2

MULTIPLE ACCESS SCHEMES OVERVIEW AND MULTI - USER DETECTOR

2.1 INTRODUCTION

In the mobile environment, multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is necessary to achieve high capacity. Improvements in capacity can be achieved by simultaneously allocating the available bandwidth, or the available amount of channels, to multiple users. Two levels of operation can be distinguished in a cell

(1) *Circuit Level Architecture* controls the link between cell site or base station and the mobile unit. At the Circuit Level, it is often desirable to allow the subscriber to simultaneously send and receive information to and from the base station. This may be achieved by using Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD).

(2) *Cell Level Operative System.* In this scheme a cell site is considered in relation to a large number of mobile units operating more or less independently of one another. At the Cell Level two main issues are raised:

– *Spectrum management,* which is concerned with how the total spectrum allocation is divided into individual mobile circuits.

– *Access.* How are individual mobile circuits assigned on demand to specific users? Access deals with set-up, handover and circuit or channel assignment strategies.

The allocated spectrum is shared among all users and may be accessed by any user for any given call. All mobile units are under the direct and continuous control of the cell site base station. Cell Level architectures can be considered as multiple access systems that treat every radio circuit as a trunk. Multiple access techniques can also be classified as narrowband or wideband systems, depending upon how the available bandwidth is allocated to users. The term narrowband is used to relate the bandwidth of single channel to the expected coherence bandwidth of the channel. The available radio spectrum is divided into a large number of channels, usually using FDD. In wideband systems, the transmission bandwidth of a single channel is much larger than the coherence bandwidth of the channel. A large number of transmitters are allowed to transmit in the same channel and the users are allowed to use a large part of the spectrum.

The available spectrum can be shared among a number of users applying three basic techniques or combinations of them. These techniques are:

- Frequency Division Multiple Access (FDMA).
- Time Division Multiple Access (TDMA).
- Spread Spectrum Multiple Access (SSMA).

2.2 FREQUENCY DIVISION MULTIPLE ACCESS (FDMA)

For systems using Frequency Division Multiple Access (FDMA), the available bandwidth is subdivided into a number of narrower band channels. Each user is allocated a unique frequency band in which to transmit and receive on. During a call, no other user can use the same frequency band. Each user is allocated a forward link channel (from the base station to the mobile phone) and a reverse channel (back to the base station), each being a single way link. The transmitted signal on each of the channels is continuous allowing analog transmissions. The channel bandwidth used in most FDMA systems is typically low (30 kHz) as each channel only needs to support a single user. FDMA is used as the primary subdivision of large allocated frequency bands and is used as part of most multi-channel systems. Fig. 2.1(a) and Fig. 2.1(b) show the allocation of the available bandwidth into several channels.

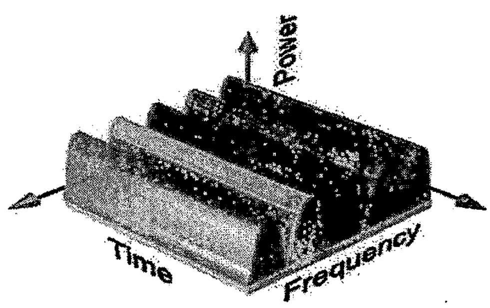

Figure 2.1(a) FDMA showing that the each narrow band channel is allocated to a single user

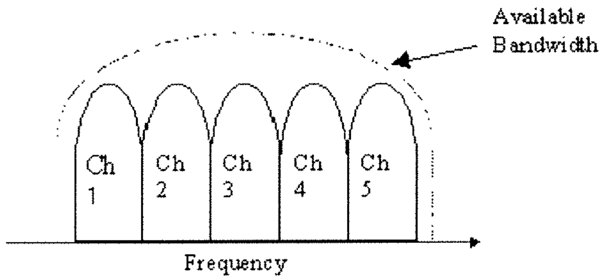

Figure 2.1(b) FDMA spectrum, where the available bandwidth is subdivided into narrower band channels

2.2.1 Advantages

- Capacity increases can be obtained by reducing the information bit rate and using efficient digital codes.
- Technological advantages required for implementation are simple

2.2.2 Disadvantages

- Since the system architecture based on FDMA, does not differ significantly from the analog system, the improvement available in capacity depends on operation on reduced S/I ratio.
- The maximum bit rate per channel is fixed and low, inhibiting flexibility in bit-rate capacity that is needed for computer file transfer.

2.3 TIME DIVISION MULTIPLE ACCESS (TDMA)

Time Division Multiple Access (TDMA) divides the available spectrum into multiple time slots, by giving each user a time slot in which they can transmit or receive. Fig. 2.2(a) shows how the time slots are provided to users in a round robin fashion, with each user being allotted one time slot per frame.

