the same variance. The path delays are distributed uniformly within the first six chips of a bit interval; i.e. the delay spread is equal to six chip periods. The DS-CDMA signal used in the analysis has a processing gain(PG) equal to eight, and uses BPSK modulation. We use random codes for spreading our data with eight chips in each code. The sampling frequency of the received signal before the chip matched filter is equal three times the chip rate, so there are three input samples per chip. The angle of arrival (AOA) is modeled as a random process uniformly distributed in the interval $[-\pi/2, \pi/2]$. E_b/N_o is set to 18dB for all users unless otherwise mentioned, where $E_b = p_k T_b$. and N_o is the PSD of the background thermal noise.

In Fig-(7.11) we assume only one element antenna and we see that there is about 2dB degradation in the MSE when the out-of-cell interference has the same code as the desired user. The interferer with the same spreading code differs from the desired signal in that it arrives with a different, random, delays and through different, random, multipath. However in Fig-(7.13) with four antenna elements we get the same result in the two cases and there is no degradation in the MSE. We repeat the same experiment in Fig-(7.15) and Fig-(7.17) with different number of taps for the FIR filter to see the effect of number of taps on the mse. From these results we draw the same conclusion, but with 14 taps FIR filters we see better MSE results.

In [2] it was found that the capacity of the DF-MMSE receiver is about 4 with processing gain equal to 8. In Figures numbered Fig-(7.12), Fig-(7.14), Fig-(7.16), and Fig-(7.18) we assume there are four users in the cell of interest and the fifth user is in the neighboring cell. Also we assume that all users have the same received power.

In Fig-(7.12) and Fig-(7.14) we assume that there are 5 users in the system with the 5th user having the same spreading code as the desired user. In Fig-(7.12) we assume one antenna element, and from the results we see that there is about 6dB degradation in the mse due to the 5th user. That is why [2] conclude that neighboring cell should not assign the same spreading codes over the same frequency band and the same spreading code should be assigned only to cells that are further apart. However with the linear space-time structure we can reduce the effect of out-of-cell inter-

ference. From Fig-(7.14) the degradation due to the 5th user is about 1 dB, which suggest that neighboring cells can be assigned the same spreading codes.

We repeat the same previous simulation with different number of the FIR filter taps. In Fig-(7.16) and Fig-(7.18) we assume that the number of forward FIR filter taps equal to 14. We came to the same conclusion as the previous results but with the 14 taps FIR filters. We see better MSE results compared to 8 taps FIR filter. Also comparing Fig-(7.14) and Fig-(7.16) we see that with the 14 taps FIR filters we reduce the effect of the 5th user with the same spreading code as the desired user. In Fig-(7.14) the degradation is around 1 dB, however in Fig-(7.18) with 14 taps the degradation is around 0.5 dB.

In Fig-(7.19) and Fig-(7.20) we conduct another experiment to see the effect of out of cell interference with the same spreading code as the desired user but with different power.

In this experiment we assume that there are 4 users in the desired user cell and the 5th user is in the neighbor cell. The 5th user which is in another cell is assumed to start transmission with -20dB less received power than the desired user. Then this interference start increasing its amplitude by 0.1 every 500 bits, simulating the effect of the 5th user moving towards the cell boundary of the desired user.

From Fig-(7.19) and with one element antenna we see that the MSE degrades as the 5th user gets closer to the cell boundary of the desired user until it reaches an unacceptable level. From this result it is clear that with one antenna element we can not assign the same spreading code set to the neighboring cells, but only to cells that are far apart. But with the four antenna elements we see that the linear space-time receiver can handle this kind of interference and make it possible for the system designer to assign the same code to neighboring cells, which will reduce the complexity associated with code planning and assignment. In Fig-(7.20) we repeat the same experiment with different numbers of taps and we also reach the same conclusion. However the MSE is better with the 14 taps structure.

In this section we studied the effect of out off cell interference with same spreading code as the desired user on the performance of the linear adaptive space-time receiver proposed in the thesis. Results show that the linear space-time receiver could perfectly handle several interference having the same code as the desired user, and eliminate the need for spreading bandwidth and spreading

Fig-(7.11) Effect of out-of-cell interference with same spreading code as the desired user on the linear MMSE receiver (time only receiver).

Fig-(7.12) Effect of out-of-cell interference with same spreading code as the desired user on the linear MMSE receiver (time only receiver).

Fig-(7.13) Effect of out-of-cell interference with same spreading code as the desired user on the linear space-time receiver.

Fig-(7.14) Effect of out-of-cell interference with same spreading code as the desired user on the linear space-time receiver.

Fig-(7.15) Effect of out-of-cell interference with same spreading code as the desired user on the linear MMSE receiver (time only receiver).

Fig-(7.16) Effect of out-of-cell interference with same spreading code as the desired user on the linear MMSE receiver (time only receiver).

Fig-(7.17) Effect of out-of-cell interference with same spreading code as the desired user on the linear space-time receiver.

Fig-(7.18) Effect of out-of-cell interference with same spreading code as the desired user on the linear space-time receiver.

Fig-(7.19) Effect of out-of-cell interference with same spreading code as the desired user and different power.

Fig-(7.20) Effect of out-of-cell interference with same spreading code as the desired user and different power.

codes planning. Results also suggest the possibility of using the same code within the same cell. Such a feature is important in systems used the same spreading codes within the same cell. In the IEEE 802.11 standard the Barker code with 11 chips is used for spreading the data sequence in wireless LAN. All users use the same code but with different shifts, because the Barker code has very good auto-correlation property. However in frequency selective fading channels, delay spread can cause many users to have the same code shift, in this situation the performance will deteriorate. So we suggest the application of the space-time receivers in the IEEE 802.11 standard.

7.6 Effect of Shadowing on the outage probability

In a wireless channel the received signal strength depends on two effects: 1) small scale fading and 2) large scale path loss. In small scale fading the received signal strength will fluctuate with small spatial changes of the transmitter, receiver, or scattering objects around the receiving antenna. This type of fading is discussed in chapter 6.

