



ADDIS ABABA UNIVERSITY  
SCHOOL OF GRADUATE STUDIES  
FACULTY OF TECHNOLOGY  
ELECTRICAL AND COMPUTER ENGINEERING  
DEPARTMENT

Performance Evaluation of Interference Cancellation using  
SIC and PIC for WCDMA Systems

By  
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A thesis submitted to the school of graduate studies of Addis Ababa  
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# Abstract

Third generation wireless communications in conjunction with multimedia services has produced an increased demand for bandwidth efficient multiple access schemes. The need for increased capacity and improved performance motivate the search for better receiver structures, of which multiuser detection is a key technology that can substantially increase the system capacity and data rate. Due to the limitations of the conventional matched filter, the capacity of a single cell using CDMA is limited by self-interference and is subject to the near-far problem, and treats multiple access interference (MAI) as if it were AWGN. This thesis presents under a category of multiuser detection the most promising sub-optimal receiver structures, successive interference cancellation (SIC) and parallel interference cancellation (PIC) which are used to combat MAI in order to increase the data rate and capacity of the system which is applicable for WCDMA system and beyond. These subtractive interference cancellation receivers treat MAI as additional information to aid in detection in order to overcome the drawbacks seen by conventional matched filter. In this work we present a performance evaluation of these interference cancellers using SIC and PIC, and their performance is compared based on theoretical analysis and simulation results in AWGN and multipath fading channels. Simulation results using bit error rate (BER) versus signal to noise ratio (SNR) in multipath fading channel for different value of data size and number of users under perfect power control condition reveals that PIC achieves significant performance over conventional matched filter and SIC. And, as the data size (in bits) from the transmitting end increases the computational complexity of the multiuser detector become higher, however in PIC as the stage of multiple access interference cancellation increases the performance is reached remarkable level. In AWGN channel, simulation results confirmed that matched filter has shown optimum performance over SIC and PIC multiuser detectors when orthogonal spreading codes are assigned for each user in the network. Additionally, in this work receiver structures are evaluated on the basis of computational complexity.

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# Acronyms and abbreviations

2G	Second Generation
3G	Third Generations
3GPP	Third Generation partnership project
AAA	Authentication, Authorization, and Accounting
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BSC	Base Station Controller
BTS	Base Transceiver station
CDMA	Code Division Multiple Access
CN	Core Network
CS	Circuit Switch
CSCF	Call Session Control Function
D/A	Digital to Analogue
DS	Direct Sequence
DS-CDMA	Direct Sequence Code Division Multiple Access
ECC	Error Correcting Code
EIR	Equipment Identity Register
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FDMA	Frequency Division multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FH	Frequency Hopping
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPRS	Generalized Packet Radio Service
GPS	Global Positioning System

GSM	Global System for Mobile communications
HIC	Hybrid Interference Cancellation
HLR	Home Location Register
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
IC	Interference Cancellation
IF-RF	Intermediate Frequency-Radio Frequency
IMEI	International Mobile Equipment Identity
IMS	IP Multimedia Sub-system
IMT-2000	International Mobile Communications 2000
IP	Internet Protocol
IS-95	Interim Standard 95
ITU	International Telecommunication Union
LAI	Location Area Identity
MAC	Media Access Control
MAI	Multiple Access Interference
MAP	Maximum A Posteriori
MC	Multi-code
Mcps	Mega cycle per second
ME	Mobile Equipment
MF	Matched filter
MGW	Media Gateway
MGCF	Media Gateway Control Function
MHz	Mega Hertz
MIMO	Multi In Multi Out
ML	Maximum Likelihood
MLS	Maximum Likelihood Sequence
MLSE	Maximum Likelihood Sequence Estimator
MMSE	Minimum Mean Squared Error

MRF	Media Resource Function
MS	Mobile Station
MSC	Mobile Switching Center
MUD	Multiuser Detection
Node B	Basestation (in WCDMA)
OFDM	Orthogonal Frequency Division Multiplexing
PCS	Personal Communication Service
PDSN	Packet Data Serving Node
PG	Processing Gain
PIC	Parallel Interference Cancellation
PLMN	Public Land Mobile Network
PN	Pseudo-Noise
PS	Packet Switch
PSK	Phase Shift Keying
PSTN	Public Switching Telephone Network
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RNC	radio Network Controller
SGSN	Serving GPRS Support Node
SIC	Successive Interference Cancellation
SIM	Subscriber Identity Module
SIP	Session Initiation Protocol
SNR	Signal to Noise Ratio
SS	Spread Spectrum
TD	Transmit Diversity
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
TRX	Transceiver
UE	User Equipment
UMTS	Universal Mobile Telecommunication Systems

USIM	UMTS Subscriber Identity Module
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
VLSI	Very Large Scale Integrated Circuit
WCDMA	Wideband Code Division Multiple Access

# Chapter 1

## 1. Introduction

Wireless communications has grown explosively during years. Third generation wireless communications in conjunction with multimedia services has produced an increased demand for bandwidth efficient multiple access schemes. The need for increased capacity and improved performance motivate the search for better receiver structures.

### 1.1 Background of the Problem

Wireless communication is one of the most vibrant research areas in the communication field today. While it has been a topic of study since the 60's, the past decade has seen a surge of research activities in the area. This is due to a confluence of several factors. First is the explosive increase in demand for higher bandwidth connectivity. Second, the dramatic progress in VLSI technology has enabled small-area and low-power implementation of sophisticated signal processing algorithms and coding techniques. Third, the success of second-generation (2G) digital wireless standards, in particular the IS-95 Code Division Multiple Access (CDMA) standard, provides a concrete demonstration that good ideas from communication theory can have a significant impact in practice. The research thrust in the past decade has led to a much richer set of perspectives and tools on how to communicate over wireless channels, and the picture is still very much evolving [19].

There are two fundamental aspects of wireless communication that make the problem challenging and interesting. These aspects are by and large not as significant in wireline communication. First is the phenomenon of fading: the time-variation of the channel strengths due to the small-scale effect of multipath fading, as well as larger scale effects such as path loss via distance attenuation and shadowing by obstacles. Second, unlike in the wired world where each transmitter-receiver pair can often be thought of as an isolated point-to-point link, wireless users communicate over the air and there is significant interference between them in wireless communication. The interference can be between transmitters communicating with a common receiver (e.g. uplink of a cellular

system), between signals from a single transmitter to multiple receivers (e.g. downlink of a cellular system), or between different transmitter-receiver pairs (e.g. interference between users in different cells). How to deal with interference is central to this work.

Nowadays wireless communication is used widely in many communication systems: mobile telephony, satellite networks, digital radio/television broadcasting, fixed wireless local loops, etc. Particularly, wireless mobile communications has exploded in popularity because of the fact that it simplifies and revolutionizes communications. The success of mobile communications lies in the ability to provide instant connectivity anytime and anywhere and the ability to provide high-speed data services to the mobile user. The quality and speeds available in the mobile environment must match 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 lie in making the movement from one network to another as transparent to the user as possible and the availability of high speed reliable data services along with high quality voice. A range of successful mobile technologies exists today in various parts of the world and every technology must evolve to fulfill all these requirements. This work particularly interested in the cellular mobile environment, in the field of multiuser detection, and primarily focused on subtractive interference cancellation.

In the early mobile radio systems a large coverage was attained by placing an antenna with a high-power transmitter in one of the highest point of the coverage area for instance, on top of a hill or a high building. Nevertheless, it meant that only a small number of users could be allocated in a large area due to the few available radio frequencies. So any attempt to reuse the same frequencies throughout the system would result in interference. Thus, the need of higher capacity with limited radio channel brought into the cellular concept.

A cellular mobile communications system uses a large number of low-power wireless transmitters to create cells which are the basic geographic service area of a wireless communications system. In cellular system each cell consists of a base transceiver station (BTS) and each BTS holds a number of Transceiver (TRX), typically between 1 and 16. Each BTS's are transmitting over a small geographic area usually depicted as a hexagon

(the true shape of a cell is not a perfect hexagon due to constraints imposed by the terrain). According to the density and demand of mobile users (MS) within a certain region, the cell size is determined. The base stations in turn are connected to a central one called the mobile switching centre (MSC) which provides connectivity between the public switched telephone network (PSTN) and the base stations. Thus a global communication network is formed with PSTN which connects the conventional telephone switching centers with MSC all over the world.

Visitor Location Register (VLR) is a database - part of the Global System for Mobile Communications (GSM) mobile phone system - which stores information about all the mobiles that are currently under the jurisdiction of the Mobile Switching Center (MSC) which it serves. Of all the information it stores about each Mobile Station (MS), the most important is the current Location Area Identity (LAI). LAI identifies the currently present MS under Base Station Controller (BSC). This information is vital in the call setup process. Whenever an MSC detects a new MS in its network, in addition to creating a new record in the VLR, it also updates the Home Location Register (HLR) of the mobile subscriber, to apprise the new location of MS. HLR is a central database that contains details of each mobile phone subscriber that is authorized to use the GSM and or WCDMA core network.

A Packet Data Serving Node (PDSN) provides access to the Internet, intranets and applications servers for mobile stations utilizing a WCDMA Radio Access Network (RAN). Acting as an access gateway, PDSN provides simple IP and mobile IP access, foreign agent support, and packet transport for virtual private networking. It acts as a client for Authentication, Authorization, and Accounting (AAA) servers and provides mobile stations with a gateway to the IP network. Mobility differentiates Cisco's PDSN from the traditional routed network.

Equipment Identity Register (EIR) ensures that all Mobile Equipment's are valid and authorized to function on the Public Land Mobile Network (PLMN). Three categories exist on the EIR, a white list, a gray list and a black list. The white list comprises the International Mobile Equipment Identity (IMEI) ranges of all the Mobile Equipment's that have been approved by any one of the three European, GSM approval centers. Any

Mobile Equipment that appears on the gray list will be allowed to function but will trigger an alert to the network operator. This facility allows the network operator to identify any subscriber that is using a lost or stolen Mobile Equipment.

The International Mobile Equipment Identity (IMEI) is a unique 15 or 17 digit code used to identify an individual mobile station to a GSM or UMTS network. The IMEI number facilitates an important function; it easily identifies a mobile phone being used on a GSM network. The IMEI is a useful tool to stop a phone that is stolen from accessing a network and being used. Mobile phone owners that have their phones stolen can contact their mobile network provider and ask them to ban or shut off a phone using its IMEI number. With an IMEI number, the phone can be banned from the network quickly and easily. It is important to note that swapping a SIM card will not stop a phone from being banned.

Figure 1.1 illustrates 3GPP Release 5 UMTS core network architecture. Functionally the network elements are grouped into the Radio Access Network (RAN, UMTS Terrestrial RAN = UTRAN) that handles all radio related functionality, and the Core Network (CN), which is responsible for switching and routing calls and data connections to external networks. To complete the system, the User Equipment (UE) interfaces with the user and defined radio network. Both UE and UTRAN are designed based on the needs of the new WCDMA radio technology. On the contrary, the definition of the Core Network (CN) is adopted from GSM. This gives the system with new radio technology a global base of known and rugged CN technology that accelerates and facilitates its introduction and enables such competitive advantages as global roaming [5].

The UE consists of two parts: the Mobile Equipment (ME) which is the radio terminal used for radio communication over the Uu interface; through Uu interface the UE can access fixed part of the system. And the UMTS Subscriber Identity Module (USIM) which is a smartcard that holds the subscriber identity which performs authentication algorithms, and stores authentication and encryption keys and some subscriber information that is needed at the terminal.

UTRAN also consists of two distinct elements:

- The Node B (Base Station) converts the data flow between the Iub and Uu interface. It also participates in radio resource management. Where Iub interface connects a Node B and an RNC.
- The Radio Network Controller (RNC) owns and controls the radio resources in its domain (the Node Bs connected to it). RNC is the service access point for all services UTRAN provides the CN, for example, management of connections to the UE.

In figure 1.1 the following building blocks of Release 5 UMTS core network architecture are defined as follows:

- GMSC (Gateway MSC) is the switch at the point where UMTS PLMN is connected to external Circuit Switch (CS) networks. All incoming and outgoing CS connections go through GMSC. Home Subscriber Server (HSS) is shown as independent item.
- SGSN (Serving GPRS (General Packet Radio Service) Support Node) functionality is similar to that of MSC/VLR but is typically used for Packet Switched (PS) services. The part of the network that is accessed via the SGSN is referred to as the PS domain. GGSN (Gateway GPRS Support Node) functionality is close to that of GMSC but is in relation to PS services.
- Iu interface is used to connect UTRAN to the CN, and gives for UMTS operators the possibility of acquiring UTRAN and CN from different manufacturers.
- Media Gateway Controller (MGW) performs the actual switching for user data and network inter-working processing, e.g., echo cancellation or speech decoding / encoding.
- IP Multimedia Sub-system (IMS) enables a standardized approach for IP-based service provision via PS domain. From a protocol perspective, the key

protocol between the terminal and the IMS is the Session Initiation Protocol (SIP), which is the basis for IMS-related signaling.

- Media Resource Function (MRF) which, e.g., controls media stream resources or can mix different media streams.
- Call Session Control Function (CSCF), which acts as the first contact point to the terminal in the IMS (as Proxy). The CSCF covers several functionalities from handling of the session states to being a contact point for all IMS connections intended for a single user and acting as a firewall towards other operator's networks.
- Media Gateway Control Function (MGCF) is used to handle protocol conversions. This may also control a service coming via the CS domain and perform processing in an MGW, e.g., for echo cancellation [5].

