TF-Domain Spreading with GA assisted Multiuser Detection for Synchronous MC-CDMA System

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A dissertation submitted to FET, IIUI, in partial fulfillment of requirement for the degree of Master of Science in Electronic Engineering

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2009

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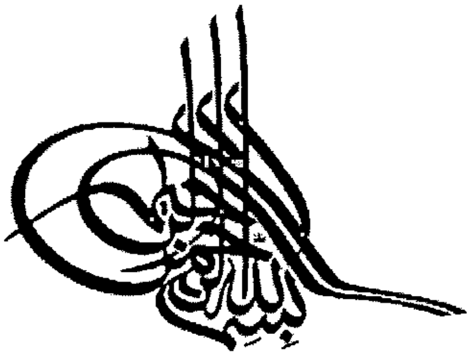
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Abstract

In this dissertation, *receiver optimization techniques* are being investigated under supervised Genetic Algorithm and Time and Frequency domain spreading, for a synchronous, multi-carrier direct-sequence code-division multiple-access MC DS-CDMA system has been used in optimization.

In case of multi-user detection, the multiple access interference (MAI) is introduced that makes the detector inefficient. The proposed system is comparatively less vulnerable to such inefficiencies in CDMA communication.

Furthermore, the performance of Decorrelating detector has been investigated for said scenario and is compared with that of Genetic Algorithm. The role of Walsh spreading sequences has also been examined for different number of users. A demonstrative comparison of this scheme in, contrast to the above two detectors is illustrated; which reveals that GA assisted MUD performs better as compared to the Decorrelating detector, which is due to inherent noise amplification factor.

Acknowledgements

First of all I am grateful to my Almighty Allah, The Kind and Merciful, Who enabled me to complete this work. Then, I would like thanking to my supervisor Dr. I. M. Qureshi, for his continual encouragements and enthusiasm. His enthusiasm in searching for new ideas in digital communications has always inspired and motivated me to reach new horizons of research, and this blessing is not stopped, in fact this was a very nice start of my research carrier. I never saw a person, who always treated me as his own child and pay special attention to my studies, my research and me in all stages. What I have been learning from him is not just a range of solutions to the communication problems, but his inspirational insight, his way of conducting research and his art of living.

My sincere thanks go to my teachers, Dr. A. N. Malik, Dr. T. A. Cheema, Dr. Abdul Jalil, and Dr. Aamir Saleem Chaudhry. I am also indebted to Mr. Shoaib Arif, Atta-ur-Rahman, and Malik Ghayas, for their wonderful friendship and warm encouragement. I would also like to thank my family for their valuable prayers and assistance, specially my sisters and my brother Dr. Tayyab Alam who catered for my research and all those who accompanied me quite for sometime but left their footprints behind forever. Finally, I would like to dedicate special words from the core of my heart, to Miss Hina Akhtar, for her sincere encouragements and moral support.

(Muhammad Zubair Alam)

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Glossary

2G	*2*nd *G*eneration
3G	*3*rd *G*eneration
AMPS	*A*dvance *M*obile *P*hone *S*ystem
AWGN	*A*dditive *W*hite *G*aussian *N*oise
BER	*B*it *E*rror *R*ate
BPSK	*B*inary *P*hase *S*hift *K*eying
CDMA	*C*ode *D*ivision *M*ultiple *A*ccess
CIR	*C*hannel *I*mpulse *R*esponse
CSI	*C*hannel *S*tate *I*nformation
DS	*D*irect *S*equence
FDMA	*F*requency *D*ivision *M*ultiple *A*ccess
FFH	*F*ast *F*requency *H*opping
GA	*G*enetic *A*lgorithm
GSM	*G*lobal *S*ystem of *M*obile
ISI	*I*nter *S*ymbol *I*nterference
ITU	*I*nternational *T*elecommunication *U*nion
MF	*M*atch *F*ilter
MMSE	*M*inimum *M*ean *S*quare *E*rror
MUD	*M*ulti *U*ser *D*etection
MRC	*M*aximum *R*atio *C*ombining
MT	*M*ulti *T*one
OFDM	*O*rthogonal *F*requency *D*ivision *M*ultiplexing

PIC	*P*arallel *I*nterference *C*anceller
SDMA	*S*pace *D*ivision *M*ultiple *A*ccess
SFH	*S*low *F*requency *H*opping
SIC	*S*uccessive *I*nterference *C*anceller
SNR	*S*ignal to *N*oise *R*atio
SSS	*S*pread *S*pectrum *S*ignal
SUD	*S*ingle *U*ser *D*etection
TF-domain	*Time and Frequency Domain*
TH	*T*ime *H*opping
TDMA	*T*ime *D*ivision *M*ultiple *A*ccess
TD-SCDMA	*T*ime *D*uplex-*S*mart antenna aided *CDMA*
UMTS	*U*niversal *M*obile *T*elecommunication *S*ystem
UTRA	*U*MTS *T*errestrial *R*adio *A*ccess
ZF	*Z*ero *F*orcing

CHAPTER 1

Introduction

1.1 Introduction to thesis

Code Division Multiple Access (CDMA) is digital technology in which each user is assigned a unique code to transmit the data over a wireless channel in the form of radio wave. Since the available bandwidth is limited. Therefore, the efficient utilization is requirement. CDMA uses the spectrum very efficiently, enabling more users to share radio waves simultaneously with the minimum interference.

Multi-carrier Code Division Multiple Access (MC-CDMA) [1] [2] [3] is a digital wireless communication technique, which combines Orthogonal Frequency Division Multiplexing (OFDM) [4, 5, 6, 7] and Direct Sequence CDMA (DS-CDMA). Conventionally, only one spreading sequence is used for each bit. This spreading sequence could be either in time domain or in frequency domain.

In MC-CDMA systems, we use spreading sequence both in times as well as in frequency domain. Hence we are capable of achieving frequency diversity gain at the cost of a reduced spreading gain.

In multi-user scenario when there are multiple users are transmitting data simultaneously; at the in receiver if we extract data of only one user, that is the user of interest, while considering rest of them as noise then this is called Single User Detection.

In contrast various Multi-user Detection (MUD) schemes have been proposed in the literature [8] [9] [13] in which all the received signals are considered useful and each user is separated. For example, the MUD based on Maximum Likelihood (ML) criterion. An Interference Cancellation (IC) based MUD has been proposed in [3], [9]. The examples are parallel interference cancellation based MUD and Successive interference Cancellation based MUD.

The Minimum Mean Square Error (MMSE) MUD has been described in [3], [8]. The noise amplification problem of the Decorrelating detector is mitigated by the linear MMSE MUD In this specific MMSE, which jointly minimizes the effect of the background noise and that of the MAI by exploiting the knowledge of the received signal power of K users. But it requires the training sequence that causes the detection process slower. Initially some known sequences are sent and hence channel is estimated subsequently.

Physically, the MMSE detector balances the desire to completely eliminate the MAI with the desire of avoiding the background noise enhancement problem. Since it takes into account the effects of the background noise, the MMSE detector usually provides a better performance than the Decorrelating detector, which is likely to be the zero-forcing algorithm. It simply applies the inverse of channel effects to recover the desired signal but at the same time accumulative noise is also enhanced. The proposed scheme is equally beneficial for the Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA).

1.2 Contribution

The novel contributions of this dissertation are given below:

Instead of using spreading sequences in the time domain or frequency domain individually we have used the combined spreading in both time as well as the frequency domain. Moreover the sequences we have investigated for time domain spreading are the Gold sequences, while Walsh codes for frequency domain spreading has been investigated. Since the carriers are few compared to the number of users, therefore, Walsh codes are easily available. The Gold sequences are more practical from users' separation point of view.

We have investigated the scheme for synchronous DS-CDMA system communication over AWGN channel for downlink scenario.

At the receiver end we separately despread time and frequency sequences by using Walsh codes for K=64 and 128 users. The Genetic Algorithm as MUD scheme have been adopted and compared with Decorrelating detector.

Simulation results show that the proposed scheme can support large number of user with low bit error rate.

1.3 Organization

The outline of the dissertation is as follows:

Chapter 2 In this chapter the cellular concepts regarding to American Mobile Phone Systems (AMPS) and Global System for Mobile (GSM) systems have been discussed.

Chapter 3 The structure of Multiuser Detectors and their history has been given in this chapter. Pros and cons of each scheme are given as well.

Chapter 4 In this chapter a TF-assisted MUD is invoked for Synchronous MC-CDMA system (base station). Simulation results are presented for K=55 and 117 number of simultaneous users, using Walsh Codes M orthogonal carriers. The complexity reduction factor is simulated versus increasing number of users.