The large scale path loss depends on two effects: 1) the distance between the receiving and transmitting antennas, which is called path loss, and 2) the spatial distribution of objects around the receiving antenna which will block line-of-sight or shadowing.

Path loss is a function of the distance between the transmitting and receiving antennas, which is defined as the ratio between the received and the transmitted powers [86].

However, due to the spatial distribution of objects around the mobile, the average received power at two different locations having the same distance from the transmitting antenna may change widely. This effect is called shadowing. Measurements have shown that the path loss a particular location is random and distributed log-normally [86]. The power received at distance d from the transmitting antenna is

$$\bar{p}(d) = \bar{p}(d_0) \Sigma \left(\frac{d_0}{d} \right)^n \quad (7.8)$$

where $\bar{p}(d_0)$ is the benchmark received power at distance d_0 , n is the propagation exponent, and Σ is a log-normal gaussian variable; i.e. its logarithm has a gaussian density.

$$y = 10\log(x)$$

$$p(y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{y^2}{2\sigma^2}\right) \quad (7.9)$$

with zero mean and variance σ^2 is in dB. A typical value of σ is 8 dB.

In the following simulations we will carry a comparison study between the linear space-time receiver and the temporal only receiver to see the capacity improvement supported by the linear space-time structure relative to the time only structure. In this study we include the effects of shadowing and distance related attenuation.

In this study we assume 3 groups of users and they are assigned letters A, B, and C respectively. All users in group A are assumed to be in the same cell as the desired user and all have the same average received power. Group B users are out-off-cell interference and have average received power of 20 dB below the desired user. Group C users are also out-off-cell interference with 40 dB average received power below the desired user.

The comparison study is conducted in three scenarios. In the first scenario we assume 2 users in group A, 2 users in group B, and 2 users in group C, for a total of six users in the system. In the second scenario we assume 4 users in group A, 4 users in group B, and 4 users in group C, for a total of 12 users in the system. This makes the system in the second scenario have double the capacity of the system in the first scenario. In the third scenario we assume that 8 users in group A, 8 users in group B, and 8 users in group C, for total of 24 users in the system. This makes that system in the third scenario have four times the capacity of the system in the first scenario. All these scenarios include the effect of shadowing with $\sigma = 8dB$ and frequency selective fading.

In Fig-(7.21) we compare the linear space-time structure with the time only structure in scenario number one. In this results we assume that the number of forward taps=8, step size equal to 0.2, and number of elements=4. From Fig-(7.21) we see that the linear space-time structure has more than 6dB gain in MSE compared to time only structure. To see how much capacity improvement that can the linear space-time receiver offer compared to the time only receiver we conduct the same simulation in scenarios number 2 and 3.

In Fig-(7.22) we simulate the linear space-time receiver in scenarios number 1, 2, and 3. We assume that the linear space-time receiver has 4 elements. Comparing scenarios number 1 and 2

we see that by doubling the number of users the structure still has the same steady state MSE, but it requires longer time to adapt. Also comparing the linear space-time structure in scenario number 3 with the time only structure in scenario number one, we see that even with four times the capacity of the time only structure the linear space-time receiver still maintains better MSE level, about 4 dB better. From this comparison we conclude that the linear space-time structure with 4 elements has more than four times the capacity of the time only receiver.

In Fig-(7.23) and Fig-(7.24) we study the outage probability of the MSE. Fig-(7.23) shows the outage probability of the MSE below -6dB and Fig-(7.24) shows the outage probability of the MSE below -12 dB. Both results confirm that the linear space-time receiver offer 4 times the capacity of the time only receiver

In the previous results we assumed that the out-off-cell interference is a structured interference, i.e. each interference has its own spreading code. In [23], the authors assumed that the out-off-cell interference is a gaussian random variable. They found that for a log-normal shadowing with standard deviation of 8 dB and propagation exponent of 4 the out-off-cell interference can be modeled as a gaussian random variable with mean less than or equal $0.247N_s$ and variance less than or equal $0.078N_s$, where N_s is the number of users per sector.

In the following results we use the same interference model as in [23]. In Fig-(7.25) and Fig-(7.26) we compare the capacity of the linear space-time receiver with the time only receiver where out-off-cell interference is modeled as gaussian random variable with mean $=0.247N_c$ and variance $=0.078N_c$, where N_c is the number of users per cell. These results also confirm that the linear space-time receiver with four antenna elements offers more than four times the capacity of the time only receiver, This conclusion is in complete consistency with the previous results.

7.7 Bit error rate results

MMSE criteria was used in evaluating the performance of the space-time structures proposed in this thesis in all previous results. MMSE is easy to calculate and it is less time consuming to simulate. Even though there is no linear relationship between the MMSE and the BER, MMSE gives us the ability to understand and characterize the space-time structures proposed in this thesis. Since $(MMSE)_{dB} \equiv (-SNR)_{dB}$ at the output of the receiver, where $SNR = E_b/N_0$, then low MMSE

Fig-(7.21) Effect of shadowing and distance related attenuation on the MSE.

Fig-(7.22) Effect of shadowing and distance related attenuation on the linear space-time receiver.

Fig-(7.23) Outage probability of the mse in shadowing environment.

Fig-(7.24) Outage probability of theMSE in shadowing environment

Fig-(7.25) Capacity comparison, out-off-cell interference is modeled as gaussian random variable $\text{Normal}(0.247N_s, 0.078N_s)$.

Fig-(7.26) Outage probability of the MSE where out-off-cell interference is modeled as gaussian random variable $\text{Normal}(0.247N_s, 0.078N_s)$.

values means low BER. E_b/N_0 between 3 to 6 dB is considered a good performance for DS-CDMA, [2].

To find the derived BER formula for the MMSE receiver is a very difficult task. Previous efforts to derive an exact error probability formula for the MMSE receiver is turned out to be a very complicated procedure [2].