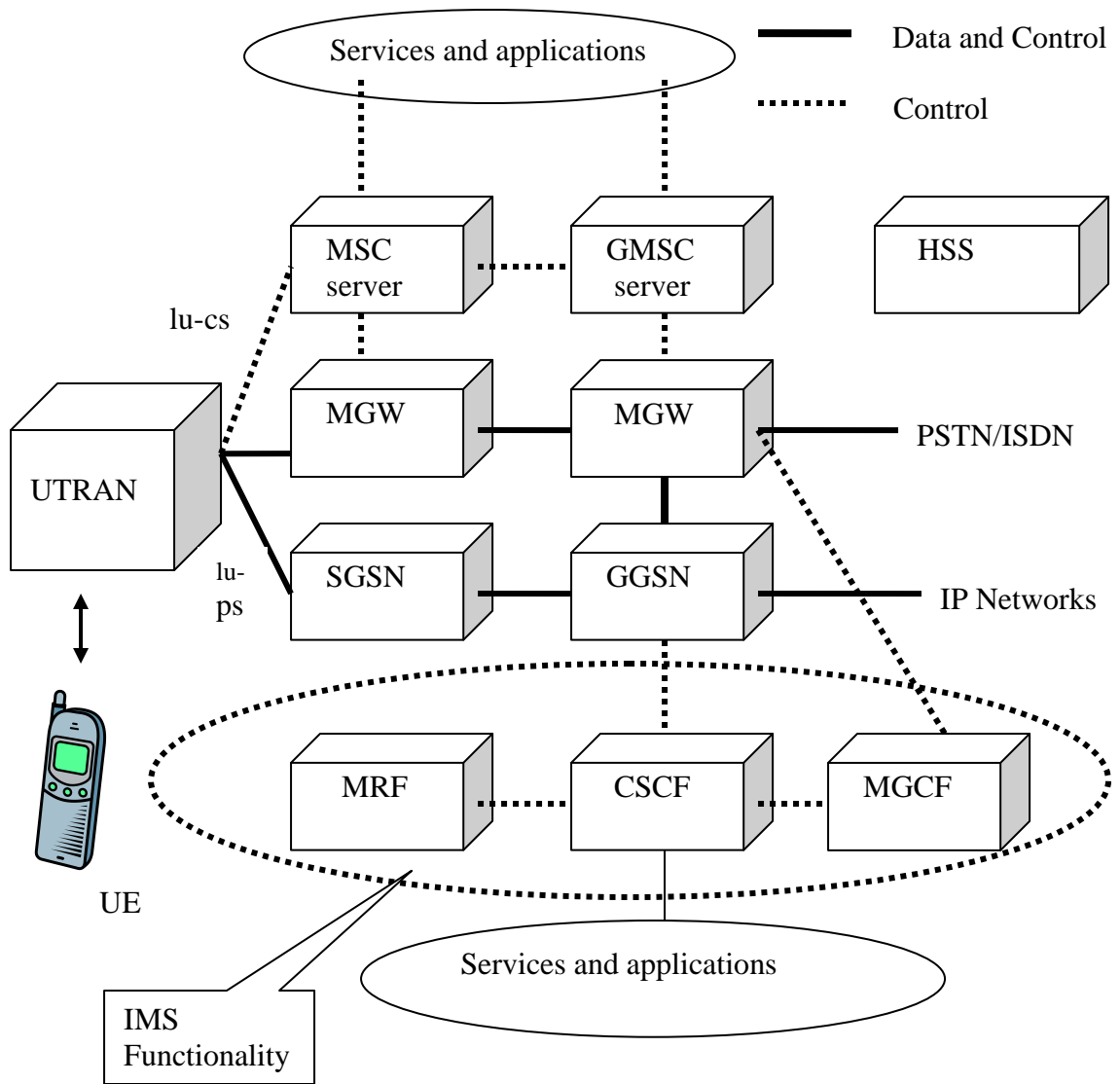


Figure 1.1 Release 5 UMTS core network architecture (source: Reference 5)

The power control can regulate the transmit power of the terminal and base station, which results in less interference and allows more users on the same carrier. For each subscriber service the aim is that the base station shall receive the same power level from all handsets in the cell regardless of distance from the base station. If the power level from one handset is higher than needed, the quality will be excessive, taking a disproportionate share of the resources and generating unnecessary interference with the other subscribers in the network. On the other hand, if power levels are too low this will

result in poor quality. In order to keep the received power at a suitable level, WCDMA has a fast power control that updates power levels 1500 times every second. By doing that the rapid change in the radio channel is handled. To ensure good performance, power control is implemented in both the up-link and the down-link, which means that both the output powers of the handset and the base station are frequently updated [5].

Power control also gives rise to a phenomenon called “cell breathing”. This is the trade-off between coverage and capacity, which means that the size of the cell varies depending on the traffic load. When the number of subscribers in the cell is low (low load), good quality can be achieved even at a long distance from the base station. On the other hand, when the number of users in the cell is high, the large number of subscribers generates a high interference level and subscribers have to get closer to the base station to achieve good quality [11].

## **1.2 Motivation of the work**

The rapidly growing demand for personal communications services, as well as emerging applications such as mobile computing, wireless local area networking, and wireless Internet access, has focused considerable attention on the design of advanced, high-capacity, multiple-access signaling formats capable of supporting such heterogeneous services. Among the several options available for the implementation of the air interface of future multimedia wireless networks, the leading technology is represented by direct-sequence code division multiple access (DS/CDMA), which has emerged as the basic technique for the realization of the physical layer of third-generation (3G) wireless networks, both terrestrial and satellite-based. When compared with conventional multiple access techniques, such as those based on time and/or frequency division multiplexing, the CDMA technique appears to be quite advantageous. In particular, it is able to achieve higher system capacities, may be implemented with lighter signaling protocols, has higher frequency-reuse capabilities, is characterized by a superior immunity to co-channel interference and multipath distortion, and can easily support the transmission of multirate information streams [23].

In recent years, increasing attention has been focused on this latter issue of multirate CDMA systems, in which users are allowed to transmit at one out of a set of available data-rates. Indeed, the possibility of transmitting several kinds of data, each with its own bit-rate and required quality-of-service (QoS), is one of the most attractive features of 3G wireless systems. A very simple way to accommodate multiple-rate transmissions is to use a “conventional” single-rate CDMA network, assigning multiple signature waveforms to the high-rate users. That is, in each signaling interval, high-rate users are allowed to simultaneously transmit several bits by modulating as many signatures, so that they are actually split into several “virtual” users. This technique is referred to as multicode (MC), and has been incorporated in the standard proposal for wideband-CDMA (WCDMA).

WCDMA radio access has evolved strongly alongside high-speed downlink packet access (HSDPA) and high-speed uplink packet access (HSUPA), together called ‘high-speed packet access’ (HSPA). When the International Telecommunication Union (ITU) defined the targets for IMT-2000 systems in the 1990s, the required bit rate was 2Mbps. 3rd Generation Partnership Project (3GPP) Release 99 does support up to 2Mbps in the specifications, but the practical peak data rate chosen for implementations is limited to 384 kbps. By the time of this thesis was written HSPA is able to push practical bit rates beyond 2Mbps and is expected to exceed 10 Mbps in the near future. In addition to the higher peak data rate, HSPA also reduces latency and improves network capacity. The new radio capabilities enable a new set of packet-based applications to go wireless in an efficient way. For operators the network upgrade from WCDMA to HSPA is straightforward as the HSPA solution builds on top of the WCDMA radio network, reusing all network elements [24].

With the advent of high performance mixed-signal devices, high-speed processors, reconfigurable computing devices, and the incorporation of advance receiver concepts, the practical implementation of advanced multiuser receivers will be more feasible into future systems. Today, a significant research activity is carrying out to solve several of the practical and theoretical open issues that still exist in the field of multiuser detection. Therefore, the prime motivation for this work is mainly the day today demand of high

data rate and quality of service from the user; and the researchers' dedication to meet this demand with high quality of service in the field of wireless communications technology encourage evolving in this study.

### **1.3 Objective of the work**

Combating impairments due to multiple access interference (MAI) leads to higher coverage capacity and speed up the data rate, where as MAI treated in IS-95 as thermal noise and it become a potential problem for capacity and data rate limitation together with multipath fading. In this work the performance evaluation of MAI cancellation using sub-optimum multiuser detection category is studied, specifically subtractive interference cancellation methods; i.e., successive interference cancellation (SIC), and parallel interference cancellation (PIC). And to investigate a multiuser receiver structure with a satisfactory tradeoff between performance and complexity.

### **1.4 Organization of the Thesis**

The remainder of the thesis is organized as follows. Chapter 2 presents a literature survey on Multiple Access Methods, WCDMA and Multiuser Detection Systems. In which multiple access methods with the emphasis on CDMA technology is discussed, secondly a survey of WCDMA system is shown with supporting tables and lastly but not least an overview of multiuser detection system for both linear and non-linear sub-optimum multiuser detection systems is briefly mentioned with supporting analytical findings and block diagrams.

Chapter 3 presents system model description of interference cancellation in CDMA systems for successive and parallel interference cancellation with channel estimation characterization basically in the Additive White Gaussian Noise (AWGN) channel and for fading multipath channel is discussed. The basic conventional matched filter which is the front end for all multiuser detectors is briefly mentioned. Under subtractive interference cancellation methods the SIC and PIC system model thoroughly discussed with mathematical analysis and supporting block diagrams for each receiver.

Based upon the work in Chapter 3, in Chapter 4, the performance comparison of SIC and PIC based on system model and computational complexity is explained. Tables for

comparison purpose on different multiuser detection systems are attached. And analytical BER calculations for both SIC and PIC is mentioned.

Chapter 5 presents simulation results for the performance measurement of these interference cancellation methods, i.e. SIC and PIC using Signal-to-Noise Ratio versus Bit Error Rate (BER) figures. These figures with associated explanation state the performance evaluation for different cases in AWGN and multipath fading channel.

In the last chapter, Chapter 6, summary of the thesis using conclusion and future work will be given.

# Chapter 2

## 2. Multiple Access Methods, WCDMA and Multiuser Detection Systems Overview

### 2.1 Multiple Access Methods

Users in a cellular system can be separated using one of three multiple access schemes; i.e., frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA) as shown in (Figure 2.1). In FDMA, all users transmit simultaneously, but use disjoint frequency bands. In TDMA, all users occupy the same RF (radio frequency) bandwidth, but transmit sequentially in time. The number of users that can be supported is determined by the number of slots available, either in frequency or time. Both the above systems are inherently inflexible in that the number of frequency or time slots (or channels) allocated is fixed a priori; this wastes resources when the number of users is less than the number of channels.

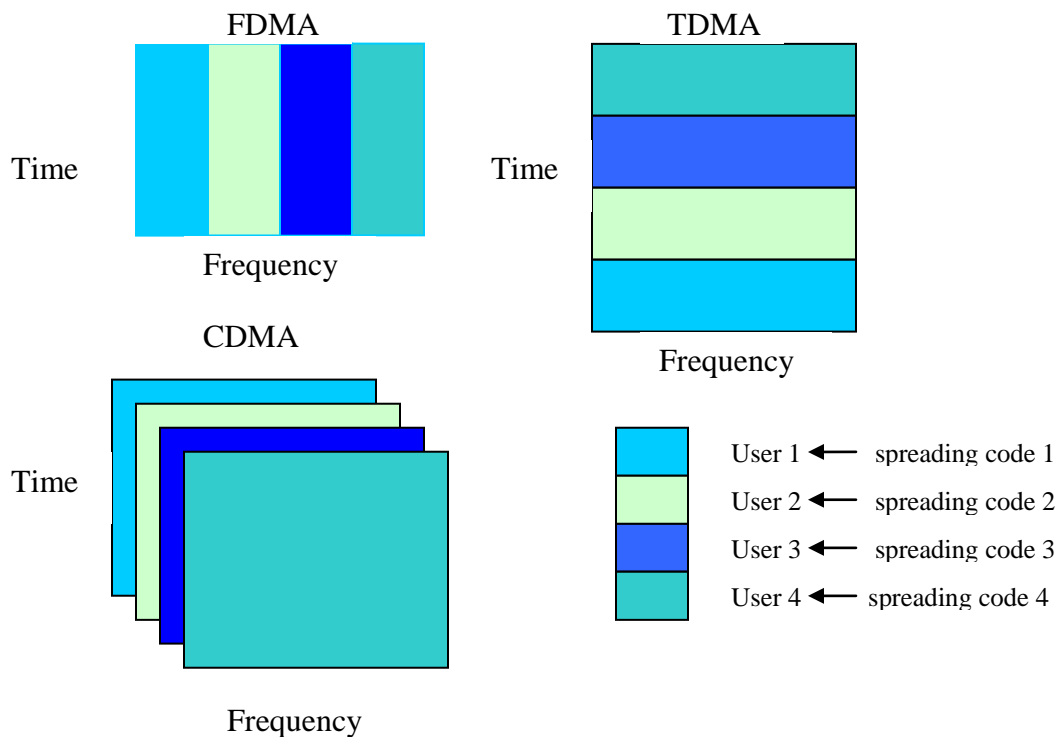


Figure 2.1: Multiple Access Schemes

When users are allowed to transmit simultaneously and occupy the same bandwidth, some other means of separating the users should be used - Code Division Multiple Access (CDMA) provides such a scheme. All the users occupy the entire time-bandwidth plane with the overall system performance degrading gracefully as the number of user's increases.

The frequency reuse factor is another major factor favoring CDMA over either TDMA or FDMA. In the later techniques, the bandwidth used in a particular cell cannot be used in any immediately adjacent cells to prevent excessive interference. Due to the reduce number of radio frequency channels available for mobile systems, a reuse of the frequency channels had to be implemented into the cellular concept. This reuse process means that the radio frequency channels used in one cell can also be reused in another cell some distance away. Usually clusters of cells (no frequency channels are reused in a cluster) are reused in a regular pattern during the entire coverage area as it shown in Figure 2.2. Hence, the frequency reuse factor in a system is determined by the available frequency channels, i.e. for the particular case depicted in Figure 2.2 the frequency reuse factor of the system is  $1/7$ .

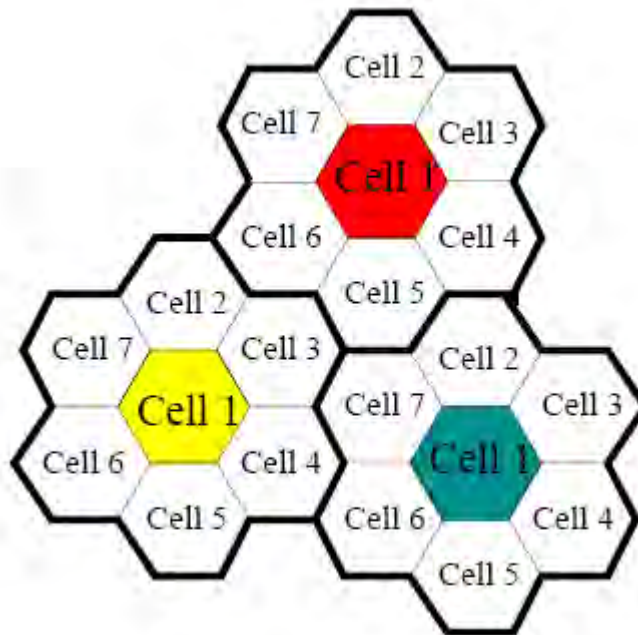


Figure 2.2: Frequency reuse pattern in a cellular system

In DS-CDMA it is possible to have a reuse factor of one, thus alleviating the problem of frequency planning. CDMA also provides a natural way to exploit the voice activity factor, which is the percentage of time during a two-way telephone conversation, each channel is actually used. Due to all these advantages, DS-CDMA has recently emerged as a commercially viable strategy for cellular wireless communications.

CDMA falls under a class of techniques called spread spectrum techniques. The term spread spectrum implies that the data stream is modulated or coded so that the overall transmission rate is much higher than the maximum needed to transmit the actual data. Each user's data bits are modulated by a coded waveform that can only be detected at the receiver which also knows the coding function. The two common modulation techniques for spread spectrum are direct sequence (DS) and frequency hopping (FH). In frequency hopping, the carrier is caused to shift frequency according to a pattern. This pattern is also known at the receiver and allows for detection of the signal. Direct sequence CDMA (DS-CDMA) signals are generated by multiplying the desired signal by a larger-bandwidth spreading sequence, also called spreading codes (Figure 2.3). Again, the spreading codes are known at the receiver and this allows detection of the data bits.