Chapter 5 In this chapter, the conclusions and future extendable dimension regarding this scheme are mentioned which is followed by the list of references.

CHAPTER 2

Cellular concepts

2.1 Wireless mobile communications

The wireless communication is being used in number of communication systems in these days. Satellite networks, fixed wireless local loops, digital radio/television broadcasting & mobile telephony are few examples of wireless communication systems. Wireless mobile communications is very significant because of the fact that it has basic and revolutionized the communications.

The instant connectivity, anytime and anywhere is the main reason of success of mobile communications. Providing high-speed data services to the mobile user is big advantage of wireless system. The speeds and quality of mobile environment should be equals to the fixed networks if the convergence of the mobile wireless and fixed communication networks is to happen in the real sense. So, the challenges for the mobile networks are to deliver the high speed and reliable data services along with high quality voice signal.

High quality mobile technologies are existing in different parts of the world and they are evolving to fulfill the requirements. Here we are particularly interested in the cellular mobile environment therefore our attention will be focused to this area. In next section the brief introduction of the cellular concepts is given however the general idea behind this type of wireless communications.

2.1.1 Cellular communications

In early mobile radio systems less number of users could be allocated in a large area due to the small number of available radio frequencies, so we place an antenna with a high-power transmitter on the point of the coverage area for instance, on the top of a hill or a high building for attaining a large coverage. So frequency reuse causes the interference in the system.

Thus it required higher capacity with limited radio channels in the cellular system. The cellular mobile system uses number of low-power wireless transmitters to create cells, which called geographic service area of a wireless system. Figure 2.1 shows the structure of a cellular communication system. Each cell (usually depicted as hexagon) has a base station (BS) transmitting over a small area. The cell size is determined according to the density and demand of mobile station (MS) within a certain region.

Base stations are connected to the mobile switching centre (MSC) which provides connectivity between the public switched telephone network (PSTN) and the base stations. A communication network is formed with PTSNs which connects the telephone switching centers with MSCs all over the world.

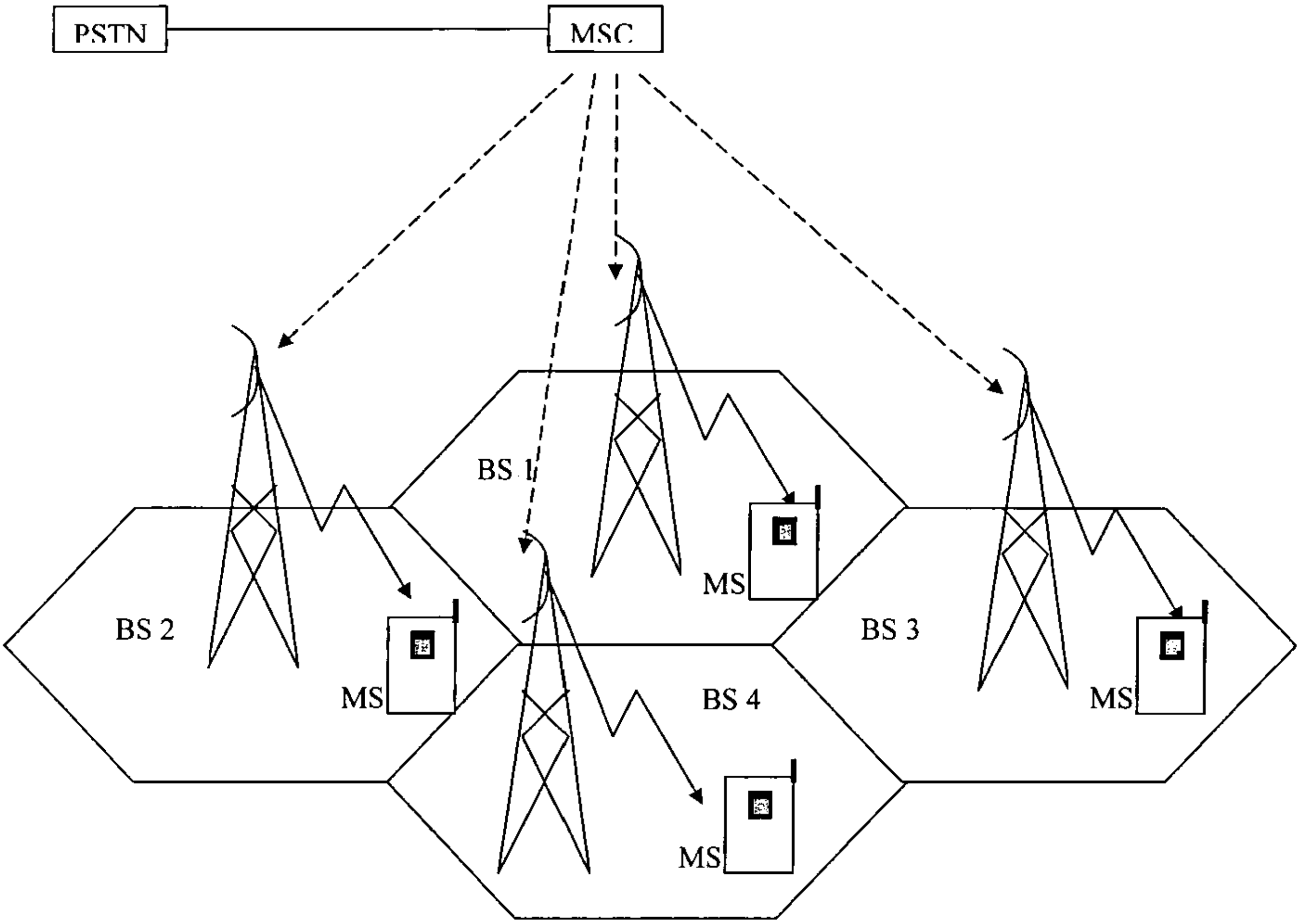

Figure 2.1 Structure of a cellular communication system

An obstacle arises in the cellular network, when a mobile user travels from one cell to another during a call. For keeping mutual interferences between users remains low. The adjacent cells do not use same radio frequency channel. Then if a user moves from a cell then the call has to be transferred to another stronger frequency channel. This thing is called hand-off or hand-over. The hand-off is changing a call from one cell to another without being notice by the users.

Frequency planning or frequency reuse is one more concept in cellular systems. Due to limited radio frequency channels available in mobile systems, the rule of frequency channels reuse is implemented into the cellular concept. The reuse process means that the radio frequency channels can be used in one cell can also be reused in another cell at some distance. Usually clusters of cells are reused in a regular pattern in the entire coverage area. So frequency reuse factor in a system is determined by the available frequency channels, *i.e* if there 7 cells per cluster in the system then its frequency reuse factor is 1/7.

2.1.2 Mobile cellular environment

Cellular system provides with a full duplex communication between the mobile user and base stations for a normal conversation talk. For this type of radio transmission both mobile users and the base station need circuitries to transmit on one frequency while receiving on another. The communication link from the base station to the mobile phone is called as downlink (or forward link) and the inverse process is called uplink (or reverse link).

All the users' signals are transmitted by the same single source, base station, in the downlink; therefore the received signals at each mobile terminal are synchronous. But in the uplink the signals received in the base station are asynchronous.

In a mobile cellular system interference is a big limiting factor in increasing capacity. The major interference sources are mentioned below

- Other base station transmitting in the same frequency band.
- Another mobile user in the same cell.
- A call in progress in a neighboring cell.

- Impairments caused by the propagation of radio waves.

There are different types of system interference are yielded in the network. Among those interferences the most important are the following:

Co-channel interference (CCI). It is caused by the interference between co-channel cells due to the frequency reuse. To reduce CCI, the minimum distance to provide sufficient isolation because of propagation distance must separate co-channel cells.

Adjacent channel interference (ACI). This type of interference accurse when two frequency channels are adjacent in the frequency spectrum and one of them is leaking into pass-band causing interfering into the adjacent channel. It is due to imperfect receiver filters. The problem can minimized with a careful filtering and channel assignments.

Inter-symbol interference (ISI). objects in the transmission path can create multiple echoes of the transmitted signal if the signal travels through a channel. The echoes occur on the receiver and overlap in successive time slots. This process is called inter-symbol interference. Equalizers can be used to compensate the effect of ISI created by multipath within time dispersive channels, at the receiver end.

Fading. Signal fading accurse if a signal passes through a time-varying multipath channel. So due to this channel the propagation delays & the random impulse responses of the channel will invoke some attenuation and time spread of the signal transmitted.