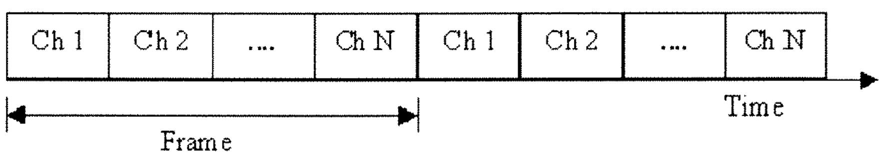

Figure 2.2(a) TDMA scheme where each user is allocated a small time slot

TDMA systems transmit data in a buffer and burst method, thus the transmission of each channel is non-continuous. The input data to be transmitted is buffered over the previous frame and burst transmitted at a higher rate during the time slot for the channel. TDMA can not send an analog signal directly due to the buffering required, thus is only used for transmitting digital data. TDMA can suffer from multi-path effects as the transmission rate is generally very high, resulting in significant inter-symbol interference.

TDMA is normally used in conjunction with FDMA to subdivide the total available bandwidth into several channels. This is done to reduce the number of users per channel allowing a lower data rate to be used. This helps reduce the effect of delay spread on the transmission. Fig. 2.2(b) shows the use of TDMA with FDMA. Each channel based on FDMA, is further subdivided using TDMA, so that several users can transmit of the one channel. This type of transmission technique is used by most digital second generation mobile phone systems. For GSM, the total allocated bandwidth of 25MHz is divided into 125, 200 kHz channels using FDMA. These channels are then subdivided further by using TDMA so that each 200 kHz channel allows 8-16 users.

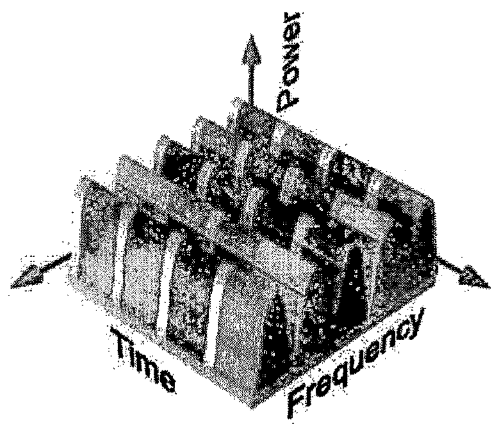

Figure 2.2(b) TDMA / FDMA hybrid, showing that the bandwidth is split into frequency channels and time slots

2.3.1 Advantages

- TDMA permits flexible bit rate, not only for Multiple of Basic single channel rate but also submultiples for low-bit-rate Broadcast traffic system.

- TDMA offers frame-by-frame monitoring of signal strength and bit error rates to enable either MSs or BSs to initialize and execute handover.

2.3.2 Disadvantages

- TDMA requires a substantial amount of signal processing for matched filtering and correlation detection for synchronizing with a time slot.

FDMA and TDMA are presently the most widely used systems. Commercially mobile systems use combination of both techniques to manage the existing bandwidth. Some of the standards are shown in Table 2.1.

Standard	Type	Multiple Access
Advance Mobile Phone System (AMPS)	1^{st} Generation	FDMA/FDD
Extended Total Access Communication System (ETACS)	1^{st} Generation	FDMA/FDD
Cordless Telephone (CT2)	Digital Cordless	FDMA/TDD
Digital European Cordless Telephone (DECT)	Digital Cordless	FDMA/TDMA/TDD
Global System for Mobile (GSM)	2^{nd} Generation	TDMA/FDMA/FDD
U.S. Digital Cellular IS-54 (USDC)	2^{nd} Generation	TDMA/FDMA/FDD
Japanese Digital Cellular (JDC)	2^{nd} Generation	TDMA/FDMA/FDD
Digital Communication System (DCS 1800)	PCS	TDMA/FDMA/FDD
Personal Access Communication System (PACS)	PCS	TDMA/FDMA/TDD
Personal Handy phone System (PHS)	PCS	TDMA/FDMA/TDD

Table 2.1 Commercial applications of TDMA and FDMA

2.4 CODE DIVISION MULTIPLE ACCESS (CDMA)

In CDMA, all users use same frequency and may transmit their data simultaneously through the channel. In this scheme narrowband message signal is multiplied by wide band spreading signal called codeword. Each user assigned separate pseudo-codeword which is orthogonal to others. Receiver knows the codeword for particular user. In receiver only desired codeword is detected and others are appeared as noise.