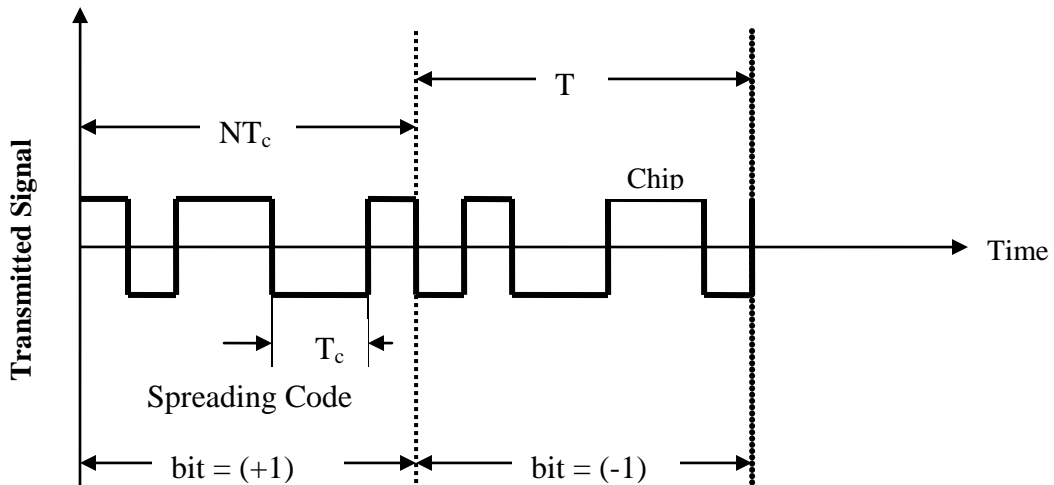


Figure 2.3: Spreading result with short codes: where, spreading code =  $\{1, -1, 1, 1, -1, -1, 1\}$ ; chip duration  $T_c$ ; bit duration  $T$ ; spreading gain 7.

In order to maximally differentiate between the users, the codes assigned to the users should be mutually orthogonal. In practice, this is not realistic due to the asynchronous manner of operation that CDMA supports, i.e., the bit intervals of the different users do not have to coincide. This makes the design of the spreading codes and also the CDMA system more difficult and recently a large part of the research in this field has focused on this issue.

Historically, the initial applications of spread spectrum systems have been in military communications. This is because the spread spectrum nature of the signal results in a number of benefits, such as anti-jamming properties and low probability of intercept. In recent years, there has been a steadily growing interest in using CDMA in mobile radio networks. Certain properties of the spread spectrum waveforms give CDMA some distinct advantages over FDMA or TDMA for cellular systems [9]. The two basic problems which the cellular radio designer faces are multipath fading [7] of the radio link and interference. Direct sequence techniques offer fine resolution in time and can therefore be used to enhance overall performance by diversity combining of the multipath in a rake receiver [7]. Due to their wide bandwidth, spread spectrum signals are also useful in mitigating interference.

Code Division Multiple Access (CDMA) offers many attractive properties as an access scheme for mobile communications. However, the conventional composed of a bank of matched filters suffers from the Multiple Access Interference (MAI). The capacity and performance degrades when the number of users increases or the system operates in severe near-far environments; when the mobile users have different geographical locations relative to the receiver and signals of the closer transmitting users undergo less amplitude attenuation than the signals of users that are further away from the receiver this condition is known as the near-far problem. These conditions are inherent in cellular systems. Since the work of prominent scientist in the study of multiuser detection, Sergio Verdu, on the optimum detector, several suboptimum multiuser detectors have been proposed for improving capacity and mitigating MAI problem of conventional method. Amongst them are linear detectors. Decorrelator and MMSE (Minimum Mean Square Error) are the well-known approaches. These methods have several attractive properties but suffer from

implementation complexity, which is mainly due to a need for inverting a large matrix [1, 2].

Multiple Access Interference (MAI) is a factor which limits the capacity and performance of DS-CDMA systems. MAI refers to the interference among direct- sequence users. This interference is the result of the random time offsets between signals, which make it impossible to design the code wave forms to be completely orthogonal. While the MAI caused by any one user is generally small, as the number of interferers or their power increases, MAI become substantial. The conventional detector does not take in to account the existence of MAI. It follows a single-user detection strategy in which each user is detected separately without regard for other users [12].

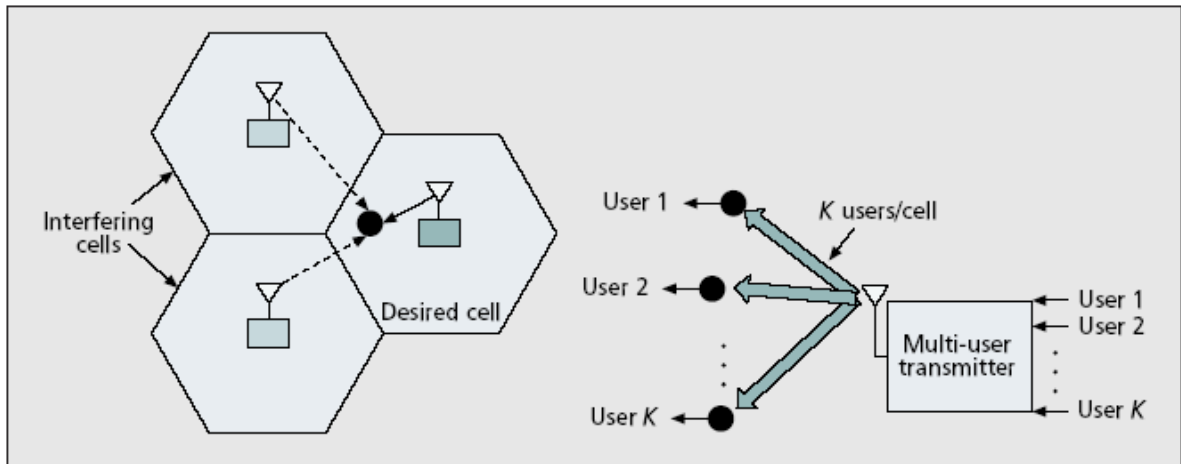


Figure 2.4. Downlink scenario

In the downlink scenario, each receiver only needs to decode its own signal, while suppressing other-cell interference from just a few dominant neighboring cells. Because all  $K$  users' signals originate at the base station, the link is synchronous and the  $K - 1$  intracell interferers can be orthogonalized at the base station transmitter. Typically, though, some orthogonality is lost in the channel.

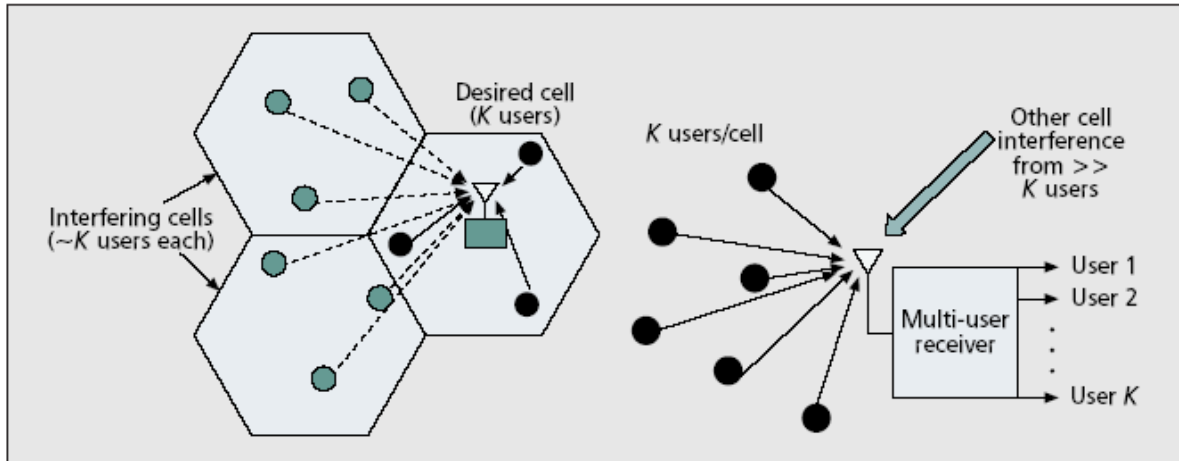


Figure 2.5. Uplink scenario

In the uplink scenario, the base station receiver must decode all  $K$  desired users, while suppressing other-cell interference from many independent users. Because it is challenging to dynamically synchronize all  $K$  desired users, they generally transmit asynchronously with respect to each other, making orthogonal spreading codes unviable.

Sergio Verdu's seminal work [13], published in 1986, proposed and analyzed the optimum multi user detector, or the maximum likelihood sequence detector. Unfortunately, this detector is much too complex for practical DS-CDMA systems. Therefore, over the last decade or so, most of the research has focused on finding suboptimal multi-user detector solutions which are more feasible to implement [2].

## 2.2 WCDMA System Overview

Third generation systems are designed to make a large set of new services to go wireless as well. These systems make new attractive services possible for the customers, and can provide new sources of revenues for the operators. These systems are also designed to deliver high bit rates and high capacities.

Wideband Code Division Multiple Access (WCDMA) technology has emerged as the most widely-adopted air interface for 3G cellular telephony in the standardization process. All the schemes try to take advantage of the WCDMA radio techniques without ignoring the numerous advantages of the already existing GSM networks.

The standard that has emerged is based on European Telecommunications Standard Institute (ETSI) and Universal Mobile Telecommunication System (UMTS) and is commonly known as UMTS Terrestrial Radio Access (UTRA). The access scheme for UTRA is Direct Sequence Code Division Multiple Access (DS-SS). The information is spread over a bandwidth of approximately 5 MHz. This wide bandwidth has given rise to the name Wideband CDMA or WCDMA. There are two different modes namely Frequency Division Duplex (FDD) and Time Division Duplex (TDD).

Since different regions have different frequency allocation schemes, the capability to operate in either FDD or TDD mode allows for efficient utilization of the available spectrum. A brief description of FDD and TDD modes is given next. In WCDMA FDD mode the uplink and downlink transmissions employ two separate frequency bands i.e., 1920-1980 MHz for uplink and 2110-2170 MHz for downlink [5]. The system description provided in this work holds for the FDD mode only. Whereas in WCDMA TDD mode, uplink and downlink transmissions are carried over the same frequency band by using synchronized time intervals. The frequency of the carrier is shown in the table below (the exact spectrum available remains country-specific) [6]:

Table 2.1 Frequency of the carrier in WCDMA systems

<b>Frequency division duplex (FDD)</b>		<b>Time division duplex (TDD)</b>	
Region 1 (e.g. Europe and Africa)		Region 1 (e.g. Europe and Africa)	
1920-1980 MHz	Uplink	1900 – 1920 MHz	Uplink and Downlink
2110-2170 MHz	Downlink	2010 – 2025 MHz	
Region 2 (e.g. America)		Region 2 (e.g. America)	
1850-1910 MHz	Uplink	1850 – 1910 MHz	Uplink and Downlink
1930-1990 MHz	Downlink	1930 – 1990 MHz	
		1910 – 1930 MHz	

The WCDMA scheme has been selected for the frequency division duplex (FDD) mode of UMTS due to its service flexibility and improved performance over second generation systems. Despite the uplink capacity offered by WCDMA, the expected demand is likely to exceed the available resources. The capacity of a WCDMA mobile radio system on the uplink can be significantly increased by enhancing the receiver structure at the base station.

To understand the background of the differences between the second and third generation systems, we need to look at the new requirements of the third generation systems which are listed below [5]:

- Bit rates up to 2 MBps;
- Variable bit rate to offer bandwidth on demand;
- Multiplexing of services with different quality requirements on a single connection, e.g. speech, video and packet data.
- Delay requirements from delay-sensitive real time traffic to flexible best effort packet data.
- Quality requirements for 10 % frame error rate to  $10^{-6}$  bit error rate.
- Co-existence of second and third generation systems and inter-system handovers for coverage enhancements and load balancing.
- Support of asymmetric uplink and downlink traffic, e.g. web browsing causes more loading to downlink than to uplink.
- High Spectrum efficiency.

Table 2.2 lists the main difference between WCDMA and GSM, and Table 2.3 those between WCDMA and IS-95. In this comparison only the air interface is considered. GSM also covers services and core network aspects, and this GSM platform will be used together with the WCDMA air interface [5].

Table 2.2 Main differences between WCDMA and GSM air interfaces

	WCDMA	GSM
Carrier spacing	5 MHz	200 KHz
Frequency reuse factor	1	1-18
Power control frequency	1500 Hz	2 Hz or lower
Quality control	Radio resource management algorithms	Network planning (frequency planning)
Frequency diversity	5 MHz bandwidth gives multipath diversity with rake receiver	Frequency hopping
Packet data	Load-based packet scheduling	Time slot based scheduling with GPRS
Downlink transmit diversity	Supported for improving downlink capacity	Not supported by the standard, but can be applied

The differences in the air interface reflect the new requirements of the third generation systems. For example, the larger bandwidth of 5 MHz is needed to support higher data rates. Transmit diversity is included in WCDMA to improve the downlink capacity to support the asymmetric capacity requirements between downlink and uplink. Transmit diversity is not supported by second generation standards. The mixture of different bit rates, services and quality requirements in third generation systems requires advanced radio resource management algorithms to guarantee quality of service and to maximize system throughput. Also, efficient support of non real time packet data is important for the new services.

Table 2.3 Main differences between WCDMA and IS-95 air interfaces

	WCDMA	IS-95
Carrier spacing	5 MHz	1.25 MHz
Chip rate	3.84 Mcps	1.2288 Mcps
Power control frequency	1500 Hz, both uplink and downlink	Uplink:800 Hz, downlink: slow power control
Base station synchronization	Not needed	Yes typically obtained via GPS
Inter-frequency handovers	Yes, measurements with slotted mode	Possible, but measurement method not specified
Efficient radio resource management algorithms	Yes, provides required quality of service	Not needed for speech only networks
Packet data	Load-based packet scheduling	Packet data transmitted as short circuit switched calls
Downlink diversity	Supported for improving downlink capacity	Not supported by the standard

Both WCDMA and IS-95 utilize direct sequence CDMA. The higher chip rate of 3.84 Mcps in WCDMA enables higher bit rates. The higher chip rate also provides more multipath diversity than the chip rate of 1.2288 Mcps, especially in small urban cells and gives higher trunking gain, especially for high bit rates, than do narrowband second generation systems.

In a conventional CDMA system, each user is detected non-cooperatively treating all other users as noise. This basic scheme has a low implementation complexity but a limited overall spectral efficiency due to multiple-access interference (MAI). Higher spectral efficiency can be achieved by reducing the MAI. Interference cancellation is a very promising multiuser detection (MUD) technique for enhancing the interference limited uplink capacity of CDMA cellular systems. The major advantage of this scheme is its relatively low complexity compared to other MUD techniques. Interference cancellation receivers belong to the class of non-linear suboptimal MUD techniques and

their complexity is a linear function of the number of users compared to polynomial and exponential complexity for linear suboptimal and optimal MUD receivers, respectively. Interference cancellation can be done parallel to the users leading to Parallel Interference Cancellation (PIC) or serially leading to Successive Interference Cancellation (SIC). This work focuses on the performance evaluation of interference cancellation using multiuser receivers for the enhancement of the uplink capacity of the WCDMA FDD mode.

The performance of the WCDMA cellular radio network is highly dependent on the amount of interference in the system caused by the random time offsets between signals. High interference reduces cell size and increases the power outage probability of mobile users in the uplink. Interference is increased as the number of admitted users grows in the system [10].