Thermal noise. Thermal noise always corrupts a transmitted signal through a communication channel. Generally it is assumed to be an additive white Gaussian noise (AWGN).

Therefore, advanced signal processing techniques in the receivers are required to overcome these types of interferences. Lot of mobile systems exist today each having influence in specific parts of the world. GSM, TDMA (IS 136), and CDMA (IS 95) are the main technology in the 2G mobile market.

Up till now GSM has been the most successful standard due to its coverage. All systems have distinct features and capabilities. Both GSM and TDMA networks use time division multiplexing on the air interfaces but their channel sizes, structures and core networks are different. CDMA has different air interface.

CHAPTER 3

Multiuser detection schemes

An intelligent way of overcoming the limitations of the traditional DS-CDMA detector and efficient utilization of the available frequency spectrum is known as Multiuser detection (MUD). Major benefit of using MUD in a cellular system is significant increase in capacity, but the receiver complexity is a main limitation of MUD. However the basic concern is the constraints in cost, weight and size of the receiver. Therefore to ensure practical implementation, it needs to provide mobile multiuser receivers that have reasonable computational complexity with acceptable performance.

An overview of MUD is presented in Figure 3.1. MUD can be divided mainly into following three categories:

1. Interference cancellation (IC).
2. Joint detection (JD).
3. Structures with combined schemes.

The interference cancellation schemes are characterized by the regeneration and subtraction of interference based on the data estimates. The 2^{nd} category is a bank of conventional detectors followed by filters that performs non-linear or linear transformations. Joint detection structures are generally computationally more expensive due to complex matrix calculations and inversions as compared to the conventional detector. Finally, a third category of MUD is considered as the group of multiuser detectors that combine detection techniques from the two groups of MUD as mentioned above

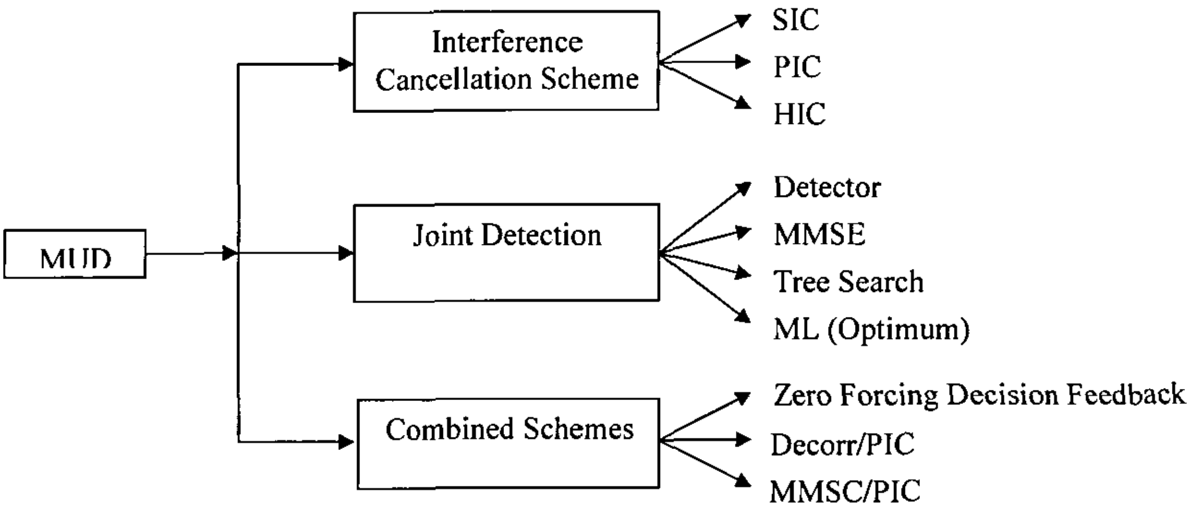

Figure 3.1: Classification of multiuser detection structures.

To simplify the discussion on the multiuser detector structures, we will assume a conventional synchronous DS-CDMA system model over an AWGN channel (without multipath). The received signal can be expressed in a matrix notation as follow

$$\mathrm{r}(t) = \mathrm{CAb}(t) + \mathrm{n}(t) \tag{3.1}$$

A is the user's amplitude matrix of dimensions $U*U$ and denoted by

$$\mathrm{A} = \begin{bmatrix} \sqrt{P_1} & 0 & \cdots & 0 \\ 0 & \sqrt{P_2} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \sqrt{P_U} \end{bmatrix} .$$

Where the $N*U$ matrix of codes C is given as

$$C = \begin{bmatrix} c_{1,1} & c_{2,1} & \cdots & c_{U,1} \\ c_{1,2} & c_{2,2} & \cdots & c_{U,1} \\ \vdots & \vdots & \vdots & \vdots \\ c_{1,N} & c_{2,N} & \cdots & c_{U,N} \end{bmatrix}$$

The users' data and noise components are mentioned respectively in vector form are

$$\mathrm{b}(t) = [b_1(t) \quad b_2(t) \quad \cdots \quad b_U(t)]^T \ \& \ \mathrm{n}(t) = [n_1(t) \quad n_2(t) \quad \cdots \quad n_N(t)]^T.$$

The noise vector elements of are considered independent and identically distributed (i.i.d) Gaussian noise samples with zero mean and two-sided power spectral density equals to $\sigma^2 = N_o/2$. In this section we will present some of the multiuser detector.

3.1 Interference cancellation schemes

Second way of performing MUD is using an interference cancellation. This Type of detectors can be classified mainly into three categories: parallel interference cancellation (PIC), successive interference cancellation (SIC) and hybrid interference cancellation (HIC).

The principle of these schemes is to estimate MAI generated by each user at the receiver the in order to subtract it.

SIC detector.

The SIC detector [15, 16] takes the serial approach for canceling interference. Initially SIC detector consists of sorting the users' signals out in the descending order according to theirs powers, which are estimated by the output of the conventional detector. The first stage of SIC is to regenerate the transmitted signal of the strongest user. Then this regenerated signal provides an estimate of the MAI caused by the strongest user, $b_1(t)$, then it is subtracted from the total received signal $r(t)$ yielding a partially cleaned version of the received signal $r_1(t)$.If the estimate of user is accurate, then the remaining users see less MAI in the next stages. So, this new version of the received signal can used to detect the next strongest user in the system. This process is continued til all users are detected.

PIC detector.

With known powers and codes of all interfering users, the PIC detector [16, 29] makes an estimate of MAI for each user and subtracts them in a parallel scheme. The first bit estimates, $\hat{b}_u(t)$ for $u \in \{1,2,\cdots,U\}$ are provided by the output of a bank of conventional detectors. These estimates are then again spreaded and added to regenerate the MAI estimates for each of the user.

Hybrid detector.

When the group of subtractive interference cancellation schemes combine certain positive features of the SIC and PIC detector into a hybrid scheme. Advantage of these schemes is that at the expense of some performance degradation, they offer hardware reduction & delay over the conventional SIC and PIC. Some examples of this type of structures are the schemes proposed in [15, 16, 19–20, 30].

3.2 Joint detection

In this section the most important JD techniques proposed in the literature is to be discussed. The most widely recognized joint multiuser receiver s is the optimal multiuser detector or the maximum likelihood (ML) detector introduced by Verd'u in 1986 [10]. However, but its computational complexity which grows exponentially with the number of users, $O(2^U)$. There is a big difference in performance and complexity between the conventional detector and the ML detector, over the last 15 years. Therefore most of the search has been in finding sub-optimal multiuser detectors that show good performance and complexity. Instead of the high complexity of the ML, its performance serves as a benchmark for the comparison with other sub-optimal multiuser detector structures. The sub-optimal structures are divided into two classes, namely linear and non-linear detection methods. A brief description of these detectors is given in the sections given below.