Due to the non availability of closed analytical formula for the probability of error in CDMA systems with interference the BER rates performance is usually obtained by assuming that the interference is gaussian. A simple method was proposed in [31]. This method is based on the gaussian model for interference to calculate the bit error rate.

$$P_e = Q\left(\frac{1}{\sqrt{MMSE}}\right) \quad (7.10)$$

In Fig-(7.27) we calculate the BER using the above formula. The BER is calculated by averaging P_e over 500 runs. This results is conducted in frequency selective fading channel discussed in chapter 6. In each run we randomly pick the spreading codes, delays, AOA, Rayleigh fading coefficients, and the channel impulse response for each user. In the following results we assumed that $E_b/N_0=18dB$, number of forward taps is set to 14.

In Fig-(7.27) we draw the BER curve as a function of number of users. Up to 16 users are assumed in the system, this gives us the ability to accommodate more users than processing gain which is assumed to be equal to 8. From Fig-(7.27) we see that with one antenna element we can accommodate less than 4 users with $BER < 10^{-3}$, however with the space-time receiver we can accommodate 8 users with 2 elements and 16 users with 4 elements. From this results it is clear that the space-time structure offered a significant improvement in the DS-CDMA system capacity by adding more elements. Also with the space-time structure we can support systems requires good quality of service (QOS). For example with 4 elements and 6 users we can get $BER < 10^{-5}$ with processing gain equal 8.

In Fig-(7.28) to Fig-(7.31) we study the outage probability of the space-time structure and compare it with the outage probability of the linear MMSE multiuser receiver (time only receiver). The outage probability of X is defined as the number of runs such that the probability of BER less than X out of the 500 runs we conducted in this simulation. Fig-(7.28) to Fig-(7.31) shows the

Fig-(7.27) Bit error rate performance of the linear space-time receiver.

Fig-(7.28) Outage probability of $X=10^{-2}$.

Fig-(7.29) Outage probability of $X=10^{-3}$.

Fig-(7.30) Outage probability of $X=10^{-4}$.

Fig-(7.31) Outage probability of $X=10^{-5}$.

outage probability of $X = 10^{-2}$, 10^{-3} , 10^{-4} , and 10^{-5} respectively.

From Fig-(7.28) to Fig-(7.31) we see the superior performance of the linear space-time receiver compared to the linear MMSE receiver (time only receiver) in terms of BER. For example with $P(\text{BER} < 10^{-3})$ in Fig-(7.29) we have an outage probability of 0.2 for one element receiver with 6 users, however with the space-time receiver we have 6×10^{-3} outage with two elements and zero outage with 4 elements. Also notice that we have zero outage with 4 antenna elements up to 12 users in the system and the processing gain equal to 8. We conclude from the BER results that the space-time structure offers large improvement in the capacity and should be considered as a serious candidate for any DS-CDMA receiver design in the future.

7.8 Conclusion

In this chapter we discussed several issues that effect the application of the space-time structures in cellular systems. The linear adaptive space-time receiver was selected among the other space-time structures for the study for its simplicity and can be considered as a bench mark for all the space-time receivers developed in this thesis.

In section 7.2 we study the transient behavior of the linear space-time structures with the LMS algorithm. From the study we conclude that by using that space-time receiver we can reduce the effect of number of users and their powers on the training period.

In section 7.3 we discuss the effect of time varying user population and packet transmission. Results shows that with the linear space-time receiver we are not only able to reduce the effect of sudden death and birth of interference on the system but also we can eliminate the effect of sudden birth of packets of departed interference by retaining some memory of departed interference. Effect of spreading codes is studied in section 7.4 and results shows that the space-time structure not only depends of the correlation properties among the codes but also on the spatial properties too. The study shows that there are no difference in performance between the random and the orthogonal code for the space-time receiver. This reduces the complexity associated with code planing and management.

Effect of out-of-cell interference is studies in section 7.5, the study shows that the space-time structure can handle interferer with the same code as the desired user and eliminate it. In section

7.6 we study the effect of shadowing and distance related attenuation in cellular system and show that system employ the linear space-time receiver can offer more that four times the capacity of the system employing the time only receiver

BER results is given in section 7.7, we found that the BER results are in complete consistency with the MMSE results.

From this chapter we conclude that the space time receiver offer more than four times the capacity of the time only receiver and it is a very attractive structure for high data rate systems with packet transmission.

Conclusion and future research

8.1 Conclusion

We have developed several spatial-temporal processing algorithms that can enhance and improve the performance of the CDMA systems. These algorithms showed that they have the ability to substantially improve the performance and capacity of the adaptive multiuser structures (temporal only) previously proposed in the literature.

Chapter 2 gave an overall review of multiuser detection in CDMA systems and adaptive antenna array with the description of some multiuser structures.

In chapter 3 we developed the linear adaptive space-time multiuser receiver. Analysis of the optimum tap weights and the MMSE in synchronous and asynchronous CDMA systems is also given in chapter 3. Closed form expressions for the auto-correlation matrix and the cross-correlation vector are given in this chapter. Numerical results of the MMSE in synchronous and asynchronous CDMA systems is calculated and a comparison study is carried out between the linear space-time structure and the linear time only structure. The results show the inherent potential advantage of the space-time receiver compared to the time only receiver.

The decision feedback space-time receiver is proposed in chapter 4. Analysis of the optimum tap weights and the MMSE in MAI and ISI CDMA channels is also given in this chapter. Comparison study between the linear and the decision feedback space-time and time only structures in MAI and ISI CDMA channels is also given in chapter 4. Analytical results based on the MMSE criteria showed that the decision feedback space-time structure has the ability to cancel MAI and ISI. Also we found that in very small angle spread channels the decision feedback structure outperforms the linear space-time structure. However in large angle spread there is no advantage of the decision feedback over the linear space-time structure; the linear space-time receiver will be preferable for its simplicity.

Another new structure is proposed in chapter 5, which is called the centralized decision feedback space-time structure. The analysis for the optimum tap weights and the MMSE in MAI and ISI channels for the centralized receiver is also given in chapter 5. Analytical results based on the MMSE for the centralized receiver is drawn in chapter 5. The results showed that the centralized receiver has the ability to cancel the MAI and the ISI. A comparison study in MAI and ISI CDMA channels for all the proposed structures are done in chapter 5. It is found that the centralized structure outperforms the linear and the decision feedback structure, but extra complexity is needed for the centralized filters which makes the centralized structure complexity grow linearly with number of users. Because of its centralized nature, it can only be applied at the base station where the symbols of all users are available.