At the moment, the Wideband Code Division Multiple Access (WCDMA) is largely preferred as the multiple access technology for 3G systems. Unlike the Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) schemes which rely on orthogonal user portioning in the time-frequency plane, wasting spectrum in between time/frequency channels, in CDMA the whole spectrum is available to each user and the separation is in the code domain, resulting in more bandwidth. The main attraction of CDMA is potential capacity, coverage and efficiency improvements.

However, despite its advantages, there are challenges in the design of WCDMA receivers due to complexities associated with the detection and degradation of performance due to the Multiple Access Interference (MAI), which limits the capacity of the system, performance not only degraded due to MAI, it is also affected by the channel fading due to multipath propagation.

## **2.3 Multiuser Detection System Overview**

Tight power control has been used to eliminate the near-far effect in IS-95 (CDMAone, one of 2nd Generation Systems). Another important approach, multiuser detection technique, has been developed in the recent years to solve the near-far problem and consequently increase the user capacity of the CDMA system. The optimal multiuser detector, which yields the minimum achievable probability of error (and optimum

asymptotic multiuser efficiency, as well as optimum near-far resistance) in CDMA channels, was presented and analyzed in [13]. But the complexity of the optimal multiuser detector increases exponentially with the number of users which makes it difficult to implement in the practical system. It triggered the new research effort on suboptimal multiuser detectors and serves as a baseline of comparison for suboptimal multiuser detectors [21].

The technique which is used to enhance the performance of uplink in this work mainly considers Multi-User Detection (MUD). In a conventional CDMA system, all users interfere with each other. Theoretically, significant capacity increase and near-far resistance can be achieved if the negative effect that each user has on the others can be minimized. A more fundamental view of this is multi-user detection, where the signals from different users are jointly used to better detect the signal from each individual user.

In a cellular system, a number of mobiles communicate with one base station (BS). Each mobile is concerned only with its own signal while the BS must detect all the signals. Thus, the mobile has information only about its own chip sequence while the base station has the knowledge of all the chip sequence. For this reason multiuser detection is being envisioned mainly for the BS, or in the Uplink (Mobile station to BS). It is important to realize, however, that the BS maintains information only on those mobiles in its own cell. This plays a role in the limitations on improvements to be expected in a MUD system [7].

Although the application of interference cancellation to multi-user systems is relatively new and unproven, other forms of interference cancellations have been in widespread use for years. Since the phrase has been used quite loosely, interference cancellation should be interpreted to mean the class of techniques that demodulate and/or decode desired information, and then use this information along with channel estimates to cancel received interference from the received signal. In other words, the front-end may have any type of structure, but for the system to be classified as interference cancellation, signal processing is used after detection to reduce the influence of the interference on future decisions [1].

### 2.3.1 Maximum-Likelihood Sequence Detection

The detector which yields the most likely transmitted sequence,  $\mathbf{d}$ , chooses  $\mathbf{d}$  to maximize the probability that  $\mathbf{d}$  was transmitted given that  $r(t)$  was received, where  $r(t)$  extends over the whole message. This probability is referred to as joint a posteriori probability,  $P(\mathbf{d} | \{r(t), \text{ for all } t\})$  [7]. Under the assumption that all possible transmitted sequences are equally probable, this detector is known as the maximum-likelihood sequence (MLS) detector [7].

In 1986, Sergio Verdu, one of the prominent scientist in the field of multiuser detection, showed that MAI has definite structure and it is possible to exploit this structure to perform a joint demodulation for all users, resulting in better performance [13]. However, his optimal maximum likelihood sequence estimator (MLSE) had a complexity that was exponential with the number of users, thus precluding it from practical implementation. However, his work spurred research into sub-optimal techniques, which attempted to provide a trade-off between implementation complexity and performance.

Another disadvantage of the MLS detector is that it requires knowledge of the received amplitudes and phases. These values, however, are not known a priori, and must be estimated. Despite the huge performance and capacity gains over conventional detection, the MLS detector is not practical. A realistic direct sequence system has a relatively large number of active users; thus, the exponential complexity in the number of users makes the cost of this detector too high [2].

The optimum multiuser demodulator can be obtained based on a maximum likelihood sequence detection formulation. If all the information matrices are equiprobable, the maximum likelihood sequence detector is obtained by maximizing the joint a posteriori probability [3]:

$$P[\mathbf{B} | \{r(t); t \in \mathcal{R}\}] \quad (2.1)$$

where,  $r(t)$  denotes the received signal,  $\mathbf{B}$  represents the information bit matrix, the  $(k,i)^{\text{th}}$  element of which is the  $i^{\text{th}}$  bit of the  $k^{\text{th}}$  user denoted as  $b_k^{(i)}$ . If the packet length of the information bit sequence of each user is  $(2P+1)$  and the number of users in the system is  $K$ , then an exhaustive maximization of the joint a posteriori probability needs its

computation for each of the  $2^{(2P+1)K}$  possible values of B. Such brute-force maximization is practically useless [3].

The drawback of optimal multiuser detection is one of complexity so that suboptimal approaches are being sought [4]. Therefore, interference cancellers, which have simple structures and low complexity, are proposed. Successive Interference Canceller (SIC) and Parallel Interference Canceller (PIC), which are the two main types of cancellers, estimate the MAI and subtract it from the received signal. By using an iterative approach, the MAI effects can be reduced or completely removed, that in turn results in better system performance.

### **2.3.2 Sub-optimal Detector**

Sub-optimal detectors are largely classified into two groups - Linear detectors and Interference Cancellers. Of these, the linear equalizer type detectors such as the decorrelator and the MMSE are still regarded to be too computationally complex for real-time implementation on current DSP.

Hence, presently, nonlinear suboptimum multi-user detectors; i.e. interference cancellation receivers both successive interference cancellation (SIC) and parallel interference cancellation (PIC) remain the most viable solution for 3G systems.

#### **2.3.2.1 Linear Detectors**

Linear techniques are simpler and require fewer assumptions, such as accurate knowledge of amplitude and phase information of the users to be canceled, than non linear interference cancellers. However, linear interference cancellation techniques require a fundamentally different CDMA system design philosophy than IS-95. In IS-95, the coding gain from error control codes bears the burden of handling interference, while a linear canceller uses dimensional separation of users [29]. The two most popular linear detectors are decorrelating and minimum mean-squared error detectors (MMSE).

### 2.3.2.1.1 Decorrelating Detector

The decorrelating detector applies the inverse of the correlation matrix  $L_{dec} = R^{-1}$ , to the matched filter output in order to decouple the data. It's optimal according to three different criteria: least-squares, near-far resistant and maximum-likelihood when the receiver powers are unknown.

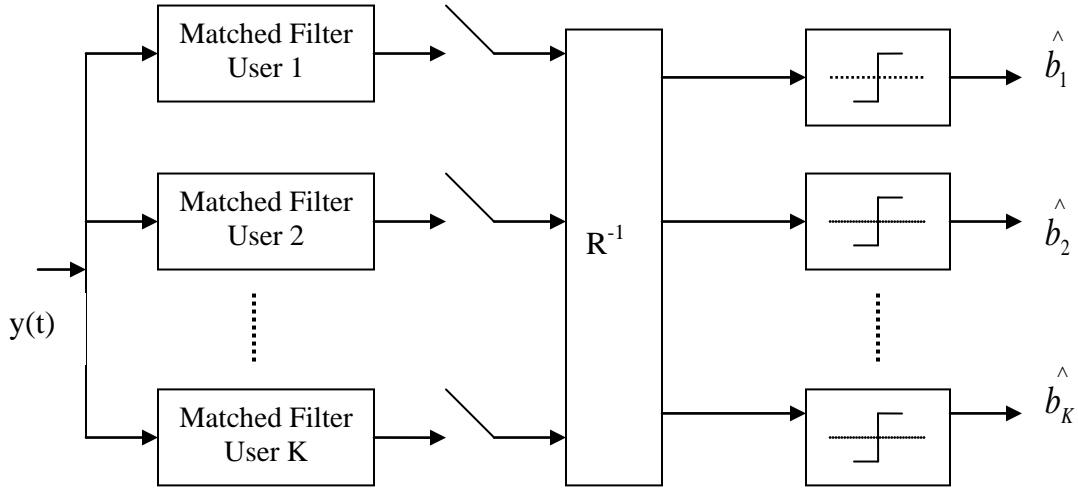


Figure 2.6. Decorrelating detector

$$\text{Since; } y = RA\mathbf{b} + \mathbf{z} \quad (2.2)$$

For a  $K$  user system, the vectors  $\mathbf{b}$ ,  $\mathbf{z}$ , and  $\mathbf{y}$ , are  $K$ -vectors that hold the data, noise, and matched filter outputs of all  $K$  users, respectively; the matrix  $A$  is a diagonal matrix containing the corresponding received amplitudes; the matrix  $R$  is a  $K \times K$  correlation matrix, whose entries contain the values of the correlations between every pair of codes, detail will be explained in signal model description at chapter 3.

From Eq. (2.2), the soft estimate of this detector is:

$$\hat{\mathbf{d}}_{dec} = R^{-1}\mathbf{y} = A\mathbf{d} + R^{-1}\mathbf{z} = A\mathbf{d} + \mathbf{z}_{dec} \quad (2.3)$$

This is just the decoupled data plus a noise term. Thus, we see that the decorrelating detector completely eliminates the MAI. However, the receiver considerably enhances the noise in the system. Bit decision after decorrelating detector is made by;

$$\begin{aligned}
 \hat{b}_k &= \text{sgn}((R^{-1}y))_k \\
 &= \text{sgn}((R^{-1}(RAb + n))_k) \\
 &= \text{sgn}((Ab + R^{-1}n)_k)
 \end{aligned} \tag{2.4}$$

Attractive properties of decorrelating detector are:

- It does not require the knowledge of the user's power, and its performance is independent of the power of the interfering users. The only requirement is the knowledge of timing which is necessary for the code spreading at the centralized receiver [4].
- Provides substantial performance/ capacity gains over the conventional detector.
- Does not need to estimate the received amplitudes. In contrast, detectors that require amplitude estimation are often quite sensitive to estimation error.
- Has computational complexity significantly lower than that of the maximum likelihood sequence detector. The per-bit complexity is linear in the number of users, excluding the costs of re-computation of the inverse mapping.
- Has a probability of error independent of the signal energies. This simplifies the probability of error analysis, and makes the decorrelating detector resistant to the near-far problem [2].

A disadvantage of this detector is that it causes noise enhancement. The power associated with the noise term  $R^{-1}$  at the output of the decorrelating detector is always greater than or equal to the power associated with the noise term at the output of the conventional detector. Despite the drawback, the decorrelating detector generally provides significant improvements over the conventional detector [2].

A more significant disadvantage of the decorrelating detector is that the computations needed to invert the Matrix  $R$  are difficult to perform in real time. For synchronous systems, the problem is somewhat simplified: we can decorrelate one bit at a time. In other words, we can apply the inverse of a  $K \times K$  correlation matrix. For asynchronous systems, however,  $R$  is of order  $NK$ , which is quite large for a typical message length,  $N$ .

### 2.3.2.1.2 Minimum Mean-Squared Error (MMSE) Detector

The Minimum Mean-Squared Error (MMSE) Detector is a linear detector which takes into account the background noise and utilizes knowledge of the received signal powers. This detector implements the linear mapping which minimizes  $E\|d - Ly\|^2$ , the mean-squared error between the actual data and the soft output of the conventional detector.

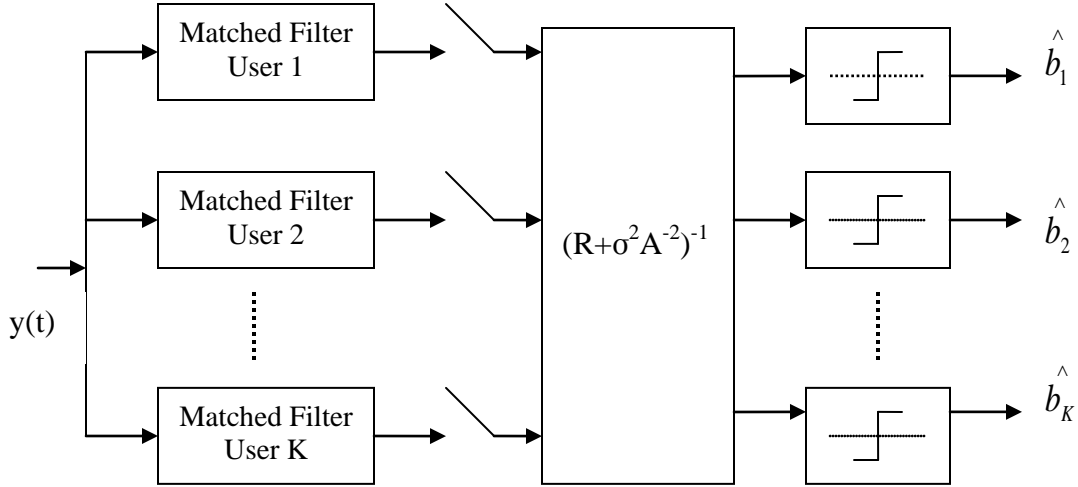


Figure 2.7. MMSE receiver

This results in:

$$L_{MMSE} = [R + (N_o / 2)A^{-2}]^{-1} \quad (2.5)$$

Thus, the soft estimate of the MMSE detector is simply

$$\hat{d}_{MMSE} = L_{MMSE} y \quad (2.6)$$

As can be seen, the MMSE detector implements a partial or modified 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 enhancements. Thus, the MMSE detector balances the desire to decouple the users (and completely eliminate MAI) with the desire not to enhance the background noise. Because it takes the background noise into account, the MMSE detector generally provides better probability of error performance than the decorrelating detector. As the background noise go to zero, the MMSE detector converges in performance to the deccorelating detector.

An important advantage of this detector is that, unlike the decorrelating detector, it requires estimation of the received amplitudes. Another disadvantage is that its performance depends on the powers of the interfering users [2].

Therefore, there is some loss of resistance to the near-far problem as compared to the decorrelating detector.

Like the decorrelating detector, the MMSE detector faces the task of implementing matrix inversion. So the decision bit for the  $k^{\text{th}}$  user is made based on

$$\begin{aligned}\hat{b}_k &= \text{sgn}(((R + \sigma^2 A^{-2})^{-1} y)_k) \\ &= \text{sgn}(((R + \sigma^2 A^{-2})^{-1} (RAb + n)_k))\end{aligned}\quad (2.7)$$

### 2.3.2.2 Non-linear Detectors

The nonlinear detectors are based primarily on subtractive interference cancellation method. The basic principle 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 seen by each user. Such detectors are implemented with multiple stages, where the expectation is that the decisions will improve at the output of successive stages.

#### 2.3.2.2.1 Successive Interference Cancellation

Successive Interference Cancellation (SIC): detects just one user per stage. The strongest received signal is detected first, then the next strongest, and so on. After each user's transmitted data is estimated, the received signal for that user can be reconstructed by recreating the transmit signal and applying an estimate of the channel to it. This can be subtracted from the composite received signal, which then allows subsequent users to experience a cleaner signal.