2.4.1 Concept of Spread Spectrum and CDMA

Spread spectrum communications have long been used in military applications. The distinguishing feature of spread spectrum communications is that the transmission bandwidth is significantly higher than that required by the information rate, resulting in the "spread" terminology. Typically, a pseudo random code is used to 'spread' the information signal to allocated frequency bandwidth.

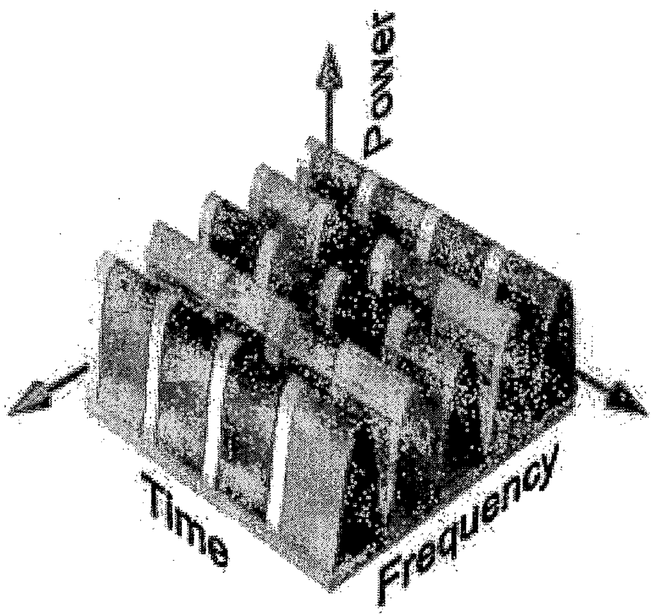

Figure 2.3(a). CDMA Scheme : 3D

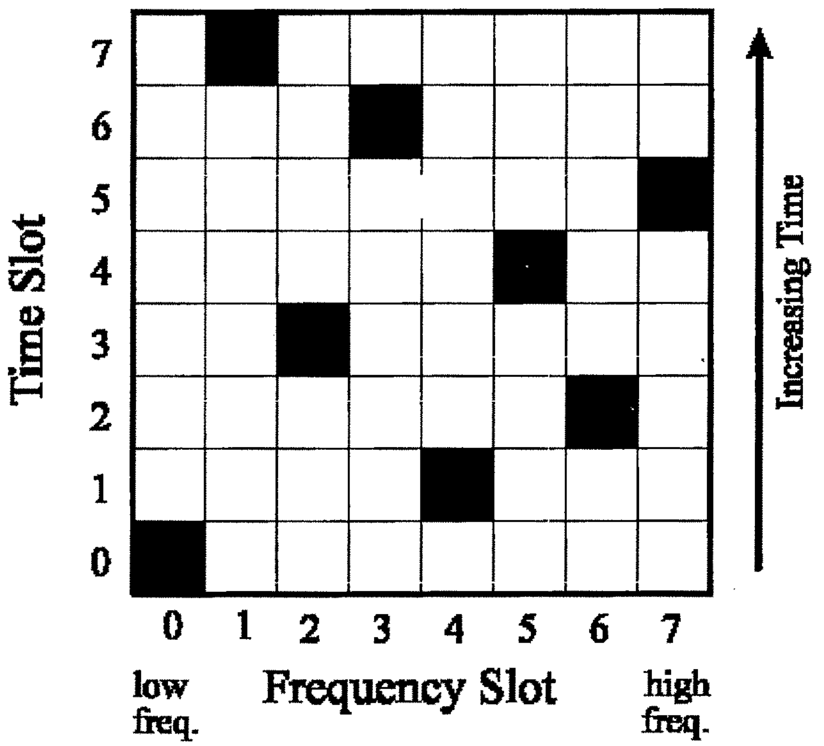

Figure 2.3(b). CDMA Scheme : 2D

CDMA is a multiple access technique that allows multiple users to transmit independent information within the same bandwidth simultaneously. Each user is assigned a pseudo random code that is either orthogonal to the codes of all other users or the code possesses appropriate cross correlation properties that minimize the multiple access interference (MAI). This code is superimposed on the information signal, making the signal appear noise like to all other users. Only the intended receiver has a replica of the same code and uses it to extract the information signal. This then allows the sharing of the same spectrum by multiple users without causing excessive MAI. It also ensures message privacy, since only the intended user is able to "decode" the signal. This code is also known as spreading code, since it spreads the bandwidth of the original data signal into a much higher bandwidth before transmission. Therefore the term Spread Spectrum Multiple Access (SSMA) is also used interchangeably with the term CDMA.

The modulation of a user's data by the code assigned to that user in a DS-CDMA system is accomplished by multiplication of the user's code with the user's data. An example of this process for an eight "chip" code is shown in Figure 2.4, where a "chip" is a defined as a single code element.