In chapters 3, 4, and 5 we consider the synchronous, asynchronous, MAI, and ISI CDMA channels. These channels were selected to demonstrate the ability and the potential power behind the space-time processing to cancel MAI and ISI. However, we proposed these structures for wireless CDMA systems, where in the wireless channels there are many other impairments which may limit the application of any system. Chapter 6 is devoted to study the performance of the linear space-time receiver in frequency selective fading channels, where multipath and fading can degrade the performance of any system. The analysis of the optimum tap weights and the MMSE of the linear space-time structure in frequency selective fading channels is given in chapter 6. Analytical results are also presented in this chapter. From the results we found that the linear space-time receiver is not only capable of canceling MAI and ISI but also has the ability to collect

the energy of the different multipath components. We found that these structures combine the function of multiuser detection, antenna arrays, ISI equalizer, and RAKE reception in one single structure. Also from the comparison study between the linear MMSE multiuser receiver (temporal only) and the linear space-time receiver we conclude that the space-time receiver has the ability to improve the performance of the CDMA system significantly.

In chapter 7 we study practical issues related to the application of the adaptive linear multiuser detection to cellular wireless systems. We show how the linear space-time receiver overcomes many of the shortcomings of the linear MMSE receiver (temporal only). First in chapter 7 we discuss some issues related to the transient behavior of the linear space-time receiver and compare it with the linear temporal receiver. Even though the space-time structure has more coefficients to adapt, from the results we found that it has a shorter training period, adapts faster, has less steady state MSE, and its training period is less sensitive to the number of interferers than that of the linear temporal multiuser detector. Also results show that with much less bandwidth the linear space-time receiver still has better convergence characteristics and steady state MSE.

The effect of a time varying user population and packet transmission is studied in chapter 7. From these simulations we made three important observations. The first is that the combined space-time receiver alleviates the effect of sudden birth of interference and there is no need to retrain the detector because the detected symbols are still reliable and the MSE is still low. The second observation is that, at start-up, or after a new interference arrives, the filter coefficients converge faster to lower MSE levels than that of the adaptive linear MMSE receiver (time only), thus reducing the required training period. The second observation is in complete consistency with the transient behavior results. Finally, we found the space-time receiver has some memory of the packets of departed interferers. New packets of departed interference will cause less harm than the first packet. From the last observation we conclude that we have to adapt only for the first packet of new users, so we use the ramp access power technique with the space-time structure to reduce the effect of the sudden birth of interference. Results show that the effect of sudden birth of interference on the MSE could be reduced further by almost 7.5 dB by using the ramp access power technique.

In chapter 7 we examine also the effect of spreading codes selection on the performance of the linear space-time receiver. We found that the linear space-time receiver is less sensitive to spreading code selection. This is because the space-time receiver does not depend only on the cross-correlation properties among the codes, but on the spatial signature too. This feature can reduce the complexity associated with the spreading codes planning and assignment.

Another issue we study in chapter 7 is the effect of out-of-cell interference. In this experiment we study the effect of interference in neighboring cell that has the same spreading code as the desired user. Simulation results show that the linear space-time receiver can perfectly handle out-of-cell interference having the same code as the desired user, whereas [2] found that with the decision feedback MMSE multiuser receiver, the CDMA system designer should not assign the same codes set to the neighboring cells; otherwise the overall capacity of the system will be much lower. Also with the space-time structure we eliminate the need for the code planning suggested by [2].

Out-of-cell interference results also suggest the possibility of using the same code within the same cell. Such a feature could be very important in systems such as wireless LAN (IEEE 802.11). In IEEE 802.11 standard the Barker code with 11 chips is used for spreading the data sequence in wireless LAN. All users use the same Barker code but with different shifts, because the Barker code has very good auto-correlation property. However, in frequency selective fading channels, delay spread can cause many users to have the same code shift. In this situation the performance will deteriorate. So with the space-time structures we can reduce this effect.

In chapter 7 we study the capacity improvement that can be achieved using the linear space-time receiver. In section 7.6 we found that the linear space-time receiver with antenna element offers four times the capacity of the time only receiver. In these results we include the effect of shadowing.

The BER performance was also considered in chapter 7, and results showed consistency with the MMSE results. It was concluded that the space-time receiver can provide very low BER results for high data rate transmission. This make the space-time structure very attractive for high data rate systems with packets transmission such as IEEE 802.11 or next generation standards.

8.2 Future work

The areas of multiuser detection and smart antennas have gained a lot of attention in the last few years. These two areas are believed to provide the capacity needed for the future wireless systems which must support different services such as voice, data, and video transmission. In this thesis we jointly combined the spatial and temporal domains and proposed several adaptive space-time structures. These two area are not fully developed and require a lot of research. During this thesis we found many open problems that need more study in the future. In this section we describe some of the these open problems.

Joint space-time processing and power control

Strict or tight power control is an essential technique for the conventional DS-CDMA receiver to over come the near-far problem. The multiuser detection technique came to alleviate the near-far problem, which reduces the complexity associated with the power control design. However, power control has some features that make it essential for any system. For example, power control provides a feedback to the mobile users to adjust their transmitted power to maintain equal received power at the base station. By doing so, each mobile user will only transmit the needed power to maintain a certain SNR, which will result in extended battery life of the mobile and reduced overall MAI in the cellular system. Combined power control and space-time multiuser detection is an interesting area for future research.

Space-time receiver for multirate reception

Next generation mobile communication systems are necessary to support several different communication services, i.e. multimedia, voice transmission, data transmission, and video transmission. To support these, next generation systems should handle multirate transmission with different qualities of service.

In multirate transmission different users with different data rates will arrive at the receiver with different received power even with strict power control. This is because high rate users are assigned more power than low rate users. So in multirate transmission the near-far problem is inherent, and the conventional receiver will fail to handle multirate transmission.

A suggested solution to this problem is the use of multiuser detection and adaptive antenna array techniques separately or combined. One interesting future research is the design and analysis of a multi-rate combined space-time receiver that can solve and handle different rate reception for next generation wireless systems.