3.2.1 Optimum multiuser detector

The optimum multiuser detectors are divided into two categories, jointly optimum and individually optimum multiuser detector. In jointly optimum multiuser detector receiver selects the most likely transmitted vector of symbols $\mathrm{b}(t)$ given that $\mathrm{r}(t)$ was received. In other words, the minimum probability of sequence error decision is obtained by selecting the vector $\mathrm{b}(t)$ that maximises the joint *a* posteriori probability (APP) $p(b(t) \mid r(t))$.The objective of the individually optimum multiuser detector is to find the most likely transmitted symbol $b_u(t); u \in \{1,2,....U\}$, i.e to maximize the APP $p(b_u(t) \mid r(t))$. The two decision criteria either for jointly or individually detection is the MAP and the ML criteria. So the individually optimum multiuser detector achieves the minimum probability of error for each user. Now we are focusing our attention to the analysis on only this type detector structure. Mathematically, the MAP decision criterion is given as

$$\begin{aligned}\hat{b}_u(t) &= \arg_{b\in\{-1,1\}}^{\max} p(b_u(t)=b \mid r(t)) \\ &= \arg_{b\in\{-1,1\}}^{\max} \sum_{\Omega_b} p(b(t) \mid r(t))\end{aligned} \tag{3.2}$$

Where Ω_b is the set of vectors $b(t)$ with $b_u(t)=b$.

By Using Bayes' theorem the APP in (3.2) can be expressed as

$$\hat{b}_u(t) = \arg_{b\in\{-1,1\}}^{\max} \sum_{\Omega_b} \frac{p(r(t) \mid b(t))pr(b(t))}{pr(r(t))} \tag{3.3}$$

Where $p(r(t) \mid b(t))$ is the conditional probability of the observed signal, $r(t)$, given $b_u(t)$ and $pr(b(t))$ is the *a priori* probability of $b(t)$ being transmitted. So $pr(r(t))$ is not dependent on $b_u(t)$, it can be neglected from equation (3.3) resulting

$$\hat{b}_u(t) = \arg_{b\in\{-1,1\}}^{\max} \sum_{\Omega_b} p(r(t) \mid b(t))pr(b(t)). \tag{3.4}$$

The probability function $p(r(t) \mid b(t))$ can be computed as

$$p(r(t) \mid b(t)) = \frac{1}{(2\pi\sigma^2)^{N/2}} \exp\left(-\frac{\|r(t)-x(t)\|^2}{2\sigma^2}\right) \tag{3.5}$$

Where

$$\|r(t)-x(t)\|^2 = \sum_{n=1}^{N} (r_{t,n} - x_{t,n})^2 \tag{3.6}$$

Where at time t the received vector is $r(t) = [r_{t,1}, r_{t,2}, \cdots, r_{t,N}]^T$ and $x(t) = [x_{t,1}, x_{t,2}, \cdots, x_{t,N}]^T$ is the channel input when $b(t)$ is transmitted.

Therefore in the case of the ML criterion, the *a priori* probability of $\mathrm{b}(t)$ *i.e* $pr(b_u(t))$ for all $u \in \{1,2,\cdots,U\}$ is not taken into account as it is assumed that all symbols occur with equal probability. Therefore, (3.4) is simplified to

$$\hat{b}_u(t) = \arg\max_{b\in\{-1,1\}} \sum_{\Omega_b} p(r(t) \mid b(t)) \tag{3.7}$$

Where Ω_b is defined as before. It is clear, however, that if the *a priori* probabilities are equal, so the results of both the MAP and the ML criteria will be the same. In other words, the optimum multiuser detector searches through all possible combinations in $\mathrm{b}(t)$ and selects only the closest to the received signal $\mathrm{r}(t)$ based on the Euclidean distance.

Euclidean distance can be calculated either at the chip level (3.6) or at the bit level. The decision rule of the ML multiuser detector with equal *a priori* information and using (3.6) can be then written as

$$\hat{b}_u(t) = \begin{cases} 1 & \mathit{if} \sum_{\Omega_1} \exp\left(-\dfrac{\|r(t-x(t))\|^2}{2\sigma^2}\right) > \sum_{\Omega_{-1}} \exp\left(-\dfrac{\|r(t-x(t))\|^2}{2\sigma^2}\right) \\ -1 & \mathit{otherwise} \end{cases} \tag{3.8}$$

For a synchronous DS-CDMA system in AWGN channel, the resulting complexity of the ML multiuser detector is $O(2^U)$.

RBF detector. In [11] it was shown that if all of the system parameters are known (number of users and their spreading codes) then individually optimum multiuser detector for a synchronous DS-CDMA system can be implemented with a radial basis function (RBF) network. The RBF detectors output is a linear combination of 2^U with U as the number of users. Mathematically, the RBF detector output can be expressed as

$$f(r(t))=\sum_{l=1}^{2^U} w_l \phi_l(\|r(t)-a_l(t)\|)$$

Where $\phi_l; l \in \{1,2,\cdots,2^U\}$ is a scalar and radially symmetric non-linear function (normally a Gaussian kernel function [12]) with $a_l(t)$ and w_l as the lth centre and lth weight that optimize some performance criterion. The norm of a vector $\|\cdot\|$ is the Euclidean distance between the vectors $r(t)$ and $a_l(t)$. For all possible combinations of the data vector $b(t)$ the noise free received vectors represented as the vector of centers $\{a_l(t)\}; l \in \{1,2,\cdots,2^U\}$. For the RBF detector the decision rule is then given as

$$\hat{b}_u(t)=\operatorname{sgn}\left[\sum_{l=1}^{2^U} w_l \exp\left(-\frac{\|r(t)-a_l(t)\|^2}{2\sigma^2}\right)\right] \tag{3.9}$$

As w_l is substituted by the value of $b_u(t)$ (+1 or -1) associated with the lth centre $a_l(t)$.

This detector can also be applied when the received signal are preprocessed by the conventional detector, *i.e* detection at the bit rate. The noise components are neither correlated with the signal nor other noise components without pre-processing the received signal. Therefore Euclidean distance is the optimum measure for the chip rate RBF detector. However, due to pre-processing the noise components becomes correlated [7, 12] and Euclidean distance measure non-optimum. So, the bit rate RBF detector will reflect the correlated nature of the noise components by using the Mahalanobis distance [13] rather than using Euclidean distance.

$$\hat{b}_u(t)=\operatorname{sgn}\left[\sum_{l=1}^{2^U} w_l \exp\left(-\frac{(r(t)-a_l(t))^T \mathrm{V}^{-1}(r(t)-a_l(t))}{2}\right)\right] \tag{3.10}$$

Where

$$V = E[(r(t) - a_l(t))(r(t) - a_l(t))^T]$$

Similarly the ML detector, the complexity of the RBF detector is $O(2^U)$ for an AWGN channel.

3.2.2 Linear multiuser detectors

A number of reduced complexity detectors based on linear techniques have been proposed due to the complexity of the optimum detector. By applying a linear transformation to the output vector of the conventional DS-CDMA detector, this group of detectors mitigates interferences. In this section we study the two most common linear detectors, the minimum mean squared error (MMSE) detectors and decorrelator. First, the decorrelator detector [14–16] is a transformation which applies the inverse of the correlation matrix leaving the received signal without interference. The drawback of this detector is noise enhancement. The other detector is the MMSE detector [28, 17] which takes into account the background noise and utilizes the knowledge of the received signal powers.

The output vector of the conventional detector (bank of U matched filters), equation (3.1) is multiplied by C^T

$$Y(t) = \mathrm{RAb}(t) + z(t) \qquad (3.11)$$

Where Z(t) is the vector with the correlated noise created by the bank of matched filters and R is the correlation matrix.

Decorrelator detector. By considering that the correlation matrix R is positive definite (*i.e* invertible) and inspection of (3.11), it is clear that by multiplying both sides of (3.11) with the inverse of R the users signals in the system can be decoupled. Thus, the soft decision estimate of the decorrelator detector is

$$\begin{aligned} R^{-1}y(t) &= Ab(t) + R^{-1}z(t) \\ \hat{b}(t) &= Ab(t) + z^{dec}(t) \end{aligned} \tag{3.12}$$

Now $z^{dec}(t)$ is a noise vector with zero mean and covariance matrix $V^{dec} = \sigma^2 R^{-1}$, and $\hat{b}(t) = [\hat{b}_1(t), \hat{b}_2(t), \cdots \hat{b}_U(t),]^T$ .From (3.12), we can see that the user u(uth component of$\hat{b}(t)$) does not contain interference from other users, therefore, the MAI is completely canceled by the decorrelator detector. Performance gain is provided by this detector over the conventional detector. One more significant feature is that it does not need to estimate the amplitudes of received users. Moreover the level power of the users are independent from each other. The decorrelator detector performs the optimum near-far resistance performance metric. Furthermore the complexity is linear with the number of users $O(U)$.