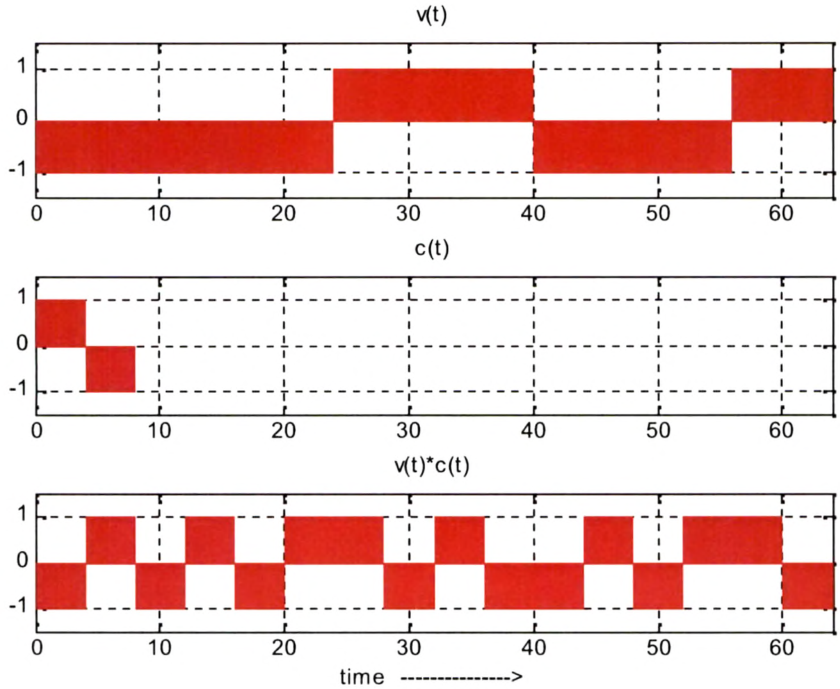

Figure 2.4 Waveforms of One User Data (chirp) in Genetic Algorithm

The waveform shown in Figure-2.4 indicates,

(1) c (t), the chipping waveform over two user data symbols.

(2) v (t), the user's data waveform over two data symbols.

(3) The product of the chipping and data waveforms v(t)c(t).

Figure 2.4 shows a classification tree of the various types of CDMA techniques. These techniques differ from each other in the way that the information signal is transformed to produce a high-bandwidth spread signal.

2.5 MULTI USER DETECTION FOR CDMA SYSTEM

The wireless domain is the current area of interest. But the growing number of users cannot afford to cause hindrance for others; Multi-User Detection Technique is going to be the key to this problem.

A problem facing the communication industry is that there is limited frequency spectrum. This reduces the capacity of a region. Spread Spectrum technology has been used in military for long. This has been helpful in anti-jamming. Because of the difficulty to jam or detect spread spectrum signals, the first applications were in the military field. However nowadays spread spectrum systems are gaining popularity also in commercial applications.

Recently, Spread spectrum-based code-division multiple access (CDMA), has taken on a significant role in cellular and personal communications. Multiple access allows multiple users to share limited resources such as frequency (bandwidth) and time. There are number of multiple access schemes more than one type of CDMA. Specially, Direct Sequence CDMA (DS-CDMA) has been found to be attractive because of such characteristics such as potential capacity increases over competing multiple access methods, anti-multi-path capabilities, soft capacity, and soft handoff.

The conventional approach for the demodulating DS-CDMA is to employ a correlation demodulator matched to the signature of the desired user. This approach is optimal for the case of single user transmission in AWGN channels and orthogonal synchronous multi-user communications. In a multiple access channel, network information theory indicates that a larger capacity region can be achieved by using a decoder that jointly processes the information received from all the transmitters. Thus there is improvement in performance by making use of MAI. There are two key limits to present DS-CDMA systems:

- All users with all other users and the interferences add to cause performance degradation.
- The near/far problem is serious and tight power control, with attendant complexity, is needed to combat it.

2.5.1 Multi-path Propagation

On the other aspect of CDMA that we need to review is the ability to combat multi-path reception of signals. Due to multiple reflections, the received signal contains delayed, distorted replicas of original transmitted signal. First consider what happen in non-spread spectrum signal. When the multi-path reflection, called multi-path signals or simply multi-paths, from one transmitted bit are received within the time duration of one bit, the received signal consists of the superposition of several signal replicas, each with its own amplitude and phase. Due to the motion of mobile, the relative phases of the received signals are continually changing. This results in successive reinforcement and interference of the superposed multi-path signals, resulting in very large time variations in the received signal. Such variations are referred to as Rayleigh fading. The variations due to Rayleigh fading are a serious cause of performance degradation and a communication system must be designed carefully, taking that in to account. One can combat multi-path interference by multi-path reception, whereby the different multi-path arrivals are considered as independent receptions of the signal and are used to give benefit time diversity, called RAKE receiver.