Comparison study between the long code design philosophy and short code design philosophy

When the IS'95 standard appeared the only available receiver was the matched filter receiver i.e. the conventional receiver. The research on multiuser detection techniques was just started at that time [104]. The problem was facing the IS'95 group was that the conventional receiver is optimum only in AWGN channel, i.e. it is not optimum in MAI channel. To overcome this problem the standards group came up with the idea of long codes to randomize the interference and make it look like Gaussian noise. After many years of multiuser detection research and development, multiuser detection matured, and was found to be a promising technique to increase the capacity of the CDMA system. But the problem with IS'95 long codes is that it hinders the use of multiuser detection techniques. Due to this problem the idea of short codes or pulse on code becomes relevant. The long code design is called random CDMA or R-CDMA and the short code design is called deterministic CDMA or D-CDMA, [102]. Adaptive multiuser detection techniques is one of the simplest multiuser detection algorithms and it proves to be a promising technique [106]. But adaptive multiuser detection requires the that the spreading code should be repeated every transmitted bit, i.e. D-CDMA. In the literature there is a big debate about which design philosophy will lead to the larger capacity and better performance. For example, [102] claims that R-CDMA has better capacity than D-CDMA. But many other papers prove the opposite [107], [34]. Even though this debate still going on there is no complete standard design for CDMA system except the one which utilizes the long code idea. A comparison study between these two designs is very important. This study may change our view to any future standard for CDMA system.

References

- [1] Abdulrahman M., A. U. H. Sheikh, D. D. Falconer, "Decision Feedback Equalization for CDMA in Indoor Wireless Communication," IEEE JSAC, vol. 12, no. 4, pp. 698-706, May 1994.
- [2] Abdulrahman M., A., "DFE for Interference and Multipath Suppression in a CDMA System," Ph.D thesis, 1994, Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada.
- [3] Abdulrahman M., D. D. Falconer, "Cyclostationary Crosstalk Suppression by Decision Feedback Equalization on Digital Subscriber Loops," IEEE JSAC, vol. 10, no. 3, pp.640-649, Apr 1992.
- [4] Alam M., "Performance of Multirate CDMA Transmission in Cellular Environment," M.Sc. thesis, 1998, Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada.
- [5] Anderson S., M. Millnert, M. Viberg, and B. Wahlberg, "An Adaptive Array for Mobile Communication Systems," IEEE Trans. Comm., vol. 40, no. 1, pp. 230-236, Feb 1991.
- [6] Balaban P., J. Salz, "Optimum Diversity Combining and Equalization in Digital Transmission with Application to Cellular Mobile Radio -Part I Theoretical Considerations," IEEE Trans. Comm., vol. 40, no. 5, pp. 885-894, May 1992.
- [7] Balaban P., J. Salz, "Optimum Diversity Combining and Equalization in Digital Transmission with Application to Cellular Mobile Radio -Part II Numerical Results," IEEE Trans. Comm., vol. 40, no. 5, pp. 885-894, May 1992.
- [8] Bang S. C., H. R. Park, and Y. Han, "Performance Analysis of a Wideband CDMA System for FPLMTS," VTC 97.
- [9] Bernstein X. and A. M. Haimovich, "Space-Time Optimum Combining for CDMA Communications," Wireless Personal Comm., vol. 3, Nos. 1-2, pp. 73-89, 1996.
- [10] Cox D. C., "Universal Digital Portable Radio Communications," Proceedings of the IEEE, vol. 75, no. 4, pp. 436-475, Apr 1987.
- [11] Despins C. L., D. D. Falconer, and Mahmoud S. A., "Compound Strategies of Coding, Equalization, and Space Diversity for Wide-Band TDMA Indoor Wireless Channels," IEEE Trans. Comm., vol. 41, no. 4, pp. 369-379, Nov 1992.

- [12] Duel-Hallen A., "Decorrelating Decision-Feedback Multiuser Detector for Synchronous Code-Division Multiple-Access Channel," IEEE Trans. Comm., vol. 41, no. 2, pp. 285-290, Feb 1993.
- [13] Duel-Hallen A., "A Family of Multiuser Decision-Feedback Detectors for Asynchronous Code-Division Multiple-Access Channel," IEEE Trans. Comm., vol. 43, no. 2/3/4, pp. 421-434, Feb/ Mar/ Apr 1993.
- [14] Duel-Hallen A., J. Holtzman, and Z. Zvonar, "Multiuser Detection for CDMA Systems," IEEE Personal Comm., pp. 46-58, Apr 1995.
- [15] El-Ezabi A., A. Duel-Hallen, "Combined Error Correction and Multiuser Detection for Rayleigh Fading Synchronous CDMA Channels,"
- [16] El-Ezabi A., A. Duel-Hallen, "A Novel Interleaving Scheme for Multiuser Detection of Coded CDMA Systems,"
- [17] Falconer D.D., A.M. Legnain, S. Roy "Receiver Spatial-Temporal Signal Processing For Broadband Wireless Systems", Invited paper to the IEEE PIMRC'2000, London, UK.
- [18] Falconer D. D., M. Abdelrahman, N. W. K. Lo, B. R. Petersen, And A. U. H. Sheikh, "Advances in Equalization and Diversity for Portable Wireless Systems," Digital Signal Processing, vol. 3, pp. 148-162, 1993.
- [19] French R. C., "The Effect of Fading and Shadowing on Channel Reuse in Mobile Radio," IEEE Trans. Vehic. Tech., vol. VT-28, no. 3, pp. 171-181, Aug 1979.
- [20] Fulghum T., K. Molnar, A. Duel-Hallen, "The Jakes Fading Model Incorporating Angular Spread,"
- [21] Grag V. K., J. E. Wilkes, "Wireless & Personal Communications Systems," Prentice Hall PTR, 1996.
- [22] Geraniotis E. A., M. B. Pursley, "Error Probability for Direct-Sequence Spread-Spectrum Multiple-Access Communications-- Part II: Approximations," IEEE Trans. Comm., vol. 30, no. 5, pp. 985-995, May 1982.
- [23] Gilhousen K. S., I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver, Jr., and C. E. Wheatley III, "On the Capacity of a Cellular CDMA System," IEEE Trans. Vehic. Tech., vol. 40, no. 2, pp. 303-312, May 1991.
- [24] Glisic S. G., P. A. Leppanen, "Code Division Multiple Access Communications," Kluwer Academic Publishers, 1995.
- [25] Godara L. C., "Applications of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations," Proceedings of the IEEE, vol. 85, no. 7, pp. 1029-1060, Jul 1997.