More over there are two significant disadvantages of this detector. Firstly, it causes noise enhancement which can be observed from the term $R^{-1}z(t)$ in (3.12). It has been shown in [18] that at the output of the conventional detector, the noise power associated with the noise term $R^{-1}z(t)$is always greater or equal to the noise term. So, it can occur that if the MAI is weak, the conventional detector will outperform the decorrelator. It is simply due to the MAI terms is smaller than the noise enhanced term in (3.12). The second and drawback is the need to invert the matrix R. For synchronous systems the problem is somewhat simplified to invert a $U{*}U$ matrix, where detection can be performed at a bit basis. However, the dimensions of this matrix increase with the message length for asynchronous systems. The computation required is substantially increased. This situation cans worst in multipath channels where the paths are treated as an indusial users. Many suboptimal approaches to implementing the decorrelator detector have already been presented in literature [19–20].

Minimum mean squared error (MMSE) detector. Just like the decorrelator detector, the MMSE detector applies a linear transformation to the output of the conventional detector (3.11). However, as distinct from the decorrelator, the MMSE detector takes into account utilizes knowledge of the received signal power and background noise. The MMSE detector makes a balance between the residual interference and the noise enhancement. This transformation is selected to minimize the mean-square error between its output and the data, *i.e*

$$\min_{T \in R^{U \times U}} E[\|b(t) - Ty(t)\|^2]$$

Where T is the $U*U$ transformation matrix. Thus, the soft decision estimate vector of the MMSE detector is given as [21]

$$\hat{b}(t) = (R + \sigma^2 A^{-2})^{-1} y(t) \tag{3.13}$$

The MMSE detector minimises the squared error in presence of noise, and becomes the decorrelator detector without noise. Its performance is very similar to the decorrelator, when the SNR is relatively high $(\sigma^2 \to 0)$ but MMSE is better at low SNR's. Alternatively, if the MAI is small as compared with the noise, the MMSE detector approaches the conventional detector. For combating ISI for a single-user channel, the analogy to the MMSE detector is the MMSE linear equalizer [7].

Important drawbacks of this detector are that it requires an estimate of the received amplitudes and that its performance depends on the power of the interfering users. In terms of complexity, the MMSE detector faces, like the decorrelator detector, the problem of implementing matrix inversion. So most of the sub-optimal approaches are implementing by decorrelator detector are applicable to the MMSE detector.

Moreover, the DS-CDMA receiver structure can be confined to being a finite impulse response (FIR) filter. Therefore, MMSE detector can also be implemented with a single-user FIR filter without the need of pre-processing the received signal with the conventional detector. By supposing the received signal as given in (3.1), the Wiener filter theory [22, 23] states that the optimal weights for a FIR w_u is given by

$$w_u = \phi_{rr}^{-1}\phi_{rb}^{u} \tag{3.14}$$

Where the $N*N$ matrix ϕ_{rr} is the autocorrelation matrix of the input signal $r(t)$ suppose that the data is independent from different users, *i.e* $E[b_k(t)b_u(t)] = 0$ with $k \neq u$ and $k,u \in \{1,2,\cdots,U\}$ then it can be shown [24] that

$$\begin{aligned} \phi_{rr} &= E[r(t)r^T(t)] \\ &= CPC^T + \sigma^2 I \end{aligned} \tag{3.15}$$

Where $P = A^2$ is a $U*U$ diagonal matrix with A as defined in (3.1) and C is the $N*U$ matrix with the codes, and I is the identity matrix with dimensions $N*N$. The $N*1$ vector ϕ_{rb} represents the desired response, *i.e* $\phi_{rb}^{u} = P_u c_u(t)$ for the *u*th user. The soft estimate of the

For *u*th user wiener detector output is then given as

$$\begin{aligned} \hat{b}_u(t) &= w_u^T r(t) \\ &= p_u c_u(t)^T (CPC^T + \sigma^2 I)^{-1} r(t) \end{aligned} \tag{3.16}$$

3.2.3 Non-linear multiuser receivers

These detection techniques are generally overcome the problem of complexity, however, it generates poor performance in the receiver at the presence of high levels of

MAI and/or ISI. This degradation is due to that, in such scenarios the desired signals are no longer linearly separable [25]. Therefore, non-linear detection have to be considered. Recently, tree search technique, have been studied extensively. In general, tree search based sub-optimal detectors provide with the next best performance to the optimum detector but with a significant reduction in complexity. A number of such detectors have been proposed for improving performance. These include the following detector structures mentioned below:

Pre-selection maximum likelihood (PSML) multiuser detector. It is reduced complexity ML detector it uses two distinct stages in approximating the ML solution [26]. Figure 3.3 shows the structure of PSML detector.

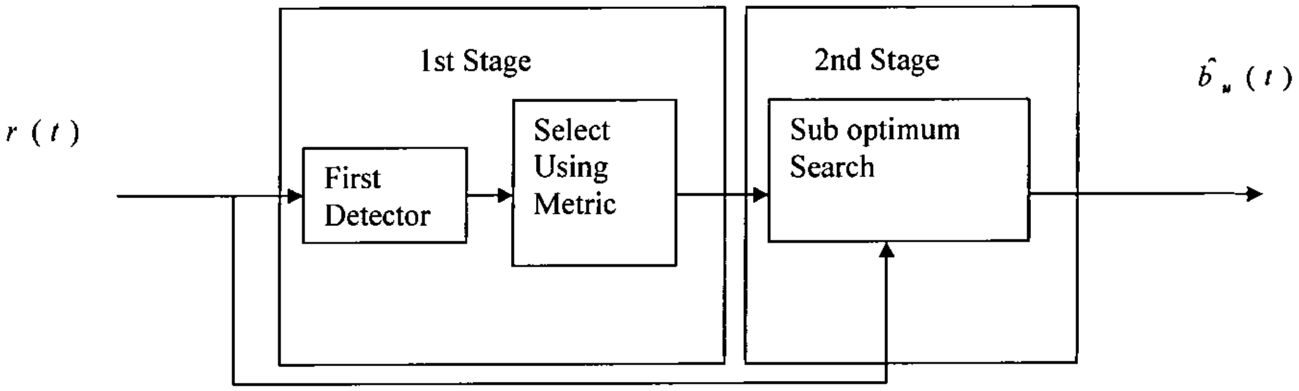

Figure 3.2: PSML multiuser detector structure.

The PSML detector uses an initial stage to assess the received signal in order to confine the search to a smaller number of possible combinations. The basic functioning of the first stage is to make the soft estimates of the interfering users which are used to provide with a measure of how likely they can be correctly detected. The initial detector provides with the soft estimates of the users' symbols & implemented by a linear detection technique, *i.e* MMSE, conventional detector or decorrelator detectors. On the bases on these estimates, a metric of how likely each symbol can be detected correctly is obtained by using the magnitude of the likelihood ratio |*LLR*|. After first stage, a hard decision is made on those users' symbols with the highest metrics. On the other way around, the symbols with lower |*LLR*| values are kept as soft estimates for the second stage of the detector. Second stage of the detector is the optimum multiuser detector with reduced complexity as the number of possible combinations has been reduced by the hard decision made by the first stage. It was shown in [26] that the PSML detector approximated the ML with less complexity at the expense of small degradation performance.

M and T-Algorithm detectors. The M or T algorithms [27] are breadth-first trellis search algorithms. It differ only in the criterion used to discard paths. M-algorithm instead maintains the M paths of minimum metrics & then a search through all M remaining paths is applied to get the soft outputs of the M-algorithm detector. In T-algorithm, the criterion to discard paths is different. It initially finds the overall best path of minimum metric and then rejects all paths whose metrics exceed this minimum metric by more than a threshold T. So the number of paths kept by the T-algorithm is variable.

Greedy detector. The most recent multiuser detector is the greedy detector (GD) which was proposed in [28]. This algorithm utilises the coefficients of the user's symbols as weights in the maximum likelihood metric to indicate the order in which symbols can be estimated.

On the bases of these coefficients, this detector forms a modified trellis tree with complexity is lower than that needed for the optimum multiuser detector. Performance gain is achieved by the GD with a complexity only of the order of $U^2 \log U$ as compared to the 2^U of the optimum multiuser detector.

3.3 Combined schemes

In Last group of multiuser detectors are those schemes that combine a linear transformation with subtractive cancellation schemes. Zeroforcing decision-feedback (ZF-DF) detector, decorrelator/PIC, MMSE/PIC, etc, [15, 16, 20, 29–31] are the examples of this detection schemes.

In ISI channels [7], ZF-DF detector is an analogous to the decision-feedback equalisers. It is a linear transformation is performed at an initial stage followed by a form of SIC detection. SIC operates by making decision and subtracting the interference in a descending order of the signal strength. This thing is clarify that, the success of any cancellation scheme relies on the initial data estimates.