2.5.2 Conventional CDMA system/Receiver

In conventional CDMA system, all users interfere with each other. Due to this interference, the sum of all the received signals at the receiver is uncorrelated with the signature waveform of that user. Normally, the correlation between different signature waveform is zero. To demodulate a signal from a specific user, the received signal is correlated with the signature waveform of that user. In that case, the output of the correlator will be the transmitted signal of the desired user. This correlation receiver is known as the conventional receiver.

2.5.3 Disadvantages with Conventional Receiver

The conventional receiver has some serious drawbacks. The underlying assumption is that the signals from different users are *uncorrelated.* In this case the conventional receiver is optimum. In practice, the signals from different users will be correlated, which means the conventional receiver will be suboptimum. Still the conventional receiver will still work rather well under these two conditions:

- The correlation between the signature sequences is small
- The signals from different users are received with approximately the same power.

The first condition can be fulfilled by careful design of the code sequences that determine the signature waveforms. The second condition can be fulfilled by accurate power control. The base station measures the received power of all the transmitting mobiles. By sending power control commands to all the mobiles, telling them to increase or decrease their transmit power, the received power levels of all the users can be kept at approximately the same level. Without power control, the received power levels may differ by 60 dB or more! If the power of the received signals differs significantly, we say we suffer from the near-far problem.

Code sequence design also has problems. It turns out that the correlation between the signals from different users is critically dependent on the relative delays of the signals from different users. It is possible to design codes that are orthogonal, i.e. have zero cross correlation if the signals arrive at the base station synchronously. It is however impossible to design code sequences (with finite length) that have very low cross correlation for all relative delays.

2.6 MULTI-USER DETECTION

Due to the problems with the conventional receiver mentioned above, a different type of detector has been derived. These detectors, which do not treat other users as noise, but as digital signals are called multi-user detectors.

Multi-user detection is central to the fulfillment of the capabilities of code-division multiple access (CDMA), which is becoming the ubiquitous air-interface in future generation communication systems. The problem of multiple access interference (MAI) is vital for a CDMA system. A variety of multi-user detectors have been proposed to mitigate the MAI. The simplest one is the single-user matched filter approach, which totally ignores the existence of MAI. Its performance is not very satisfactory and is particularly limited by the near-far problem. A wide spectrum of multi-user detectors offers performance in between the matched filter and the optimal detectors with substantially reduced complexity.

Multi-User Detection (MUD) deals with the demodulation of mutually interfering digital streams of information Cellular telephony, satellite communication, high-speed data transmission lines, digital radio/television broadcasting, fixed wireless local loops, and multi-track magnetic recording are some of the communication systems subject to MAI. Multi-user Detection (also known as co-channel interference suppression, multi-user demodulation, interference cancellation, etc.) exploits the considerable structure of the multi-user interference in order to increase the efficiency with which channel resources are employed.

2.6.1 CDMA Channel Model for Multi-user Detection

A CDMA channel with K users sharing the same bandwidth is shown in Fig.2.8. The signaling interval of each user is T seconds, and the input data bit is antipodal binary $\{+1,-1\}$. During the n^{th} signaling interval, the input vector is $x_n = (x_n^1,........x_n^k)^T$, where x_n^k is the input symbol of the k^{th} user. User $k(k=1,.......K)$ is assigned a signature waveform $s_k(t)$ which is zero and is normalized

$$\int_0^t s_k(t)^2 d(t) = 1 \qquad (1)$$

The base band signal of the k^{th} user is

$$u_k(t) = \sum_{i=0}^{\infty} x_i^k e_i^k s_k(t - iT - \tau_k) \qquad (2)$$

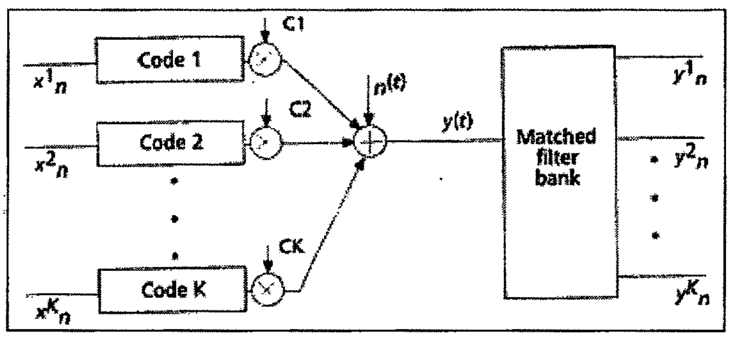

Figure 2.5 The CDMA Channel Model

Where τ_k is the transmission delay, and e_i^k is the complex channel attenuation. According to (2), each user's signal travels along a single path. For Synchronous CDMA, the delay $\tau_k = 0$ for all users. For asynchronous CDMA, the delay can be different.