- [26] Godara L. C., "Applications of Antenna Arrays to Mobile Communications, Part II: Beam-Forming and Direction-of-Arrival Considerations," *Proceedings of the IEEE*, vol. 85, no. 8, pp. 1193-1245, Aug 1997.
- [27] Goodman D. J., "Trends in Cellular and Cordless Communications," *IEEE Comm. Magazine*, pp. 31-40, June 1991.
- [28] Haykin S., "Adaptive Filter Theory," 3rd Edition, Prentice-Hall, 1996.
- [29] Haykin S., "Radar Array Processing for Angle of Arrival Estimation," *Array Signal Processing*, Chapter 4, Printice Hall, 1985.
- [30] Heeswyk F. V., D. D. Falconer, and A. U. H. Sheikh, "Decorrelating Detectors for Quasi-Synchronous CDMA," *Wireless Personal Comm.*, vol. 3, Nos. 1-2, pp. 129-147, 1996.
- [31] Holtzman, J.M., "A Simple, Accurate Method to Calculate Spread Spectrum Multiple Access Error Probabilities," *IEEE International Conference on Conference on Communication*, pp. 1633-1636, 1991.
- [32] Honig M., U. Madhow, and S. Verdu, "Blind Adaptive Interference Suppression for Near-Far Resistance CDMA," *IEEE Globecom* 1994.
- [33] Honig M. L., M. J. Shensa, S. L. Miller, and L. B. Milstein, "Performance of Adaptive Linear Interference Suppression for DS-CDMA in The Presence of Flat Rayleigh Fading," *VTC 97*.
- [34] Honig M. L., and W. Veerakachen, "Performance Variability of Linear Multiuser Detection for DS-CDMA," *VTC 96*.
- [35] Honig M. L. "Rapid Detection and Suppression of Multi-User Interference in DS-CDMA," *Proc. 1995, ICASSP, Detroit, MI, May 1995*.
- [36] Hosur S., A. H. Tewfik, and V. G. Moghadam, "Adaptive Multiuser Receiver Schemes for Antenna Arrays," *IEEE Int. Symp. on Personal, Indoor, and Mobile Comm.*, vol. 3, pp. 940-944, Sep 1995.
- [37] Hudson J. E., "Adaptive Array Principles," Peter Peregrinus LTD, 1981.
- [38] Huang H., H. Viswanathan, and G.J. Foschini, "Multiple Antennas in Random Code CDMA Systems: Transmission, Detection and Spectral Efficiency," *WCNC'99*, Sep 1999.
- [39] Jakes W. C., "Microwave Mobile Communications," IEEE Press, 1974.
- [40] Johnson D. H., and D. E. Dudgeon, "Array Signal Processing Concepts & Techniques," Prentice Hall PTR, 1993.
- [41] Juntti M., "Multiuser Demodulation for DS-CDMA Systems in Fading Channels," Ph.D. thesis, Department of Electrical Engineering, University of Oulu, Finland.
- [42] Kogiantis A., "Uplink Capacity Studies for Adaptive Antenna Arrays in Third Generation CDMA Wireless Systems," *WCNC'99*, Sep 1999.

- [43] Kohno R., H. Imai, M. Hatori, "Design of Automatic Equalizer Including a Decoder of Error-Correcting Code," IEEE. Trans. Comm., vol. 33, no. 10, Oct 1985.
- [44] Kohno R., H. Wang, and H. Imai, "Adaptive Array Antenna Combined with Tapped Delay Line Using Processing Gain for Spread-Spectrum CDMA Systems," Proc. 3rd IEEE Int. Sym. Personal, Indoor and Mobile Radio Comm., PP. 634-638, Oct. 1992.
- [45] Kohno R., "An Adaptive Canceller of Cochanel Interference for Spread-Spectrum Multiple-Access Communication Networks in a Power Line," IEEE JSAC, vol. 8, no. 4, pp. 691-699, May 1990.
- [46] Kohno R., H. Imai, M. Hatori, and S. Pasupathy, "Combination of an Adaptive Array Antenna and a Canceller of Interference for Direct-Sequence Spread-Spectrum Multiple-Access System," IEEE JSAC, vol. 8, no. 4, pp. 675-682, May 1990.
- [47] Kohno R., "Spatial and Temporal Filtering for Co-Channel Interference in CDMA," Code Division Multiple Access Communications, S. G. Glisic and P. A. Leppanen, Ends., pp. 117-146, The Netherlands: Kluwer, 1995.
- [48] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "Transient Behavior of the Linear Adaptive Combined Space-Time Receiver for CDMA Systems," IEEE PIMRC'2000, London, UK.
- [49] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "Centralized Decision Feedback Adaptive Combined Space-Time Detector for CDMA Systems", IEEE International Conference on Communication ICC'99.
- [50] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "Effect of Time-Varying User Population on the Performance of the Adaptive Combined Space-Time Receiver for DS-CDMA Systems", IEEE WCNC'99.
- [51] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "Performance of New Adaptive Combined Space-Time Receiver for Multiuser Interference Rejection in Multipath Slow Fading CDMA Channels", IEEE GLOBECOM 98.
- [52] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "Decision Feedback Adaptive Combined Space-Time Receiver for Multiuser Interference Rejection in CDMA Systems", The 10th International Conf. on Wireless Communication (Wireless'98), vol. 1, pp. 164-170, July 1998.
- [53] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "Near Far Resistance of New Adaptive Combined Space-Time Receiver for Multiuser Interference Rejection in Asynchronous CDMA Systems", 19th Biennial Symp. on Comm., pp. 101-105, Jun 1998.
- [54] Legnain A.M., D.D. Falconer, and A.U. Sheikh, "New Adaptive Combined Space-Time Receiver for Multiuser Interference Rejection in Synchronous CDMA Systems", IEEE CCECE'98, vol. 1, pp. 421-424, May 1998.