CHAPTER 4

The Genetic Algorithm

4.1 Introduction

Main idea in this Theory of Charles R. Darwin is the survival of the fittest, it is also known as natural selection. According to the theory, in a population of living things, better chance to stay alive which is fitter generally. So, they, and their offspring who inherit their genetic content partially or completely from their parents, have a more probability to go into next generations, and thus have a more chance to transfer their genetic material to individuals which will appear in successor generations. Genetic Algorithms, which is also known as Evolutionary Algorithms, is a well known and widely accepted local search algorithm, which tries to simulate this theory.

4.2 Concepts of Genetic Algorithm

Genetic algorithm provides number of potential solutions in parallel. GA initially creates a *population*. The population is a set of *individuals*, from which each has its own genetic content: *chromosome*. In GA, this genetic content, which is represented as a string over a finite alphabet, belongs to a potential solution instance to the problem, and it is accordingly coded to a problem-specific coding scheme. In the initial population creation process, the genetic contents of individuals "chromosomes" are generally produced in a random fashion in order to assure diversity in the initial population. After that, in process of *evolution*, individuals and their offspring are transferred to new generations & then taking into consideration the quality of their chromosomes, which is called *fitness*. Fitness is the function which takes an individual as an argument, evaluates its eligibility as a solution to that problem by examining its genetic content (chromosome), and assigns a fitness value to the individual as a result. The stronger fitness value gives to an individual a better chance to be selected for survival or reproduction.

The individual that exists in the current generation may be selected directly, or it may be matched with another individual and the resulting offspring may be transferred to the next generation. The parameter that determines what percentage of the new generation will be composed of the individuals directly transferred from the previous generation and what percentage will be composed of newly produced offspring is *Reproduction probability*.

At some point GA should stop the simulation of the evolution process. GA may be terminated after exceeding a predetermined time threshold, after producing a predetermined number of generations or reaching a desired fitness threshold. GA is generally terminated when it *converges*. Convergence occurs when most of the individuals in a population have very similar genetic properties. In some situations, this may happen very rapidly so that it becomes impossible to reach to the desired solution. This problem, which is called *premature convergence*, is just like to the problem of stuck on a local maximum that is encountered in local search methods. In order to overcome the problem of premature convergence, *mutation* can be employed

While the transfer of genetic contents from parents to offspring, something may go wrong, and random changes may occur in chromosome. Such changes may also occur when an individual is exposed to extreme conditions such as radiation. As a result, the fitness value of the individual can be degrading. However, this helps to keep diversity in population and such changes provide very good results in the next generations.

By introducing a *mutation probability* parameter, in GA the concept of mutation is employed. Before inserting an individual to the next generation, random changes on its chromosome is performed according to this probability.

CHAPTER 5

TF-domain assisted MUD for MC DS-CDMA

5.1 Introduction

Multi-carrier Code Division Multiple Access (MC-CDMA) is a digital transmission technique, which combines orthogonal Frequency Division Multiplexing (OFDM) and Direct Sequence CDMA (DS-CDMA). In MC-CDMA systems, instead of using spreading sequences in the time domain or frequency domain for spreading each bit, we use spreading sequences both in Time and the frequency domain. Hence we are capable of achieving frequency diversity gain at the cost of a reduced spreading gain.

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Each bit of each user is initially spread using a code in time domain. Then each chip of that spread sequence is further spread over all the carriers using a frequency domain spreading code.

System considered here consists of K number of simultaneous users communicating over AWGN channel with known channel parameters. Each bit of each user is spread using spreading sequence in time domain (T-Domain signature) of length N (Gold sequences) Then we spread signal into M parallel branches, where each branch of is multiplied by frequency domain (F-Domain signature) spreading sequence of length M. We have assumed that length of frequency domain spreading code (Walsh codes) is equal to the number of sub-carriers. Then independently modulated over orthogonal frequencies in order to get frequency diversity gain by mean of maximum ratio combining.

5.2 System Model

Following are the component of the system assumed.

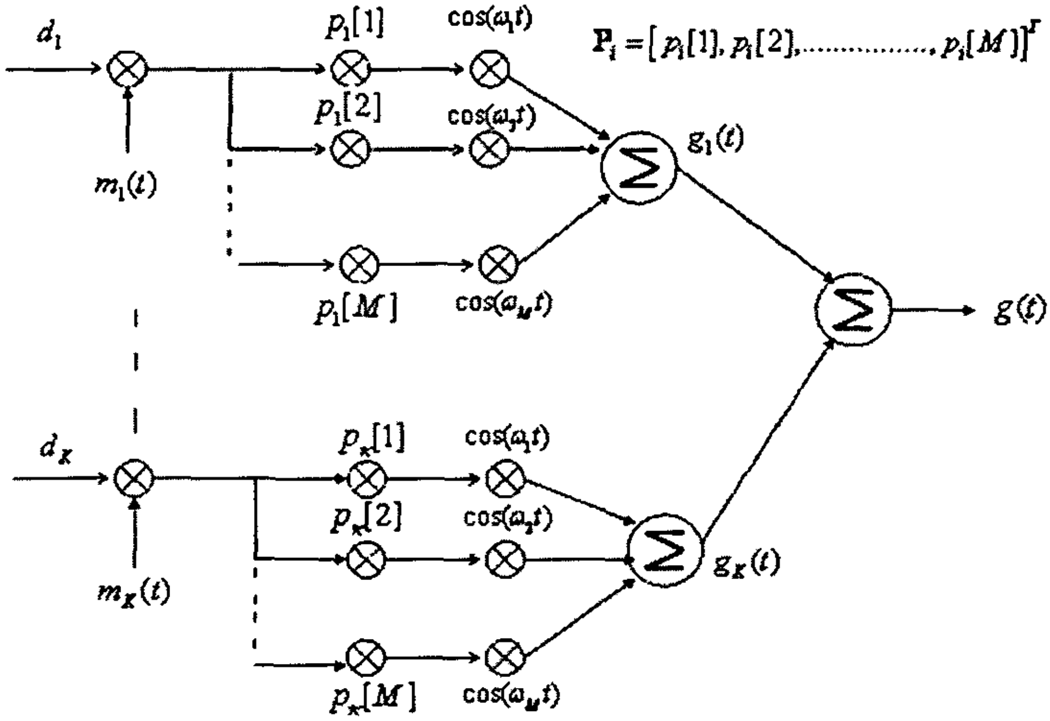

Figure 5.1 Transmitter model of MC DS-CDMA using both Time & Frequency domain spreading

5.2.1 Transmitter

We consider a bit-synchronous MC DS-CDMA system illustrated in Figure 5.1. It can be seen from the figure given above that the binary data stream $d_k(t)$ of *k*th user is spreaded in time using spreading sequence $m_k(t)$. Each chip of this spreaded signal is then divided into *M* parallel branches, where each branch of signal is multiplied by corresponding chips of Frequency domain spreading sequence

$\mathrm{P}_k = [p_k[1], p_k[2], \ldots\ldots\ldots\ldots, p_k[M]]^T$ of length M. Following the F-domain spreading, each of the M branch signals modulates a subcarrier frequency using binary phase shift keying (BPSK). Then the M numbers of subcarrier-modulated substreams are accumulated in order to make the transmitted signal. Hence, the composite transmitted signal of *k*th user can be expressed as:

$$g_k(t) = \sqrt{\frac{2P}{M}} \sum_{q=1}^{M} d_k(t) m_k(t) p_k[q] \cos(\omega_q t) \qquad (5.1)$$

$$g(t) = \sum_{k=1}^{K} g_k(t)$$

where P represents the identical transmitted power of each user and $\{\omega_q\}$, q = 1,2,...,M represents the subcarrier frequency. The binary data stream's waveform can be written as:

$$d_k(t) = \sum_{j=0}^{\infty} d_k \phi(t - jT_b) \qquad , \mathrm{k} = 1, 2 \ldots \mathrm{K} \qquad (5.2)$$

Where $d_k \in [-1,1]$ is the kth user's bit and $\phi(t)$ is the waveform consisted of rectangular pulses with a duration T_b.

The spreading sequence in time domain (T-Domain) of the kth user can be expressed as:

$$m_k(t) = \sum_{j=0}^{\infty} m_{k,j} \varphi(t - jT_c) \qquad (5.3)$$

Where i = 1, 2,....., K ,where $\varphi(t)$ represents is the rectangular T-domain chip waveform, which is defined over the interval $[0, T_c]$.We assume that the T-domain spreading factor is:

(5.4)

$$N = T_b / T_c$$

That tells the number of chips per bit or chip rate and Time domain spreading codes are used. Furthermore, we assume that the subcarrier signals are orthogonal and they do not interfere each other so no Inter-symbol Interference.