The received signal is the sum of all the users' signals:

$$y(t) = \sum_{k=1}^{K} u_k(t) + n(t) \tag{3}$$

Where $n(t)$ is the complex additive white Gaussian noise (AWGN). The first step in the detection process is to pass the received signal $y(t)$ through a matched filter bank. It consists of K filters matched to individual signature waveforms followed by samples at instances $nT + \tau_{k,} k = 1........K, n = 1,2,.......$ The output of the matched filter bank form a set of sufficient statistic about the input sequence x_n given $y(t)$. thus, we can consider above model which arises at the output of the matched filter bank.

2.7 DIFFERENT TYPES OF MULTIUSER DETECTORS

Multi-user detectors can be of suboptimal or optimal. Optimal detectors are based on the Viterbi algorithm. They give optimal theoretical performance, but the complexity increases exponentially with users and so not practical for CDMA system. Sub-optimal detectors are easier to implement.

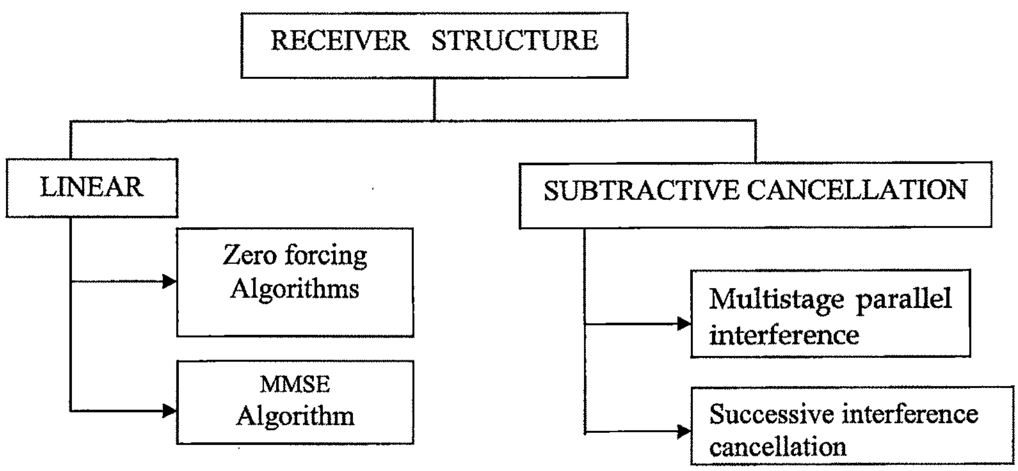

Figure 2.6 Receiver structure

2.7.1 Linear Detectors

Linear Multi-User Detectors are an important class of suboptimal techniques. The goal of linear MUD is to attain as much capacity increase from optimum MUD as possible, with a feasible and low-complexity implementation based on well-understood linear filters. A linear MUD is simply a filter that is designed to attenuate MAI according to specific criterion, as shown in Fig-2.6. In discrete-time these have low complexity and can be implemented using Finite Impulse Response (FIR) filters. We will discuss two types of Linear MUD, the Zero Forcing detector, Minimum Mean –Squared Error (MMSE) detector.

The linear multi-user detectors apply a linear transformation to the soft outputs of the conventional detector to produce a new set of decision statistics. Effectively they tend to reduce the effect of MAI seen by each user. The most commonly used linear detectors are the zero forcing detectors and the Minimum Mean-Squared Error detector.

2.7.1.1 Zero Forcing Detectors

The linear transformation applied in this case is the inverse of the co-relation matrix $\mathbf{R}^{-1}$.

The received signal can be represented as:

$$y=RWx+z \tag{4}$$

R= Co-relation matrix.

W = Received Signal Amplitudes

z= Noise Vector.

Hence if we apply the R^{-1} transformation to y we can recover the sent signal x.