The successive interference canceller is a kind of nonlinear multiuser receivers which estimates and cancels multiple access interference successively using feedback. In the scheme, the received signal is first passed through a bank of matched filters. Then the user with the strongest correlation value (the correlations of each of the users' spreading

sequence  $S_k(t)$  with the received signal  $r(t)$  is selected for decoding. The signal of the user can be regenerated and subtracted from the received signal waveform.

$$r(t) = \sum_{k=1}^K A_k(t)s_k(t)b_k(t) + n(t), \quad t \in [0, T] \quad (2.8)$$

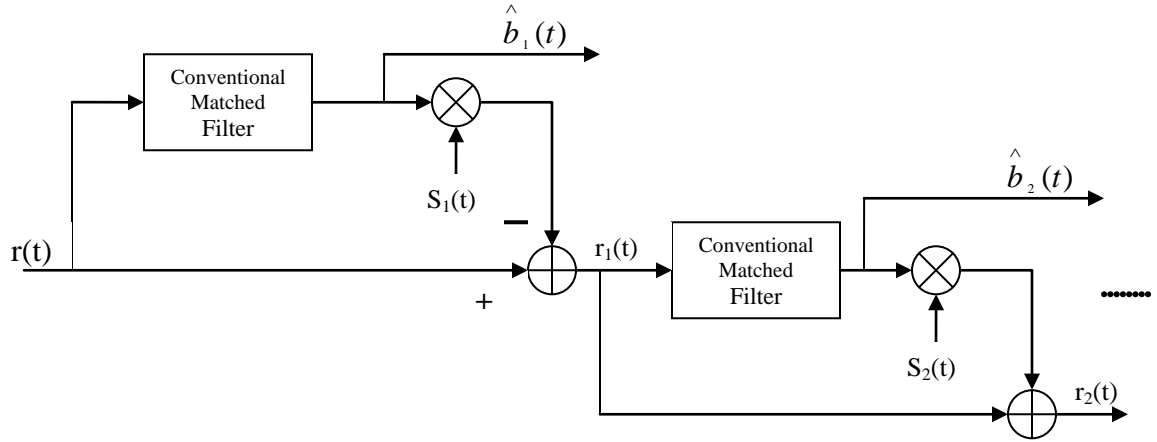


Figure 2.8: Successive Interference Cancellation

Assume the  $k^{\text{th}}$  user has the strongest correlation value,

$$\hat{r}(t) = r(t) - A_k(t)b_k(t)s_k(t) = \sum_{j=1, j \neq k}^K A_j b_j S_j(t) + A_k (b_k - \hat{b}_k) S_k(t) + n(t) \quad (2.9)$$

So this will cancel the interfering signal provided that the decision was correct. The process is repeated until the weakest user is decoded.

### 2.3.2.2.2 Parallel Interference Cancellation

Parallel Interference Cancellation (PIC): In contrast to the SIC detector, the parallel interference cancellation (PIC) detector estimates and subtracts out all of the MAI for each user in parallel. Parallel processing of multiuser interference simultaneously removes from each user the interference produced by the remaining users accessing the channel. In this way, each user in the system receives equal treatment insofar as the attempt is made to cancel multiuser interference.

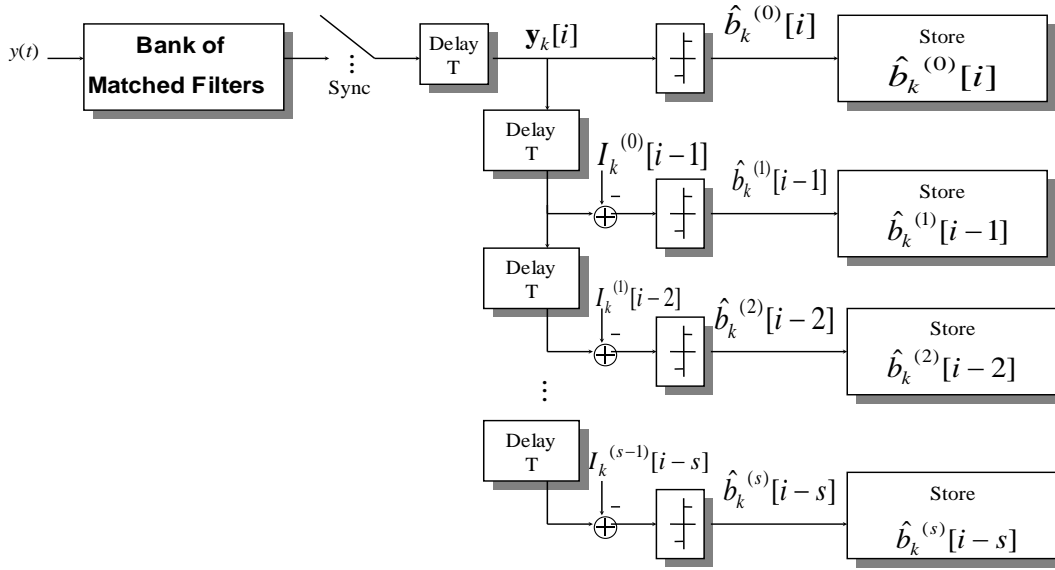


Figure 2.9: Parallel Interference Cancellation Scheme

In parallel interference cancellation (PIC), the estimated multi access interference (MAI) for each user is removed from the received signal during each cancellation stage. The estimated interference signal during each cancellation is obtained using the knowledge of spreading codes, channel fading, amplitude estimates and symbol estimates of the interfering users in the previous iteration [3]. As shown in Figure 2.8, bit decision for the  $s^{\text{th}}$  stage of cancellation is become:

$$\begin{aligned} \hat{b}_k^{(s)} &= \text{sgn}(y_k - I_k^{(s-1)}) \\ I_k^{(s-1)} &= \sum_{j \neq k} A_j \rho_{jk} \hat{b}_j^{(s-1)} \end{aligned} \quad (2.10)$$

where,

$\hat{b}_j^{(s-1)}$  is bit estimate of  $j^{\text{th}}$  user in the  $(s-1)^{\text{th}}$  stage of cancellation

$\rho_{jk}$  is crosscorrelation between user  $j$  and  $k$ .

$I_k^{(s-1)}$  is the estimated interference for  $k^{\text{th}}$  user in the  $(s-1)^{\text{th}}$  stage of cancellation.

The third generation (3G) of wireless communication systems, such as Wide-band Code Division Multiple Access (WCDMA), has been developed in the last decade. The high data rate of WCDMA allows users to have high quality data, video and audio streaming with a single mobile handset. However, with the same spectral efficiency as in second generation systems, the real Internet access will be only limited to professional users. Thus, Multiuser Detectors (MUD), which helps to improve spectral efficiency, may become very important in WCDMA systems. Rake receivers, which have been commonly used in CDMA systems, are severely affected by Multiple Access Interference (MAI). In contrast, the MUD reduces the MAI effects by jointly using information of multiple users. This increases system capacity, i.e. increases the maximum number of users in system [2].

## **2.4 Hybrid Multiuser Interference Cancellation**

Interference cancellers have been identified as the only multi-user detectors that are implementable by today's DSP standards, both the SIC and the PIC have their own pros and cons. Their relative advantages and disadvantages are rather complimentary, owing to the serial and parallel architectures employed by them. While the SIC has a good near-far resistance and it suffers from a very large decoding delay. On the other hand, the PIC though exhibiting minimal delay, it introduces a very high hardware cost apart from requiring reasonably good power control [26]. It would thus seem logical to combine the SIC and the PIC in an attempt to find a middle path solution, hence hybrid interference cancellation (HIC) technique that combines the advantages of both the successive interference canceller (SIC) and the parallel interference canceller (PIC) is the solution.

Successive interference cancellation yields better performance with lot of processing time and parallel interference cancellation is superior to SIC in terms of computation time but is inferior in terms of BER. Hence a mix of SIC and PIC will yield an optimal result. The main idea behind hybrid interference cancellation is that instead of canceling all  $K$  users either in series or in parallel, they are cancelled partially in parallel and partially in series [28]. The configuration for cancellation will be  $K$ - $P$ - $S$ , where  $K$  is the total number of users and the number cancelled in parallel and in series at each stage is denoted by  $P$  and  $S$ , respectively. The signals of the first  $P$  stronger users (out of  $K$ ) are chosen to perform

PIC between them. As a result of this action, the  $P$  most reliable users are chosen, and their signals reconstructed in order to subtract them from the buffered version of the received signal. Now, here ' $P$ ' signals are subtracted from the received signal. After that remaining  $K-S$  users are arranged according to their strength and one by one, users are detected, subtracted and ultimately using this SIC all the users are detected [28].

Obviously, HIC performs in an optimal way when compared with SIC and PIC. Many researchers worked on optimizing the value of  $P$  and  $S$ , but in this work choosing of  $P$  and  $S$  is in an optimistic way. Based on the type of service offered target BER is decided, based on the modulation scheme used SNR yielding the target BER is decided. This is used as a threshold to decide whether the user should be detected in PIC mode or SIC mode; i.e. those users having Signal-to-Interference-Ratio (SIR) greater than the threshold will be detected using PIC since it will yield the performance required and the remaining users are detected through SIC means. The HIC scheme in CDMA system provides a BER performance which is better than the PIC scheme but not to the extent of SIC scheme. The HIC scheme is an optimal scheme that is a good tradeoff between SIC and PIC scheme [28].

The performance of hybrid multiuser interference cancellation scheme in the case of each user in the same group having different received signal power is analyzed [27]. On the basis of this analysis, it is shown that the BER performance of the proposed HIC scheme is superior to that of the conventional matched filter. The smaller the power difference of users in same group, the better will be the performance of the HIC scheme. The conventional HIC divides the active users into groups of equal size and cancels the interferences. Therefore, the conventional HIC scheme experiences performance degradation due to the large difference in received signal powers when the power control is not applied or imperfect. Hence, it can be concluded that the performance of the HIC scheme will be improved by grouping the users to have similar Power [27].

## **2.5 Thesis Contribution**

The goal of this thesis is to highlight the performance evaluation of sub-optimum multiuser detectors, specifically subtractive interference cancellation methods; i.e., SIC and PIC. Using system model and computational complexity performance comparison findings, interference cancellation receivers achieves relative uplink system capacity and data rate improvement available for WCDMA systems.

In order to achieve the goal of multiuser detection, impairments due to multiple access interference (MAI) is mitigated with different models of sub-optimal multiuser detectors of which SIC and PIC are briefly studied and their performance comparison from the system model point of view and computational complexity is mentioned.

Performance evaluation of different types of receiver structures is beneficial to assure marketability, since the receiver must be inexpensive and have low power requirements. Therefore, in this work multiuser detection in general and interference cancellation in particular are discussed with simulation results. The work of this thesis is also reveals that performance of subtractive inference cancellation receivers remains the most viable solution for 3G system and beyond.

# Chapter 3

## 3. System Model Description for Interference Cancellation in CDMA Systems

In CDMA communication systems, all the subscribers share the common channel. The only way to distinguish them is to use orthogonal or nearly orthogonal codes (or so-called spreading sequences) to modulate the transmitted bits as shown in figure 3.1 below. Figure 2.3 in the previous chapter shows an example of the spreading result. The base station uses the knowledge of these codes to detect and estimate each user's bits.

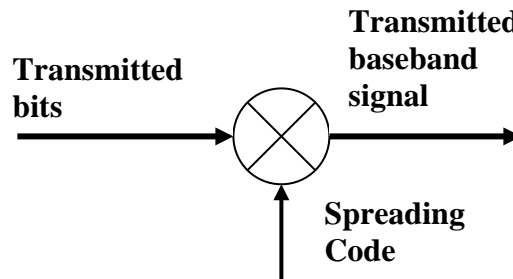


Figure 3.1: Generation of CDMA transmitted signals

Unlike TDMA (Time-Division Multiple Access) and FDMA (Frequency-Division Multiple Access), where each user is assigned a unique time slot or channel, users in CDMA experience direct interference from the other users. This is called MAI (multiple access interference), which is the major limitation in capacity for the current IS-95 CDMA standard. The other related problem is called the near-far problem [14]. When a user is far from the base station, it is likely that this signal would be overshadowed by the nearer users. In the IS-95 standard, perfect power control is utilized, which ensures that the received signal of any user within the cell is equal to each other. It requires a complicated control system on both base stations and mobile phones. Users at far end of the cell usually consume extremely large amount of power, which would inevitably shorten the battery life.

Basics of Multistage interference cancellation start from the conventional detector; but first we must define the mathematical system model. In a majority of CDMA systems of practical importance, the users transmit information independently. Therefore, the transmitted signals of different users arrive asynchronously at the receiver. Since their

relative time delays are arbitrary, it is inevitable that the cross-correlations among code waveforms for all relative time delays are obtained by the design of a set of complex code waveforms at the expense of an increased bandwidth. Since bandwidth is valuable resource, the problem of interest is to be able to accommodate as many users as can be reliably demodulated for a given bandwidth [3].

### 3.1 System Model

Assume a synchronous K-user communication system using BPSK modulation over an AWGN channel. The discrete received signal can be written in vector form as

$$r = \sum_{k=1}^K A_k b_k S_k + n.$$

In this system user  $k$ 's binary information symbol  $b_k \in \{-1, 1\}$  with

amplitude  $A_k$  is transmitted by multiplying with a spreading code

$$s_k = \begin{bmatrix} s_{k,1} \\ s_{k,2} \\ \vdots \\ s_{k,N} \end{bmatrix} = \{-1/\sqrt{N}, 1/\sqrt{N}\}^N, \text{ of length } N \text{ chips over an AWGN channel and multipath}$$

fading channel. The spreading codes transmitted by each user in any given symbol interval are assumed to be symbol synchronous, and the channel imposes no phase rotation on the transmitted signal. Symbol synchronism is assumed for clarity. Similar arguments hold for the symbol-asynchronous case. Details of system model for AWGN and multipath fading channel is described in section 3.2.1 and 3.2.2 respectively.

### 3.2 Channel Estimation Characterization

The wireless channel in mobile radio poses a great challenge as a medium for reliable high speed communications. When a radio signal is transmitted through a wireless channel, it suffers various types of distortions. When the signals are transmitted through mobile radio channel, it is affected by shadow or large scale fading; shadow fading reveals itself as an attenuation of the average signal power, it is induced by prominent terrain contours (hills, buildings, etc) between transmitter and receiver.

Hence, the receiver obtains a linear superposition of the signals transmitted by all the users, attenuated by arbitrary factors and delayed by an arbitrary amount. In addition, due to scattering and reflections from various obstacles between the transmitter and the receiver, multiple copies of the same signal reach the receiver and figure 3.2 shows the wireless propagation environment; i.e., scattering, shadowing, and reflectors between the user and the basestation. When the delay differences among various distinct propagation paths are very small compared with the symbol interval in digital transmission, the multipath components can add constructively or destructively, depending on the carrier frequency and delay differences. If the maximum differential delay spread is small compared with the symbol duration of the transmitted signal, the channel is said to exhibit flat fading. If the differential delay spread is large compared with the symbol interval, the channel exhibits frequency-selective fading. In addition, as the mobile station moves, the position of each scatterer with respect to the transmitter and receiver may change. The overall effect is that the received signal level fluctuates with time, a phenomenon called fading [15].