5.2.2 Channel

We assume that K synchronous TF-domain spread MC DS-CDMA signals according to the form of (5.1) are transmitted over the frequency selective channel, but each subcarrier of each user experiences statistically independent non-dispersive AWGN channel. We assume that the power received from each user is identical.

5.2.3 Receiver

In accordance with transmitter and channel described, the received signal can be expressed as:

$$r(t) = \sum_{k=1}^{K} \sqrt{\frac{2P}{M}} \sum_{j=1}^{M} d_k(t) m_k(t) p_k[j] \cos(\omega_j t) + n(t) \tag{5.5}$$

Where $n(t)$ represents the AWGN Gaussian noise process with zero mean and double-sided power spectral density of $N_o / 2$.

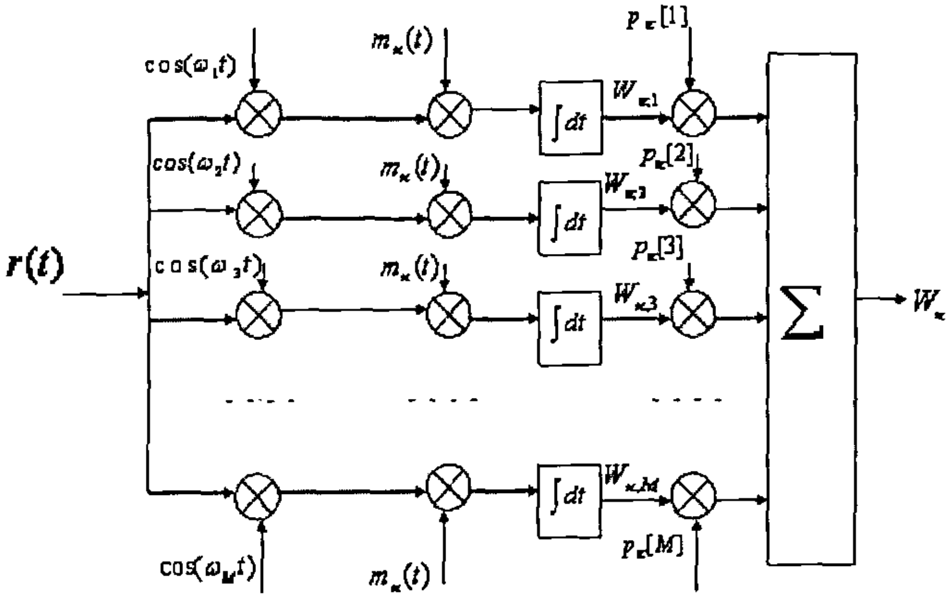

Figure 5.2 Correlator based receiver under supervision of TF-domain

We shall reverse all the processes we have made. The first step of the receiver's operation is the demodulation of all the subcarrier signals which carries out the inverse operations of the function seen in Figure 5.1. Let us consider the *k*th user be the user-of- interest, then the output variable related to the first data bit corresponding to *m*th subcarrier of the *k*th user can be expressed as;

$$W_{k,n} = \int_0^{T_b} r(t) m_k(t)\cos(\omega_n t)dt \qquad (5.6)$$

Where $k = 1,2,\dots\dots, K; n = 1,2,\dots\dots\dots, M$. Upon substituting (5.5) into (5.6) and considering the orthognality between different sub-carriers, it can be shown that the output variable $W_{k,n}$ of Fig. 5.2 can be expressed as;

$$W_{k,n} = \sqrt{\frac{P}{2M}}T_b\left\{d_k p_k[n] + \sum_{\substack{l=1\\ l\neq k}}^{K} d_l p_l[n]\rho_{kl} + N_{kn}\right\} \qquad (5.7)$$

Where $k = 1, 2, \ldots\ldots, K; n = 1, 2, \ldots\ldots\ldots, M$, where $N_{k,n}$ is Gaussian random variable having zero mean and variance of $MN_o / 2E_b$, where $E_b = PT_b$ represents the energy per bit, where

$$\rho_{ku} = \frac{1}{T_b} \int_0^{T_b} m_u(t) m_k(t) dt \qquad (5.8)$$

Above (5.8) represents the correlation factor between the T-domain spreading sequences $m_u(t)$ and $m_k(t)$ of users u and k. Following Figure 5.2 shows the receiver model,

The decision variable W_k of Figure 5.2, which corresponds to first, transmitted data bit of reference user k is obtained by dispreading of each M branch outputs $\{W_{k1,} W_{k2,\ldots\ldots\ldots,} W_{kM}\}$ using the *k*th user's F-domain spreading sequence P_k, which can be expressed as:

$$W_k = \sum_{m=1}^{M} p_k[m] W_{km}$$

$$W_k = \sqrt{\frac{PM}{2}} T_b \left\{ d_k + \sum_{\substack{l=1 \\ l \neq k}}^{K} d_l \rho_{kl} \beta_{kl} + N_k \right\} \qquad (5.9)$$

Where *k*=1, 2,….., K, where

$$N_k = \frac{1}{M} \sum_{m=1}^{M} p_k[m] N_{km}$$

Which is a Guassian random variable having zero mean and variance $N_o / 2E_b$.

Furthermore,

$$\beta_{uk} = \frac{1}{M} \sum_{m=1}^{M} p_u[m] p_k[m]$$

Which is the correlation factor between the F-domain spreading sequences P_u and P_k assigned to user to u and k.

5.2.4 Detection schemes applied on received signal

In the detection of TF-domain spread MC DS-CDMA signals we investigate jointly and separately TF-domain detection schemes. The decision of joint TF-domain detection is obtained after both TF-domain dispreading

5.2.4.1 TF-domain Decorrelating MUD

By observing Equation 5.9 and considering the detection of K users, it can be shown that after removing the common factor of $\sqrt{\frac{PM}{2}T_b}$ associated with all the different users, the decision variable of the K users can be written as;

$$\mathbf{W} = \mathbf{RAd} + \mathbf{n} \tag{5.10}$$

Where we have,

$$\mathbf{A} = diag[\sqrt{\frac{2\varepsilon_{d,1}}{M}},\dots,\sqrt{\frac{2\varepsilon_{d,K}}{M}}]$$

$$\mathbf{W} = [W_1, W_2, \dots\dots, W_K]^T \tag{5.11}$$

$$\mathbf{d} = \left[d_1, d_2, \dots\dots\dots, d_K\right]^T \tag{5.12}$$

$$\mathbf{n} = \left[N_1, N_2, \dots\dots\dots N_K\right] \tag{5.13}$$

and

$$\mathbf{R} = \begin{pmatrix} 1 & \rho_{12}\beta_{12}\cdots & \rho_{1K}\beta_{1K} \\ \rho_{21}\beta_{21} & 1\cdots & \rho_{1K}\beta_{1K} \\ \vdots & \vdots & \vdots \\ \rho_{21}\beta_{21} & \rho_{K2}\beta_{K2}\cdots & 1 \end{pmatrix} \tag{5.14}$$

Since I have utilized Walsh codes in time domain so; $\rho_{i,j} = \delta_{i,j}$. In context of the joint TF-domain Decorrelating MUD the final decision variables associated with d_k, k = 1, 2… K can be expressed as;

$$\mathbf{R}^{-1}\mathbf{W} = \mathbf{d} + \mathbf{R}^{-1}\mathbf{n} \tag{5.15}$$

And the corresponding data bit $\hat{d}_k = \operatorname{sgn}((\mathbf{R}^{-1}\mathbf{W})_k)$ for k = 1, 2… K, by hard decision.

5.2.4.2 Genetic Algorithm Assisted MUD

In GA we have to maximize the cost function. So instead of investigating all the sequences, we will restrict to few of them.

$$\begin{aligned} J(\mathbf{d}) &= 2\operatorname{Re}[\mathbf{d}^T\mathbf{A}] - \mathbf{d}^T\mathbf{A}\mathbf{R}\mathbf{A}\mathbf{d} \\ \hat{\mathbf{d}} &= \arg\left\{\max_{\mathbf{d}}[J(\mathbf{d})]\right\} \end{aligned} \tag{5.16}$$

The maximization of Equation 5.14 is a combinational optimization problem, which requires an exhaustive search for each of the 2^K combination of **d**, in order to find the one of that maximizes the metric of Equation 5.16. And in case of non binary symbols this computational complexity is even high. Hence the complexity will increase exponentially with increasing number of users.