R is a k *k correlation matrix, whose entries contain the values of the correlations between every pair codes.

$$R=\begin{bmatrix} 1 & \rho_{1,2} & \rho_{1,3} \\ \rho_{2,1} & 1 & \rho_{2,3} \\ \rho_{3,1} & \rho_{3,2} & 1 \end{bmatrix} \tag{5}$$

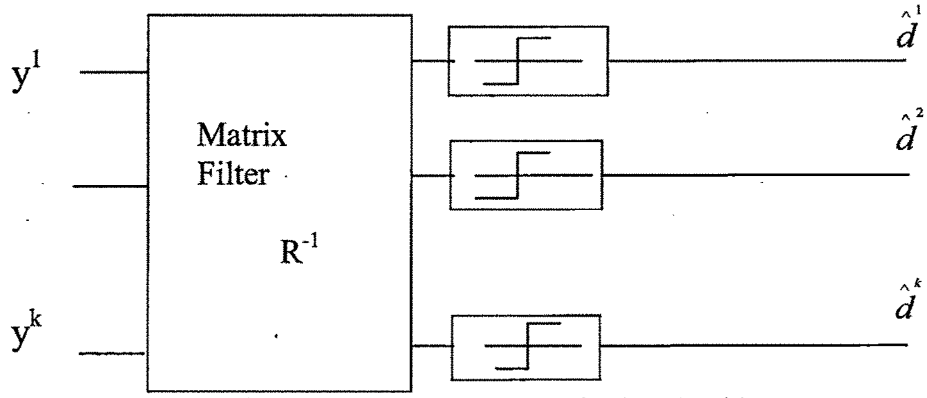

Figure 2.7. Demodulator zero forcing algorithm

2.7.1.1.1 Zero forcing algorithm performances

- Capacity gains over the conventional detector.
- Eliminates Multiple Access Interference.
- Independent of the powers of the interfering users.
- Symbol error probability was found to be independent of The signal energies
- Well Suited for near far environment.

2.7.1.1.2 Aspects of concern

- Performance of the zero forcing detector degrades as the cross correlations between the users increases
- Too much computation for R^{-1} in real time
- Causes noise enhancement
- The power associated with noise term R^{-1} z at the output of the zero forcing detector is always greater than or equal to the power associated with the noise term at the output of the conventional detector for each bit.

2.7.1.2 MMSE Detector

The MMSE detector implements a partial inverse of the correlation matrix. The amount of modification is directly proportional to the background noise, the higher the noise level, the less complete inversion of R can be done without noise enhancement. As the background noise goes to zero, the MMSE detector converges to the de-correlating detector. Hence, the de-correlating detector is a special case of MMSE detector, where the noise is zero. An important disadvantage of the MMSE detector is that unlike de-correlating detector it requires estimation of the received amplitudes. Another disadvantage is that its performance depends on the powers of the interfering users. Therefore there is some loss of resistance to the near-far problem as compared to the de-correlating detector.

A similar receiver structure can be obtained if the linear trans-formation is sought which minimizes the mean square error between the transmitted bits and the outputs of the transformation.It takes the background noise into account and utilizes the knowledge of the received signal powers. It implements a linear mapping which minimizes $E[|d-Ly|^2]$, mean squared error between the actual data and the soft output of the conventional detector

$$L_{MMSE} = [R + (N_0)A^{-2}]^{-1} \tag{6}$$

The soft output of the MMSE detector is simply given by

$$d_{MMSE} = L_{MMSE}\, y \tag{7}$$

2.7.1.2.1 Performance

- Because it takes the background noise into account, the MMSE detector generally provides a better probability of error performance than the zero forcing detector
- No noise enhancement

2.7.1.2.2 Concerns in MMSE

- Requires estimation of the received amplitudes
- The performance depends on the power of the interfering users
- Required matrix inversion

2.7.2 Linear MUD Implementation Issues

Implementing a linear multi-user detector involves several issues and does not appear straightforward. As discussed earlier, inversion of ***KxK*** matrix ***R*** is required. As ***K*** grows large, this becomes a very complex operation. In addition, knowledge of the channels and spreading codes are required for all users, along with a noise estimate. While spreading codes are typically known at the base station and required for all multi-user detectors, accurate channel and noise estimates may be impractical to attain.

The first problem of a ***KxK*** matrix inversion can be solved with an adaptive implementation for selecting the FIR taps which approximate $\boldsymbol{R}$, but this typically requires the spreading codes to repeat for each symbol in order for the changes in $\boldsymbol{R}$ from symbol to symbol to be small. Short spreading codes, however, have a number of undesirable properties with regards to their autocorrelation function and, hence, multipath suppression. The second problem of channel knowledge can be solved with a so-called blind adaptive algorithm for attaining the desired filter taps of $\boldsymbol{R}$. The term "blind" means that training sequences to estimate each user's channel are not required. While cleverly avoiding the capacity-reducing requirement for training, blind algorithms are typically quite noisy and slow to converge.