The detection of a particular user's transmitted bits involves the correlation of the received waveform with a copy of the corresponding spreading code at the receiver. Accurate correlation necessitates an accurate estimate of the user's timing offset. Once an initial estimate of each user's delay is calculated, the next task is to track these delays over the subsequent incoming bits. The two stage process of acquiring the users' timings from the baseband digital received signal, and tracking them as they change is called synchronization. In addition to the delays of the different propagation paths of the different users, certain advanced detection schemes also require estimates for the complex amplitudes of each path. Taken together, the estimation of all these parameters constitutes the channel estimation problem.

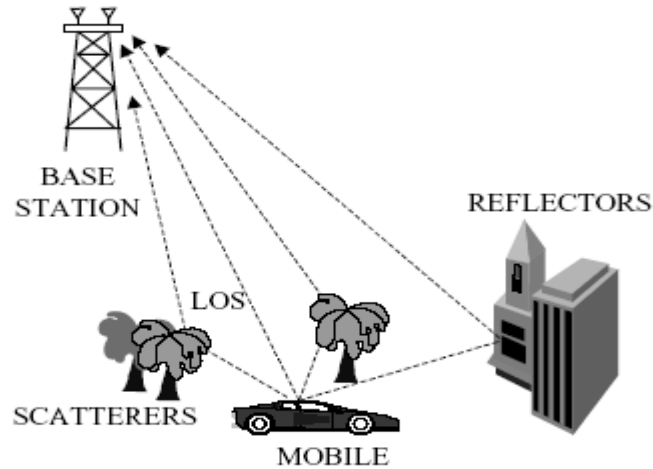


Figure 3.2: Wireless propagation environment

The proposed channel characterizations in this work from the transmitter end are AWGN channel and multipath fading channel.

### 3.2.1 Binary Signaling over AWGN Channel

We assume a K-user binary phase-shift keying (BPSK) modulated DS-CDMA communications system. To start with the channel is a single path channel with additive white Gaussian noise (AWGN). Figure 3.3 shows the structure of the multiuser communication system.

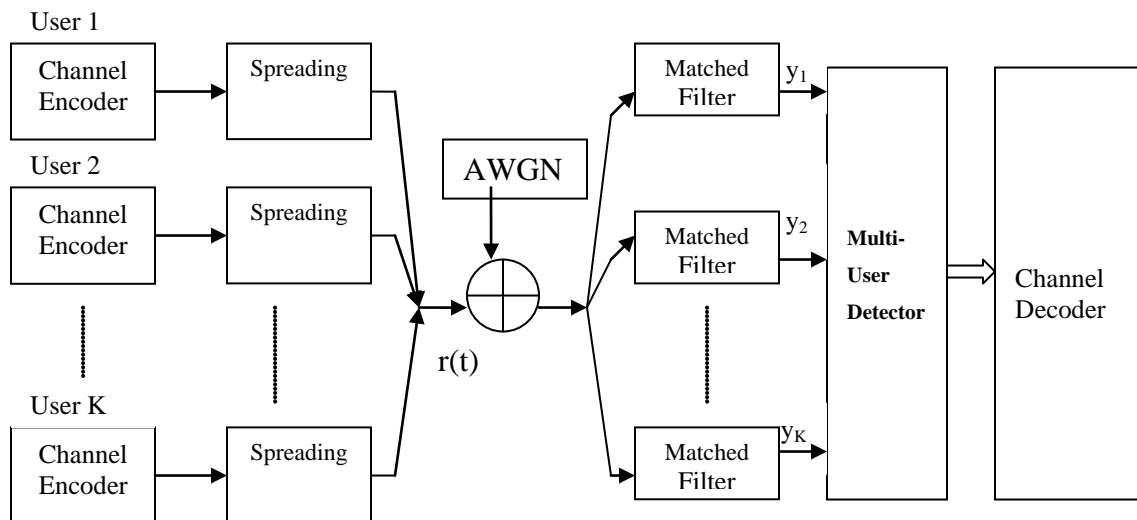


Figure 3.3: System diagram for a multiuser communication system with AWGN channel

We begin with a mathematical description of a synchronous DS-CDMA channel. In a synchronous channel all bits of all users are aligned in time. In practical DS-CDMA applications, however, the channel is generally asynchronous (i.e., signals are randomly delayed-offset from another). To simplify the discussion, we make the assumption that all carrier phases are equal to zero. This enables us to use baseband notation while working only with real signals. To further simplify matters, we also assume that each transmitted signals arrives at the receiver over a single path and that the data modulation is BPSK [7]. Figure 3.4 shows simplified CDMA channel model based on the above assumptions. Assuming there are  $K$  direct-sequence users in a synchronous single-path BPSK real channel, the baseband received signal can be expressed as:

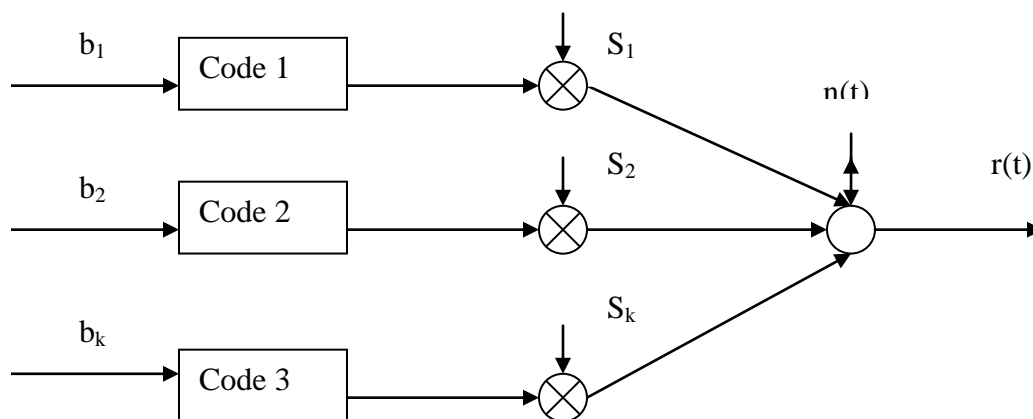


Figure 3.4: CDMA channel model

$$r(t) = \sum_{k=1}^K A_k(t) s_k(t) b_k(t) + n(t) \quad (3.1)$$

where,  $A_k(t)$ ,  $s_k(t)$ , and  $b_k(t)$  are the amplitude, signature code waveform, and modulation of the  $k^{\text{th}}$  user, respectively, and  $n(t)$  is additive white Gaussian noise (AWGN), with a two-sided power spectral density of  $N_o/2$  W/Hz. The power of the  $k^{\text{th}}$  signal is equal to the square of its amplitude, which is assumed to be constant over a bit interval. The modulation consists of rectangular pulses of duration  $T_b$  (bit interval), which take on  $b_k = \pm 1$  values corresponding to the transmitted data. We assume a total of  $N$  transmitted bits. The code waveform consists of rectangular pulses of duration  $T_c$  ('chip' interval), which

pseudo-randomly take on  $\pm 1$  values, corresponding to some binary “pseudo-noise” (PN) code sequence. The rate of the code waveform,  $f_c = 1/T_c$  (chip rate), is much greater than the bit rate,  $f_b = 1/T_b$ . Thus multiplying the BPSK signal at the transmitter by  $s(t)$  has the effect of spreading it out in frequency by a factor of  $f_c/f_b$ , (hence, the codes are sometimes referred to as “the spreading codes”). The frequency spread factor of a direct-sequence system is referred to as the processing gain, PG.

### 3.2.2 Conventional Detection

The conventional detector is also called the matched filter receiver, since it is matched to the desired user's spreading signal. For the received signal described in Eq.(3.1) a bank of  $K$  matched filters, are shown in Fig.3.5, below.

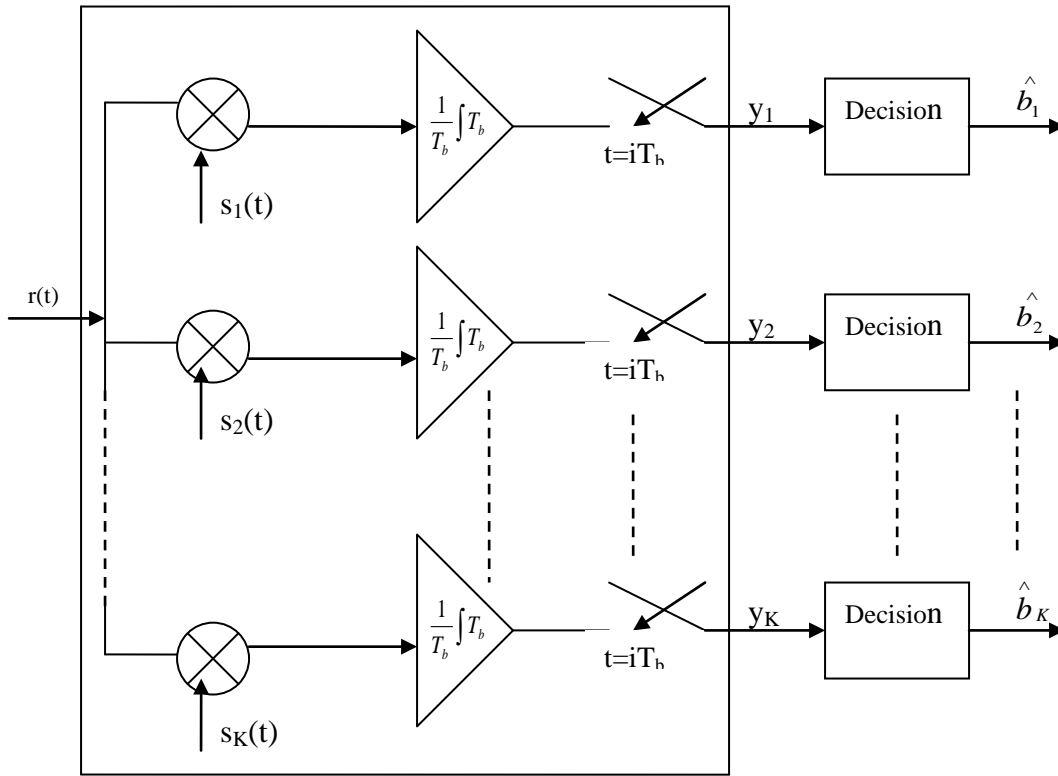


Figure 3.5: Conventional DS-CDMA detector: a bank of matched filters

Here, each code waveform is regenerated and correlated with the received signal in a separate detector branch. The correlation detector can be equivalently implemented through what is known as matched filtering [7]; thus, the conventional detector often referred to as the matched filter detector. The outputs of the correlators (or matched

filters) are sampled at the bit time, which yields “soft” estimates of the transmitted data. The final  $\pm 1$  “hard” data decisions are made according to the signs of the soft estimates [2].

It is clear from Fig.3.4 that the conventional matched filter follows a single-user detector strategy; each branch detects one user without regard to the existence of the other users. Thus, there is no sharing of multiuser information or joint signal processing (i.e., multi-user detection). The success of this detector depends on the properties of the correlation between codes. We require the correlations between the same code waveforms (i.e., the autocorrelations) to be much larger than the correlations between different codes (i.e., the cross-correlations). The correlation value is defined as

$$\rho_{i,k} = \frac{1}{T_b} \int_{T_b} s_i(t) s_k(t) dt \quad (3.2)$$

Here, if  $i=k$ ,  $\rho_{k,k}=1$ , (i.e., the integrand must be equal to one since  $s_i(t) = \pm 1$ ), and if  $i \neq k$ ,  $0 \leq \rho_{i,k} < 1$ . The output of the  $k^{\text{th}}$  user’s correlator for a particular bit interval is:

$$\begin{aligned} y_k &= \frac{1}{T_b} \int_{T_b} r(t) s_k(t) dt = A_k b_k + \sum_{\substack{i=1 \\ i \neq k}}^K \rho_{i,k} A_i b_i + \frac{1}{T_b} \int_{T_b} n(t) s_k(t) dt \\ &= A_k b_k + MAI_k + z_k \end{aligned} \quad (3.3)$$

Note that  $y_k$  consists of three terms. The first term  $A_k b_k$  is the desired information which gives the sign of the information bit  $b_k$  (which is exactly what is sought). The second term is the result of Multiple Access Interference (MAI), and the last is due to the noise that one would like to remove its influence. Its influence is felt through the cross correlations between the chip sequence and the power of users. If one knew the cross-correlations and the powers, then one could attempt to cancel the effect of one user upon another. This is in fact, the intuitive motivation for interference cancellation schemes [4].

In other words, *correlation with the  $k^{\text{th}}$  user itself give rise to the recovered data term, correlation with all the other users give rise to multiple access interference (MAI), and correlation with the thermal noise yields the noise term  $z_k$* . Since codes are generally designed to have very low cross correlations relative to autocorrelations (i.e.,  $\rho_{i,k} \ll 1$ ),

the interference effect on user  $k$  of the other direct-sequence users is greatly reduced. The bit decision after the output of the matched filter is made by:

$$\hat{b}_k = \text{sign}(y_k) \quad (3.4)$$

Where,  $\text{SIGN}(X)$  is Signum function, for each element of  $X$ , returns 1 if the element is greater than zero, 0 if it equals zero and -1 if it is less than zero. For the nonzero elements of complex  $X$ ,  $\text{SIGN}(X) = X ./ \text{ABS}(X)$ .

Nevertheless, the existence of MAI has a significant impact on the capacity and performance of the conventional direct-sequence systems. As the number of interfering users increases, the amount of MAI increases. In addition, the presence of strong (large-amplitude) users exacerbates the MAI of the weaker users. Thus, the overall effect of MAI on the system performance is even more pronounced if the user's signals arrive at the receiver at different powers. Such a situation arises when the transmitters have different geographical locations relative to the receiver, because the signals of the closer transmitting users undergo less amplitude attenuation than the signals of users that are further away. This is known as the near-far problem. In discussing multiuser detection, it is convenient to introduce a matrix-vector system model to describe the output of the conventional detector. We begin with a simple example to help illustrate our discussion: a three user synchronous system.