Hence, I have utilized GA for finding a solution approximately near to that of optimum ML detector. Also since the orthogonal codes are not very practical so non-orthogonal codes are being utilized and effect of non-orthogonality is measured on the said scenario. Now to start GA we need some initial points and considerations. If we consider K users data as a single vector then that can be designated as the initial chromosome. As $\tilde{\mathbf{d}}_n(y) = [\tilde{d}_{n,1}(y), \ldots, \tilde{d}_{n,K}(y)]$, where *y*, *y* = 1,…,*Y* denotes the *y*th generation, and *n*, *n=1,2,…N* denotes the *n*th individual of the mating pool.

We received the signal from all subcarriers; sum them up using Maximum Ratio Combiner (MRC) and took it as initial chromosome. Then by mutating it in a special manner we get entire generation. The MRC-combined output vector $\hat{d}_{MRC}$ of the matched filter output can be expressed as: $\hat{\mathbf{d}}_{MRC} = [\hat{d}_{1,MRC},\ldots,\hat{d}_{K,MRC}]$ where we have:

$$\hat{\mathbf{d}}_{k,MRC} = \sum_{l=1}^{M} w_k^l \tag{5.17}$$

Having generated $\hat{\mathbf{d}}_{MRC}$, I adopted a 'mutated' version of the hard decision vector $\hat{\mathbf{b}}_{MRC}$ for creating each individual in the initial population, where each bits of the MRC-vector is toggled according to the mutation probability used, in this case we utilized 0.1; means one of the 10 bits will be toggled. Hence, the first individual of the population namely $\tilde{d}_l(0)$ can be written as:

$$\tilde{\mathbf{d}}_l(0) = MUTATION[\hat{\mathbf{d}}_{MRC}] \tag{5.18}$$

So one can easily note that MUTATION is an operator, which when applied to a string of (1,-1), will produce toggled versions of initial vector.

5.4 Simulation Results

Figure 5.3 and 5.4 compare the BER versus SNR per bit or E_b/N_o performance of TF-domain spread MC DS-CDMA using the parameters of N=31 (Gold sequences), M = 8 (Walsh codes). The results show that GA out performs than that of decorrelating detector. Explicitly, the BER curve of the decorrelating detector exhibits an error floor at high SNR per bit values.

In Fig 5.3 we compare the BER versus SNR performance of TF-domain spread MC DS-CDMA using the parameters of N=31, M=8 as time and frequency domain signature lengths respectively. Now GA plays its role for improving the BER performance. Only at the complexity of 400 we can achieve a considerable BER.

In Fig 5.4 number of users is doubled and so we have to pay in terms of more decoding complexity of GA. We went till 1600 (4 times as in 64 users case), to achieve a better performance. But even then the price is not much since the number of users supported is quite high. One can easily say that conventional Decorrelaing Detector gives poor performance when number of users is quite high.

In Fig 5.5 there is given a complexity reduction graph with increase in number of users. So GA is capable of achieving quite moderate level complexity even in huge number of users.

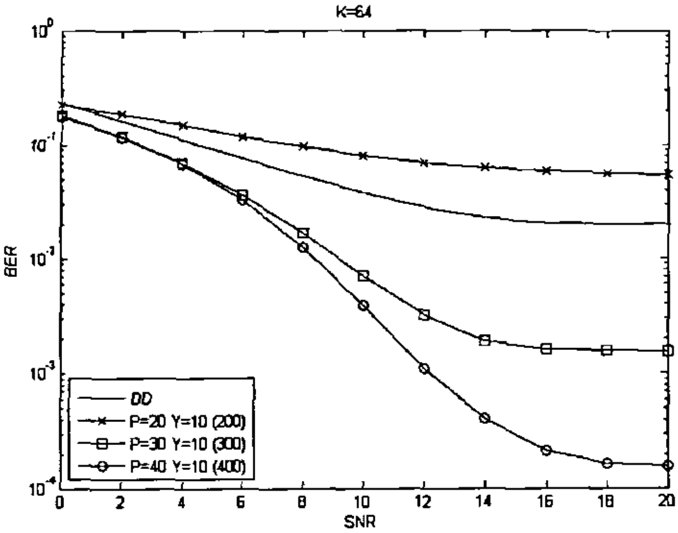

Figure 5.3 Comparison of BER performance of different MUD schemes with N=31, M=8 and K=64 users supported

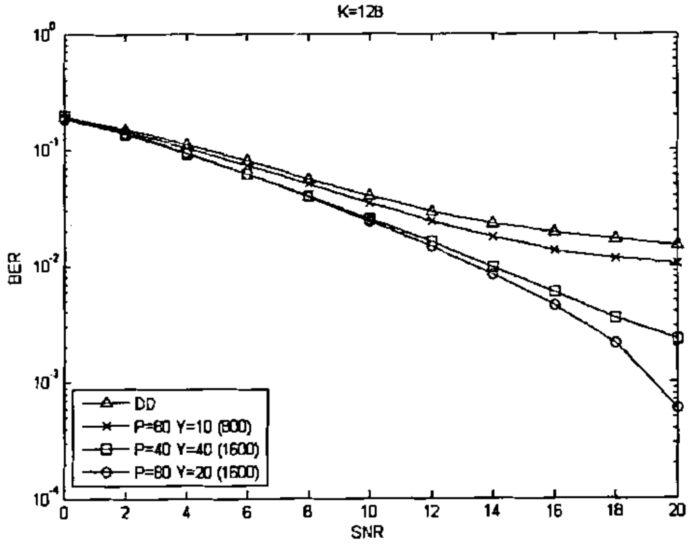

Figure 5.4 comparison of BER performance of different MUD schemes with N=31, M=8 and K=128 users supported

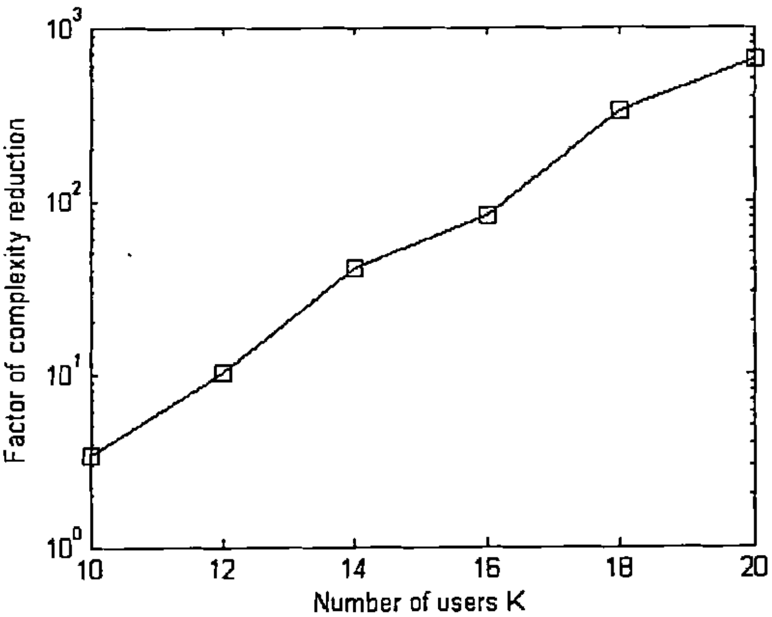

Figure 5.5 The complexity reduction factor of $\frac{2^K}{P \times Y}$ observed at BER of 10^{-3}

CHAPTER 6

Conclusions

Summary

In this study it has been demonstrated that the separate TF-domain GA assisted MUD schemes is capable of achieving a better BER performance than that of the joint Decorrelating TF-domain MUD schemes, while imposing a significantly lower detection complexity than the joint Decorrelating TF-domain MUD schemes.

By using that technique we are able to get a better BER at the cost of reduced computational complexity. Also if we increase the affordable complexity or the SNR we can achieve the single user bound. Further in this system we reduce the complexity of ML by a factor of $2^{\kappa N} / 2^{\kappa} = 2^{N}$ while achieving Mth order frequency diversity. Where M is total number of subcarriers.

This scheme can further be extended to other sub-optimum MUD schemes worked in literature with its multiple variations. So far the entire scheme was in un-coded fashion, therefore the channel-coding schemes such as Turbo Trellis Codes (TTC) and Space Time Block Codes (STBC) can be exploited to achieve further precision. Other diversity techniques can also be used instead of Frequency diversity. The different variations of CDMA can also be investigated for improved performance.

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