2.8 INTERFERENCE CANCELLATION TECHNIQUES

The basic principles underlying these detectors is the creation at the receiver of separate estimates of the MAI contributed by each user in order to subtract out some or all of the MAI as seen by each user. Such detectors are often implemented with multiple stages.

2.8.1 Successive Interference Cancellation

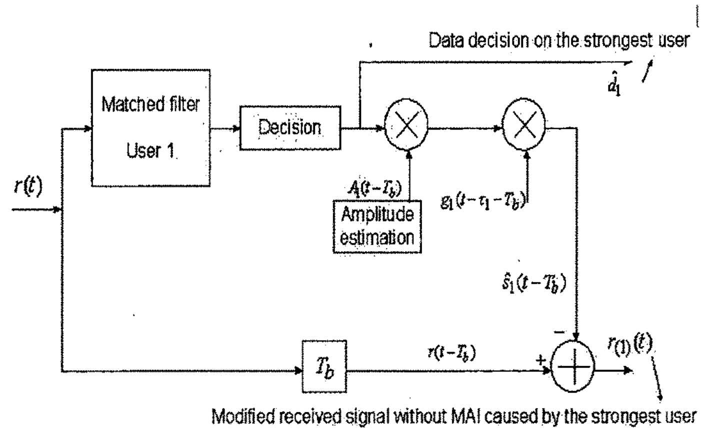

Figure 2.8 Successive Interference Cancellations – First Stage

Each stage of this detector decisions, regenerates, and cancels out one additional direct sequence user from the received signal so that the remaining users see less MAI in the next stage

2.8.1.1 Performance

- The removal of the strongest user gives the most benefit for the remaining users
- The strongest user will not benefit from any MAI reduction, but the weakest user will see a huge reduction in MAI.

2.8.1.2 Concerns in implementation

- One additional bit delay per stage
- Requires reordering signals when ever the power profile changes
- The performance degrades if the strongest estimates is not reliable

2.8.2 Parallel Interference Cancellation

Based on Estimating and subtracting out all of the MAI for each user in parallel (to reduce time delay) Usually a conventional receiver or de-corellator stage is used to determine the cancellation required in the first stage.

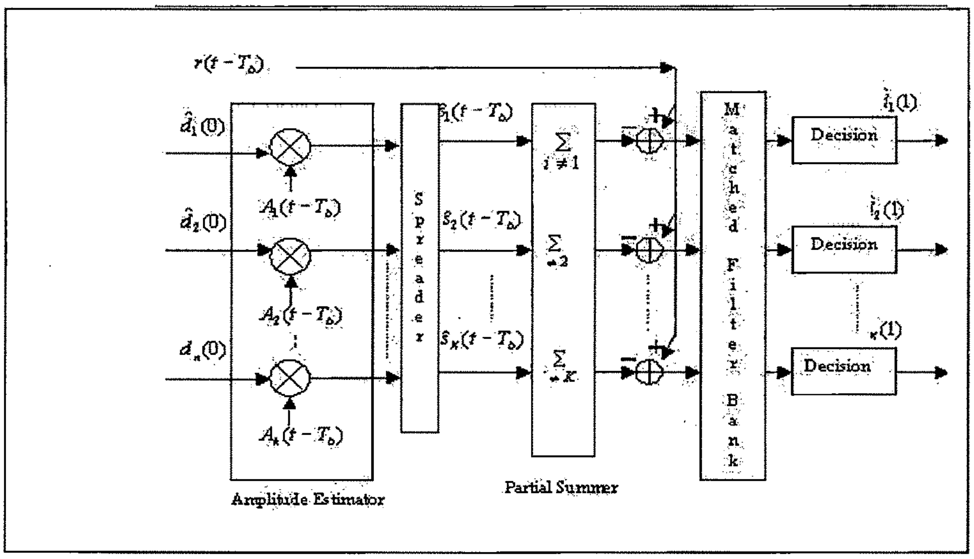

Figure 2.9 Parallel Interference cancellations

In contrast to the SIC detector the PIC detector estimates and subtracts all of the MAI for each user in parallel.

2.8.2.1 Using De-correlating detector as the first stage.

The performance of the PIC detector depends heavily on the initial data estimates. In SIC detector the subtraction of an interfering bit based on an incorrect bit estimate causes a quadrupling in the interfering power for that bit, thus too many incorrect initial data estimates degrades the performance related to the conventional detector. Therefore using Decorrelator detector as the first stage significantly improves the performance in Interference Cancellation techniques.

2.9 SUMMARY

In this chapter we have described various Multi user detection Techniques and detectors. We have compared conventional detectors and MAI techniques and also tried to describe all of them with their advantages and disadvantages. Studying MUD techniques led us to implement and analyze their performance for our goal in this thesis.