From Eq.( 3.1), the output for each of the users for one bit is:

$$\begin{aligned} y_1 &= A_1 b_1 + \rho_{2,1} A_2 b_2 + \rho_{3,1} A_3 b_3 + z_1 \\ y_2 &= \rho_{1,2} A_1 b_1 + A_2 b_2 + \rho_{3,2} A_3 b_3 + z_2 \\ y_3 &= \rho_{1,3} A_1 b_1 + \rho_{2,3} A_2 b_2 + A_3 b_3 + z_3 \end{aligned} \quad (3.5)$$

This can be written in the matrix-vector form as:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} 1 & \rho_{2,1} & \rho_{3,1} \\ \rho_{1,2} & 1 & \rho_{3,2} \\ \rho_{1,3} & \rho_{2,3} & 1 \end{bmatrix} \begin{bmatrix} A_1 & 0 & 0 \\ 0 & A_2 & 0 \\ 0 & 0 & A_3 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} \quad (3.6)$$

or,

$$\mathbf{y} = \mathbf{RAB} + \mathbf{n} \quad (3.7)$$

For a K user system, the vectors  $\mathbf{b}$ ,  $\mathbf{n}$ , and  $\mathbf{y}$ , are K-vectors that hold the data, noise, and matched filter outputs of all K users, respectively; where  $\mathbf{R}$  is the normalized cross correlation matrix whose diagonal elements are equal to one and whose off-diagonal elements are equal to the cross correlation  $\rho_{i,j}$ , the matrix  $\mathbf{A}$  is a diagonal matrix containing the corresponding received amplitudes:  $\mathbf{A} = \text{diag}\{A_1, \dots, A_k\}$ ;  $\mathbf{y} = [y_1, \dots, y_k]^T$ ;  $\mathbf{b} = [b_1, \dots, b_k]^T$  and  $\mathbf{n}$  is a Gaussian random vector with zero mean and covariance matrix  $\sigma^2 \mathbf{R}$ . The matrix  $\mathbf{R}$  is a K x K correlation matrix, whose entries contain the values of the correlations between every pair of codes. Note that since  $\rho_{i,k} = \rho_{k,i}$ , the matrix  $\mathbf{R}$  is clearly symmetric. It is instructive to break up  $\mathbf{R}$  in two matrices: one representing the autocorrelations, the other the cross correlations. Therefore parallel to Eq.(3.7), the conventional matched filter detector output can be expressed as three terms:

$$\mathbf{y} = \mathbf{A}\mathbf{b} + \mathbf{Q}\mathbf{A}\mathbf{b} + \mathbf{z} \quad (3.8)$$

where,  $\mathbf{Q}$  contains the off-diagonal elements (crosscorrelations) of  $\mathbf{R}$ , that is,  $\mathbf{R} = \mathbf{I} + \mathbf{Q}$  ( $\mathbf{I}$  is identity matrix). The first term,  $\mathbf{A}\mathbf{b}$ , is simply the decoupled data weighted by the received amplitudes. The second term,  $\mathbf{Q}\mathbf{A}\mathbf{b}$ , represents the MAI interference.

In the case of Asynchronous channel, the continuous-time model expressed in Eq.(3.1) can be modified by including the relative time delays (offsets) between signals. The received signal is now written as [2]:

$$r(t) = \sum_{k=1}^K A_k(t) s_k(t - \tau_k) b_k(t - \tau_k) + n(t) \quad (3.9)$$

where,  $\tau_k$  is the delay for user k.

Consider an asynchronous CDMA system over a multipath fading channel. The received signal  $r(t)$ , can be expressed as:

$$r(t) = \sum_{k=1}^K \sum_{l=1}^L A_{k,l}(t) s_k(t - \tau_{k,l}) b_k(t) + n(t) \quad (3.10)$$

Where K is the number of user in the system, L is the number of paths in the channel,  $b_k(t)$  is the information signal ( $\pm 1$ ) of the k<sup>th</sup> user,  $s_k(t)$  is the spreading sequence of the k<sup>th</sup> user,  $A_{k,l}(t)$  is the time varying fading amplitude of the l<sup>th</sup> path of the k<sup>th</sup> user and  $n(t)$  is the additive white Gaussian noise. The spreading sequence  $s_k(t)$  is chosen to have periods

much larger than a bit duration and is chosen to be composed of rectangular pulses.

The detection problem in an asynchronous channel is more complicated than in a synchronous channel. In a synchronous channel, by definition, the bits of each user are aligned in time. Thus, detection can focus on one bit interval independent of others; the detection of  $N$  bits of  $K$  users is equivalent to  $N$  separate “one-shot” detection problems. In most realistic applications, however, the channel is asynchronous and thus, there is overlap between bits of different intervals [2]. Here, any decision made on a particular bit ideally needs to take into account the decisions on the two overlapping bits of each user; the decisions on these overlapping bits must then further take into account decisions on bits that overlap with them and so on. Therefore, the detection problem must optimally be framed over the whole message.

### 3.2.3 Subtractive Interference cancellation

An important group of detectors can be classified as subtractive interference cancellation detectors. The basic principle 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 seen by each user. Such detectors are often implemented using multiple stages, where the expectation is that the decisions will improve at the output of successive stages.

The bit decisions used to estimate the MAI can be hard or soft. The soft-decisions approach uses soft data estimates for the joint estimation of the data and amplitudes, and is easier to implement. The hard-decisions approach feeds back a bit decision and is nonlinear; it requires reliable estimates of the received amplitudes in order to generate estimates of the MAI. If reliable amplitude estimation is possible, hard-decision subtractive interference cancellation detectors generally outperforms their soft-decision counterparts [2].

General algorithms for interference cancellation consider the received signal  $r$  as:

$$r = SAb + n \quad (3.11)$$

where  $S$ ,  $A$ , and  $b$  are the signature code wave form, amplitude and modulated symbol of the  $k^{\text{th}}$  user, respectively, and  $n$  is AWGN with the usual notation. If we single out the  $k^{\text{th}}$

symbol  $b_k$  in  $\mathbf{b}$  as the symbol of interest, we can separate the desired component of the signal from the interference as:

$$r = A_k b_k s_k + \sum_{j \neq k} A_j b_j s_j + n \quad (3.12)$$

For totally MAI-free detection, assuming that we know the symbols were transmitted by the interfering users, we would operate on

$$r_k = r - \sum_{j \neq k} A_j b_j s_j \quad (3.13)$$

To be specific, matched filtering of  $r_k$  with  $s_k$  will yield single-user performance. But we can possibly have tentative decisions about  $\{b_j\}_{j \neq k}$ , which are denoted for now by  $\tilde{b}_j$ , and thus form

$$r_k = r - \sum_{j \neq k} A_j \tilde{b}_j s_j \quad (3.14)$$

as long as we know the channels and spreading codes of all interfering users' valid assumption for base station receivers can be made.

It is from this common-basic starting point that we begin our study of interference cancellation in CDMA. The multiple detectors that belong in this class can be said to differ only in the manner in which the tentative bit decisions  $\tilde{b}_j$  are obtained.

### 3.2.3.1 Successive Interference Cancellation (SIC)

The successive interference cancellation (SIC) detector takes a serial approach to cancel interference from the system. The SIC detector [2] takes a serial approach to canceling interference as shown in Fig. 3.5. The first operation in the SIC detector consists of sorting out the users' signals in a descending order according to their powers (not shown) which are estimated from the output of the conventional detector. The first stage in this detector is to regenerate the transmitted signal of the strongest user (in terms of powers and assuming knowledge of the spreading code). This regenerated signal provides an estimate of the MAI caused by the strongest user,  $b_1(t)$ , which is then subtracted from the total received signal  $r(t)$ , yielding a partially cleaned version of the received signal  $r_1(t)$ . If the user estimate is accurate, the remaining users see less MAI in the next

stages. Thus, this new version of the received signal can be used to detect the next strongest user in the system. This process is repeated until all users are detected. Note that in each stage the estimate of the users are obtained by making a decision at the output of the conventional detector. The benefit of sorting the signals out in a descending order of power is because the strongest users can give the most accurate estimate and consequently the removal of this signal will provide the most benefit to the remaining users.

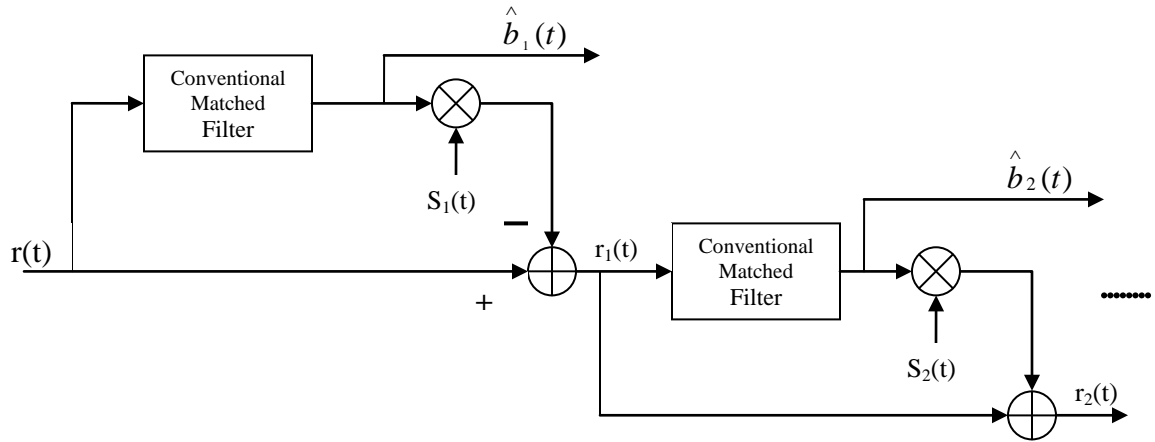


Figure 3.6: SIC Detection

where,  $r(t)$ : total received signal

$s_1(t)$ : Spreading code for the strongest power of user 1

$\hat{b}_1(t)$ : estimated user symbol of the strongest user 1

$r_1(t)$ : partially cleaned version of the received signal after detection of user 1

The SIC detector requires only a minimal amount of additional hardware and has the potential to provide significant improvement over the conventional detector. It does, however, pose a couple of implementation difficulties. First, one additional bit delay is required per stage of cancellation. Thus, a trade-off must be made between the number of users that are canceled and the amount of delay that can be tolerated. Second, there is a need to reorder the signals whenever the profile changes.

Here, too, a trade-off must be made between the precision of the power ordering and acceptable processing complexity. A potential problem with the SIC detector occurs if the initial data estimates are not reliable. In this case, even if the timing, amplitude, and phase estimates are perfect, if the bit estimate is wrong, the interfering effect of that bit

on the signal-to-noise ratio is quadrupled in power (the amplitude doubles, so the power quadruples) [2]. Thus, a certain minimum performance level of the conventional detector is required for the SIC detector to yield improvements; it is crucial that the data estimates of at least the strongest users that are canceled first be reliable.

### 3.2.3.1.1 Mathematical Algorithm for SIC

Assume that we have sorted  $K$  users so that the strongest user is user 1, and the weakest is user  $K$ . By “strong” and “weak”, what we really mean is largest signal to interference ratio (SIR) and smallest SIR respectively. In the first stage of the SIC, we detect one user at a time, starting with the strongest, form a tentative decision for that user, and then subtract its contribution from the total received signal  $r$ , before repeating the process with the next user.

Notice that in the first stage, the SIC does not attempt to cancel interference from users “below” the present user, i.e. users  $k+1$  to  $K$  when detecting user  $k$ . This is because we do not yet have any tentative decisions for those users. At the end of the first stage, after the  $k^{\text{th}}$  user has been detected and cancelled, we have the residual signal

$$r_{1,k} = r - \sum_{j=1}^K A_j b_{1,j} s_j \quad (3.15)$$

which, assuming  $\tilde{b}_{1,j} = b_j$ , contains no signal term at all. Note the insertion of the subscript “1” in the above equation, to denote the stage number. Given that the first  $K-1$  users did not benefit from full interference cancellation, having only enjoyed the removal of interfering signals from users ranked above them, it is reasonable to believe that a second stage of interference cancellation will be beneficial. To design the second stage, consider the detection of the first user, using Eq. (3.13), i.e.,

$$r_k = r - \sum_{j \neq k} A_j \tilde{b}_j s_j ; \text{ with } \tilde{b}_j = \tilde{b}_{1,j}, j = 2, \dots, K \text{ since these are the best interference}$$

estimates for user 1 at the second stage. We must thus form the signal:

$$r_{2,1} = r - \sum_{j=2}^K A_j \tilde{b}_{1,j} s_j \quad (3.16)$$

and, this may be re-written more conveniently as:

$$r_{2,1} = r - \sum_{j=1}^K A_j \tilde{b}_{1,j} s_j + A_1 \tilde{b}_{1,1} s_1 \quad (3.17)$$

$$= r_{1,k} + A_1 \tilde{b}_{1,1} s_1 \quad (3.18)$$

In words,  $r_{2,1}$  is the sum of the residual signal from the first stage and the tentative decision for bit  $b_1$  after it has been "re-spread". From  $r_{2,1}$  we form the tentative decision for  $b_1$  in the second stage,  $\tilde{b}_{2,1}$ . With  $\tilde{b}_{2,1}$  in hand, we form the signal  $r_{2,2}$  for the detection of the second user in the second stage, like so:

$$r_{2,2} = r - A_1 \tilde{b}_{2,1} s_1 - \sum_{j=3}^K A_j \tilde{b}_{1,j} s_j \quad (3.19)$$

$$= r_{2,1} - A_1 \tilde{b}_{2,1} s_1 + A_2 \tilde{b}_{1,2} s_2 \quad (3.20)$$

As with user 1, the tentative decision for user 2 in the second stage is  $\tilde{b}_{2,2}$ . To detect user 3, we form  $r_{2,3}$  by subtracting the latest interference estimate of user 2 from  $r_{2,2}$  and adding user 3's interference estimate from stage 1:

$$r_{2,3} = r_{2,2} - A_2 \tilde{b}_{2,2} s_2 + A_3 \tilde{b}_{1,3} s_3 \quad (3.21)$$

A clear pattern is now emerging, which can be generalized to these two steps for the  $k^{\text{th}}$  user in the  $m^{\text{th}}$  stage:

$$r_{m,k} = r_{m,k-1} - A_{k-1} \tilde{b}_{m,k-1} s_{k-1} + A_k \tilde{b}_{m-1,k} s_k \quad (3.22)$$

$$= e_{m,k} + A_k \tilde{b}_{m-1,k} s_k \quad (3.23)$$

Here, it is to be understood that  $b_{0,k} = 0$  and  $r_{1,0} = e_{1,1} = r$ . The most interesting feature of this detector is that, for any  $m$  and  $k$ , the signal processing required does not change. This means that a standard "Interference Cancellation Unit" (ICU) may be defined and plugged into a modular design as required to accommodate more users, or more stages.

### 3.2.3.2 Parallel Interference Cancellation (PIC)

In contrast to the SIC detector, the parallel interference cancellation (PIC) detector estimates and subtracts out all of the MAI for each user in parallel. If the power and codes of all interfering users are known, the PIC detector [2, 3] yields an estimate of all MAI for each user and then subtracts them in a parallel scheme. Fig 3.6 shows one stage of a PIC detector for  $K$  users. The initial bit estimates,  $\hat{b}_k(t)$  for  $k \in \{1, 2, \dots, K\}$ , are provided by the output of a bank of matched filter. These estimates are then re-spread and added to regenerate the MAI estimates for each user. As shown in Fig.3.6, interference cancellation is then performed on the received signal to provide the input to a second bank of conventional detectors. Thus, a new set of soft estimates are yielded by the second bank of conventional detectors in this first stage of parallel cancellation. The process can be repeated for multiple stages by taking the estimates at the output of one stage as the input of a new stage of parallel cancellation.