- [55] Lim T., Yu Gong, and B. Farhang-Boroujeny, "Convergence Analysis of LMS Multiuser CDMA Detectors," WCNC'99, Sep 1999.
- [56] Lin H. C., "Spatial Correlation in Adaptive Arrays," IEEE Trans. Comm., vol. 30, no. 2, Mar 1982.
- [57] Lin S. C., "Optimum Diversity Combining with Finite-Tap Decision Feedback Equalization in Digital Cellular Mobile Radio," ICC 97.
- [58] Lo. N. W. K., D. D. Falconer, and A. U. H. Sheikh, "Adaptive Equalization and Diversity Combining for Mobile Radio using interpolated Channel Estimates," IEEE Trans. Vehic. Tech., vol. 40, no. 3, pp. 636-645, Aug 1991.
- [59] Lupas R. and S. Verdu, "Linear Multiuser Detectors for Synchronous Code Division Multiple Access Channels," IEEE. Inform. Theory, vol. IT-35, no. 1, pp. 123-136, Jan. 1989.
- [60] Lupas R. and S. Verdu, "Near-far Resistance of Multiuser Detectors in Asynchronous Channels," IEEE Trans. Comm., vol. COM-38, no. 4, pp. 496-508, Apr 1990.
- [61] Madhow U. and M. L. Honig, "Error Probability and Near-Far Resistance of Minimum Mean Squared Error Interference Suppression Schemes for CDMA," IEEE Globecom 1992.
- [62] Madhow U. and M. L. Honig, "MMSE Interference Suppression for Direct Sequence Spread-Spectrum CDMA," IEEE Trans. Comm., vol. 42, no. 12 pp. 3178-3188, Dec 1994.
- [63] Martone M., "An Adaptive Array for Wireless Communication Systems with Frequency Selective Multipath Fading Using High Order Statistics Processing," ICC 97.
- [64] Miller S. L., "An Adaptive Direct-Sequence Code-Division Multiple- Access Receiver for Multiuser Interference Rejection," IEEE Tran. Comm., vol. 43, no. 2/3/4, pp. 1746-1755, Feb./Mar./Apr. 1995.
- [65] Miller S. L., "Transient Behavior of the Minimum Mean-Squared Error Receiver for Direct Sequence Spread Spectrum CDMA," IEEE 1994.
- [66] Monogioudis P., R. Tafazolli, B. G. Evans, "LFSE Interference Cancellation in CDMA Systems," ICC 94.
- [67] Monsen P., "Theoretical and Measured Performance of DFE Modem on a Fading Multipath Channel," IEEE Trans. Comm., vol. 25, no. 10, pp. 1144-1153, Oct 1977.
- [68] Monsen P., "Feedback Equalization for Fading Dispersive Channels," IEEE Trans. Inf. Theory, pp. 56-64, Jan 1971.
- [69] Monsen P., "Adaptive Equalization of the Slow Fading Channel" IEEE Trans. Comm., vol. 22, no. 8, pp. 1064-1075, Aug 1974.

- [70] Monzingo R. A., Thomas W. Miller, "Introduction to Adaptive Arrays," John Wiley & Sons, 1980.
- [71] Moshavi S., "Multi-User Detection for DS-CDMA Communications." IEEE Comm. Magazine, pp. 124-136, Oct. 1996.
- [72] Mydlow M. W., S. Basavaraju, and A. Duel-Hallen, "Decorrelating Detector with Diversity Combining for Single User Frequency-Selective Rayleigh Fading Multipath Channels," Wireless Personal Comm., vol. 3, Nos. 1-2, pp. 175-193, 1996.
- [73] Naguib A. F., A. Paulraj, "Performance of Wireless CDMA with M-ary Orthogonal Modulation and Cell Site Antenna Arrays," IEEE JSAC, vol. 16, no., 1995.
- [74] Naguib A. F., "Space-Time Receivers for CDMA Multipath Signals," ICC 97.
- [75] Naguib A. F., "Adaptive Antennas for CDMA Wireless Networks," Ph.D. thesis, Department of Electrical Engineering, Stanford University, USA.
- [76] Ojanpera T., P. A. Ranta, S. Hamalainen, and A. Lappetalainen, "Analysis of CDMA and TDMA for 3rd Generation Mobile Radio Systems," VTC 97.
- [77] Onoe S., K. Ohno, K. Yamagata, and T. Nakamura, "Wideband-CDMA Radio Control Techniques for 3rd Generation Systems," VTC 97.
- [78] Pados D. A., S. N. Batalama, "Low-Complexity Blind Detection of DS/CDMA Signals: Auxiliary-Vector Receivers," IEEE Trans. Comm., vol. 45, no. 12, pp. 1586-1594, Dec 1997.
- [79] Paluraj A. J., and C. B. Papadias, "Space-Time Processing for Wireless Communications," IEEE Signal Processing Magazine, pp. 49-83, Nov 1997.
- [80] Petersen B. R., and D. D. Falconer, "Minimum Mean Square Equalization in Cyclostationary and Stationary Interference- Analysis and Subscriber Line Calculations," IEEE JSAC, vol. 9, no. 6, pp. 931-940, Aug 1991.
- [81] Pillai S. U., "Array Signal Processing," Springer-Verlag New York Inc., 1989.
- [82] Proakis J. G., "Digital Communication," 3rd Edition, McGraw-Hill, 1995.
- [83] Pursley M. B., "Performance Evaluation for Phase-Coded Spread Spectrum Multiple-Access Communication- Part I: System Analysis," IEEE. Trans. Comm., vol. 25, no. 8, pp. 795-799, Aug 1977.
- [84] Pursley M. B., "Performance Evaluation for Phase-Coded Spread Spectrum Multiple-Access Communication- Part II: Coded Sequence Analysis," IEEE. Trans. Comm., vol. 25, no. 8, pp. 800-803, Aug 1977.
- [85] Pursley M. B., D. V. Sarwate, and W. E. Stark, "Error Probability for Direct-Sequence Spread-Spectrum Multiple-Access Communications-- Part I: Upper and Lower Bounds," IEEE Trans. Comm., vol. 30, no. 5, pp. 975-984, May 1982.
- [86] Rappaport T. S., "Wireless Communications Principles & Practice." Prentice Hall PTR, 1996.

- [87] Rapajic P. B., and B. S. Vucetic, "Adaptive Structures for Asynchronous CDMA Systems," *IEEE JSAC*, vol. 12, no. 4, pp. 685-697, May 1994.
- [88] Rong Z., T. S. Rappaport, P. Petrus, and J. H. Reed, "Simulation of Multitarget Adaptive Array Algorithms for Wireless CDMA Systems," *VTC 97*.
- [89] Rong Z., P. Petrus, T. S. Rappaport, and J. H. Reed, "Despread-Respread Multi-Target Constant Modulus Array for CDMA Systems," *IEEE Comm. Letters*, vol. 1, no. 4, pp. 114-116, Jul 1997.
- [90] Saleh A. M., and R. Valenzuela, "A statistical Model for Indoor Multipath Propagation," *IEEE JSAC*, vol. 5, no. 2, pp. 128-137, Feb 1987.
- [91] Shah A., A. M. Haimovich, "Bit Error Computations for Space-Time Narrow-Band Interference Suppression in CDMA Communications," *ICC 97*.
- [92] Simon M. K., J. K. Omura, R. A. Scholtz, and B. K. Levitt, "Spread Spectrum Communications Handbook," Revised Edition, McGraw-Hill Inc., 1994.
- [93] Spencer Q., M. Rice, B. Jeffs, and M. Jensen, "Indoor Wideband Time/Angle of Arrival Multipath Propagation Results," *VTC 97*.
- [94] Spencer Q., M. Rice, B. Jeffs, and M. Jensen, "A statistical Model for Angle of Arrival in Indoor Multipath Propagation," *VTC 97*.
- [95] Stuber G. L., "Principles of Mobile Communication," Kluwer Academic Publishers, 1996.
- [96] Subramanian S., "A Multiple-Antenna-Multiple-Equalizer System for CDMA Indoor Wireless Systems," Ph.D. thesis, Department of Electrical and Computer Engineering, University of Victoria British Columbia, Canada.
- [97] Tanaka S., M. Sawahashi, and F. Adachi, "Pilot Symbol-Assisted Decision-Directed Coherent Adaptive Array Diversity for DS-CDMA Mobile Radio Reverse Link," *Wireless 97*.
- [98] Turin G. L., "Introduction to Spread-Spectrum Antimultipath Techniques and Their Application to Urban Digital Radio," *Proceedings of the IEEE*, vol. 68, no. 3, pp. 328-353, Mar 1980.
- [99] Van Etten W., "An optimum Linear Receiver for Multiple Channel Digital Transmission Systems," *IEEE Trans. Comm.*, pp. 828-834, Aug 1975.
- [100] Varanasi M. K. and B. Aazhang, "Multistage Detection in Asynchronous Code Division Multiple Access Communications," *IEEE Trans. Comm.*, vol. 38, no. 4, pp. 509-519, Apr. 1990.
- [101] Varanasi M. K. and B. Aazhang, "Near-optimum Detection in Synchronous Code Division Multiple Access Systems," *IEEE Trans. Comm.*, vol. 39, no. 5, pp. 725-736, May 1991.

- [102] Vembu S. and A. J. Viterbi, "Two Different Philosophies in CDMA - A Comparison," VTC 96.
- [103] Verdu S., "Minimum Probability of Error for Asynchronous Gaussain Multiple Access Chan nels," IEEE Trans. Inform. Theory, vol. IT-32, pp. 85-96, Jan. 1986.
- [104] Verdu S., "Optimum Multiuser Asymptotic Efficiency," IEEE Trans. Comm., vol. 34, no. 9, pp. 890-897, Sep 1986.
- [105] Verdu S., "Multiuser Detection," Advances in statistical signal processing, vol. 2, pp.369-409, JAI Press 1993.
- [106] Verdu S., "Adaptive Multiuser Detection" Code Division Multiple Access Communications, S. G. Glisic and P. A. Leppanen, Eds., pp. 97-116, The Netherlands: Kluwer, 1995.
- [107] Verdu S., "Demodulation in the Presence of Multiuser Interference: Progress and Misconceptions," Intelligent Methods in Signal Processing and Communications, A. Figueira-Vidal and F. Perez-Gonzalez, pp. 15-44, Birkhauser, Bosten: 1997.
- [108] Westman T., H. Holma, "CDMA System for UMTS High Bit Rate Services," VTC 97.
- [109] Winters J. H., "Optimum Combining for Indoor Radio Systems with Multiple Users," IEEE Trans. Comm., vol. 35, no. 11, pp. 1222-1230, Nov 1987
- [110] Winters J. H., "Signal Acquisition and Tracking with Adaptive Arrays in the Digital Mobile Radio System IS-54 with Flat Fading," IEEE Trans. Vehic. Tech., vol. 42, no. 4, pp. 377-384, Nov 1993.
- [111] Winters J. H., "The Impact of Antenna Diversity on the Capacity of Wireless Communication Systems," IEEE Trans. Comm., vol. 42, n0. 2/3/4, pp. 1740-1750, Feb/Mar/Apr 1994.
- [112] Winters J. H., "Optimum Combining in Digital Mobile Radio with Cochannel Interference," IEEE JSAC, vol. 2, no. 4, pp. 528-539, Jul 1984.
- [113] Winters J. H., "On the Capacity of Radio Communication Systems with Diversity in Rayleigh Fading Environment," IEEE JSAC, vol. 5, no. 5, pp. 871-878, Jun 1987.
- [114] Xie Z., R. T. Short, and C. K. Rushforth, "A Family of Suboptimum Detectors for Coherent Multiuser Communications," IEEE JSAC, vol. 8, no. 4, pp. 683-690, May 1990.