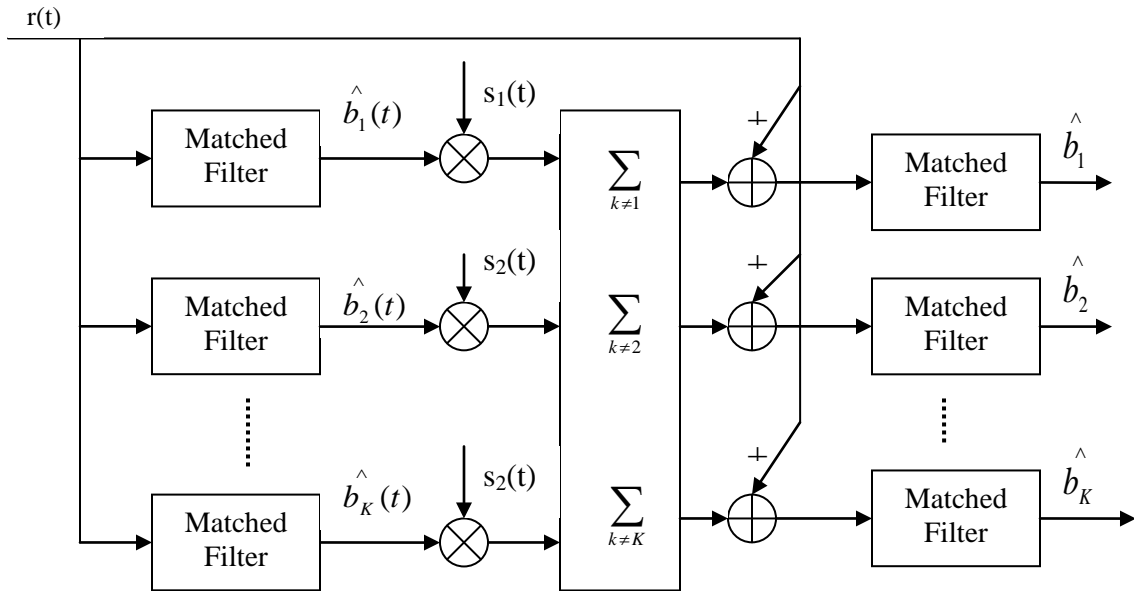


Figure 3.7: First stage of a PIC detector for  $K$  users

The initial bit-estimates,  $\hat{b}_i(0)$ , are derived from the matched filter detector, which refer to as stage 0 of this detector. These bits are then scaled by the amplitude estimates and respread by the signature codes, which produces a delayed estimate of the received signal

for each user. Assuming perfect amplitude and delay estimation, the result after subtracting the MAI estimate for user  $k$  is:

$$\begin{aligned}
r(t - T_b) - \sum_{i \neq k}^K \hat{s}_i(t - T_b) = & \\
b_k(t - \tau_k - T_b) A_k(t - \tau_k - T_b) s_k(t - \tau_k - T_b) + n(t - T_b) & \quad (3.24) \\
+ \sum_{i \neq k}^K \left( b_i(t - \tau_i - T_b) - \hat{b}_i(t - \tau_i - T_b) \right) A_i(t - \tau_i - T_b) s_i(t - \tau_i - T_b) &
\end{aligned}$$

As shown in Fig. 3.6, the result of Eq. (3.24) (for  $k=1 \dots K$ ) is passed on to a second bank of matched filters to produce a new, hopefully better, set of data estimates [2].

This process can be repeated for multiple stages. Each stage takes as its input the data estimates of the previous stage and produces a new set of estimates at its output.

We can use a matrix-vector formulation to compactly express the soft output of stage  $m+1$  of the PIC detector for all  $N$  bits of all  $K$  users as:

$$\hat{d}(m+1) = y - QA\hat{d}(m) = Ad + AQ(d - \hat{d}(m)) + z \quad (3.25)$$

The term  $QA\hat{d}(m)$  represents an estimate of the MAI (7). (As usual, for BPSK, the hard data decisions,  $\hat{d}(m)$ , are made according to the signs of the soft outputs,  $\hat{d}(m)$ ). Perfect data estimates, coupled with our assumption of perfect amplitude and delay estimation result in the complete elimination of MAI.

Parallel processing of multiuser interference simultaneously removes from each user the interference produced by the remaining users accessing the channel. In this way, each user in the system receives equal treatment insofar as the attempt is made to cancel his or her multiple-user interference. As compared with the serial processing scheme, since the IC is performed in parallel for all users, the delay required to complete the operation is at most a few bit times [8].

### 3.2.3.2.1 Mathematical Algorithm for PIC

Parallel interference cancellation uses the same general idea of Eq.(3.14), except that interference estimates are obtained simultaneously, for all users in the system, through a bank of detectors operating in parallel.

Assuming a bank of conventional detectors is used, for the first stage and  $k^{\text{th}}$  user we have no MAI cancellation for any user. However, we can now form the following K signals for use in the second stage:

$$r_{2,k} = r - \sum_{j \neq k} A_j \tilde{b}_{1,j} s_j \quad (3.26)$$

$$= r - \sum_{j=1}^k A_j \tilde{b}_{1,j} s_j + A_k \tilde{b}_{1,k} s_k \quad (3.27)$$

$$= e_1 + A_k \tilde{b}_{1,k} s_k \quad (3.28)$$

for  $k = 1, \dots, K$ , where  $e_1 = r - \sum_{j=1}^k A_j \tilde{b}_{1,j} s_j$  is a sort of residual signal that comes from subtracting all signal-component estimates from the received signal. Without difficulty, we can derive the two operations needed in the  $m^{\text{th}}$  stage for the  $k^{\text{th}}$  symbol:

$$r_{m,k} = e_{m-1} + A_{k-1} \tilde{b}_{m-1,k} s_k \quad (3.29)$$

Where,  $r_{1,k} = e_0 = r$ , for all  $k$ . The residual signal  $e_m = r - \sum_{j=1}^k A_j \tilde{b}_{m,j} s_j$  is then created for use in the next stage. Again, just as with the SIC, we note the modular nature of the detector structure, which is an important feature when it comes to implementation.

The entire concept of interference cancellation is based on the premise that the received signal can be reliably estimated. Whereas communication systems are by definition designed to allow the transmitted signal to be recovered, reconstructing the received signal requires accurate description of both what was transmitted and what the channel did to that transmission. Inaccurate channel estimation is a problem for both PIC and SIC, especially for SIC, since historically the optimal received power distribution is based on the assumption that interference has been completely cancelled, which is never fully achieved in practice. This residual interference then causes later users to have

unacceptably bad performance, causing a major fairness problem as well as an overall degradation in bit error rate and system capacity [1].

### 3.2.4 Binary Signaling over a Rayleigh Fading Channel

In a mobile radio environment, we have additional effect to consider, namely the fluctuations in the amplitude and phase of the received signal due to the multipath effects. To be specific, consider the transmission of binary data over Rayleigh fading channel, for which the (low-pass) complex envelope of the received signal is modeled as follows [16].

$$\hat{x}(t) = \alpha e^{-j\phi} \hat{s}(t) + \hat{\omega}(t) \quad (3.30)$$

Where  $\hat{s}(t)$  is the complex envelope of the transmitted signal,  $\alpha$  is a Rayleigh distributed random variable describing the attenuation in transmission,  $\phi$  is a uniformly distributed random variable describing the phase-shift in transmission, and  $\hat{\omega}(t)$  a complex valued white Gaussian noise process. It is assumed that the channel is flat in both time and frequency, so that we can estimate the phase-shift  $\phi$  from the received signal without error. Suppose then that the coherent binary phase-shift keying is used to do the data transmission. Under the condition that  $\alpha$  is fixed or constant over the bit interval, and expressing the probability of symbol error (i.e., bit error rate) due to the AWGN acting alone as follows:

$$P_e(\gamma) = \frac{1}{2} \text{erfc}(\sqrt{\gamma}) \quad (3.31)$$

where,  $\gamma$  is an attenuated version of the transmitted signal energy per-bit to noise spectral density ratio  $E_b/N_o$ , as shown by

$$\gamma = \frac{\alpha^2 E_b}{N_o} \quad (3.32)$$

Now, insofar as a mobile radio channel is concerned, we may view  $P_e(\gamma)$  as a conditional probability given that  $\alpha$  is fixed. Thus, to evaluate the average probability of symbol error in the combined presence of fading and noise, we must average  $P_e(\gamma)$  over all possible values of  $\gamma$  as shown by:

$$P_e = \int_0^{\infty} P_e(\gamma) f(\gamma) d\gamma \quad (3.33)$$

Where  $f(\gamma)$  is the probability density function of  $\gamma$ . From Eq. (3.32) we note that  $\gamma$  depends on the squared value of  $\alpha$ . In particular, we may express the probability density function of  $\gamma$  as:

$$f(\gamma) = \frac{1}{\gamma_o} e^{-\frac{\gamma}{\gamma_o}}, \quad \gamma \geq 0 \quad (3.34)$$

The term  $\gamma_o$  is the mean value of the received signal energy per bit-to-noise spectral density ratio, which is defined by

$$\gamma_o = E[\gamma] = \frac{E_b}{N_o} E[\alpha^2] \quad (3.35)$$

Where  $E[\alpha^2]$  is the mean square value of Rayleigh-distributed random variable  $\alpha$ . Substituting Eq. (3.31) and (3.34) into (3.33), and carrying out the integration, we get the final result:

$$P_e = \frac{1}{2} \left( 1 - \sqrt{\frac{\gamma_o}{1 + \gamma_o}} \right) \quad (3.36)$$

Eq. (3.36) defines the bit error rate for coherent binary phase shift keying (PSK) over a flat Rayleigh fading channel [16].

A time-variant behavior of the channel is due to motion of the receiver or changing environment such as movement of reflectors and scatters. This means the impulse response  $h(\tau, t)$  of mobile radio channel is time variant.

If  $h(\tau, t)$  has a zero mean, then the envelope  $|h(\tau, t)|$  has a Rayleigh distribution:

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (3.37)$$

where,  $\sigma^2$  is the total power in the multipath signal. Otherwise, if  $h(\tau, t)$  has a nonzero mean, which implies the presence of a significant (non faded) line-of-sight component, then the envelope  $|h(\tau, t)|$  has a Ricean distribution:

$$p(r) = \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + s^2}{2\sigma^2}\right) I_0\left(\frac{rs}{\sigma^2}\right) \quad (3.38)$$

where,  $s^2$  is the power of the line-of-sight component, and  $I_0$  denotes the zero order modified Bessel function of the first kind.

In the most general case the channel is modeled as linear time –variant system. This is described by its time-variant impulse response,  $h(\tau, t)$ .

If  $x(t)$  represents the transmitted signal through mobile radio channel, the received signal,  $y(t)$ , can be expressed as

$$y(t) = \int_{-\infty}^{\infty} h(\tau, t)x(t - \tau)d\tau \quad (3.39)$$

In this section, first, the synchronous CDMA model is established; it is used as a basis to model asynchronous CDMA. Then the asynchronous CDMA model is extended from single path model to multipath model.

In a mobile communication, the transmitted signal is corrupted by channel fading in addition to additive white Gaussian noise. The received signal for each user  $k$  is affected by a random, time-dependent complex channel coefficients  $c_k(i)$ :

$$\mathbf{r} = \sum_{i=0}^{L-1} \sum_{k=1}^K c_k(i) d_k(i) \begin{pmatrix} 0_{iNQ} \\ \text{-----} \\ \hat{\mathbf{s}}_k(i) \\ \text{-----} \\ 0_{(L-i-1)NQ} \end{pmatrix} + \mathbf{n} = \mathbf{S} \mathbf{C} \mathbf{d} + \mathbf{n} \quad (3.40)$$

where  $L$ : the total amount of data symbol sent by every active user  $k$

$K$ : the total amount active users sending data to base station

$\mathbf{C}$ : a  $LK \times LK$  diagonal matrix containing the physical channel parameters with elements  $c_j = c_k(i), j = iK+k$ .

The complex channel coefficient  $c_k(i)$  contains all the channel fading and attenuation, including small scale Rayleigh fading, large scale log-normal shadowing and path loss. This is assumed that the channel fading is constant for all the chips during one transmitted symbol interval.

## Chapter 4

### 4. Performance Comparison of Successive and Parallel Interference Cancellation

Personal wireless devices have become a consumer item, most often heavily subsidized by the service provider. The cost of both the end-user telephone and the base station are hence very sensitive. The telephones design and service facility changes rather quickly due to consumer demand for new features and trendy models, with a typical turnover on the order of two years. While it may be possible to add new network features through fast- customized phones, the added cost and complexity for advanced signal processing algorithms like MUD must be negligible due to extreme sensitivity to cost and consumed power. Base stations, on the other hand are less cost-sensitive with turnover on the order of every seven years, according to industry executives and expensive to maintain [1].

#### 4.1 Performance Comparison Based on System Model

Both successive interference cancellation (SIC) and parallel interference cancellation (PIC) have the important advantage over other types of multi-user receivers that error correction coding (ECC) is integrated into the MUD process [1]. As previously noted, both SIC and PIC is primarily applicable to the uplink in a many-user CDMA system.

There are a variety of trade-offs between SIC and PIC. PIC has decreased latency, but higher overall complexity because  $K$  users must be detected in parallel, plus there are  $P$  cancellation stages. So the latency is proportional to  $P$ , which is generally much smaller than  $K$  for cellular systems, but complexity is proportional to  $PK$ . SIC, on the other hand, has complexity and latency proportional to  $K$ , and this latency may be prohibitive if there are many users with real-time data [1].

As shown in Fig. 4.1, the PIC detects all users simultaneously. This initial very coarse estimate can then be used to cancel some interference, and then parallel detection can be repeated. This process can be repeated over several stages; hence, PIC is sometimes

called multistage interference cancellation [3]. Since the first stage generally results in very noisy data estimates, soft interference cancellation is necessary [8].

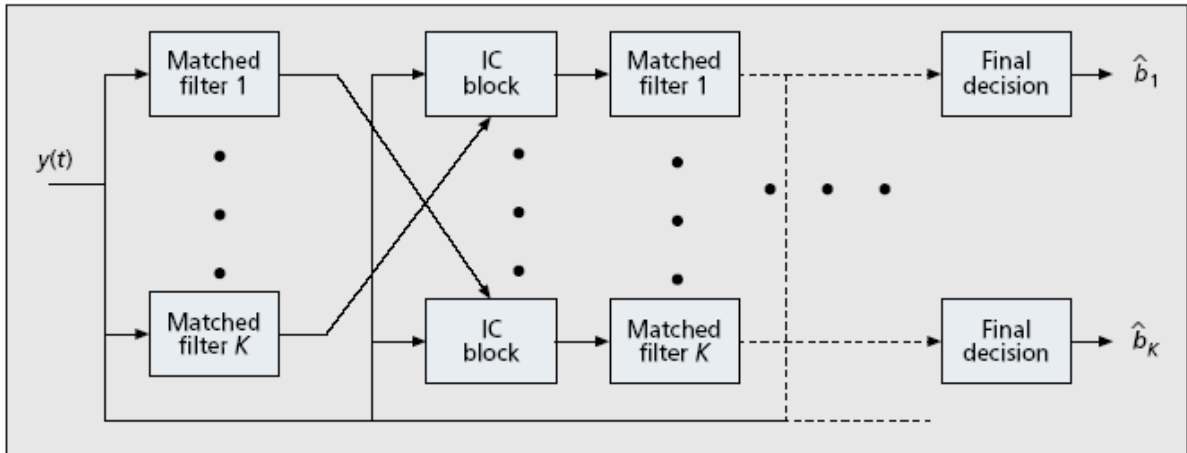


Figure 4.1: Parallel Interference Cancellation.

In SIC shown in Fig. 4.2, detects just one user per stage. Each user ranked first according to their received powers, and then estimated and cancelled in order from strongest to weakest. This cancellation approach has two advantages.

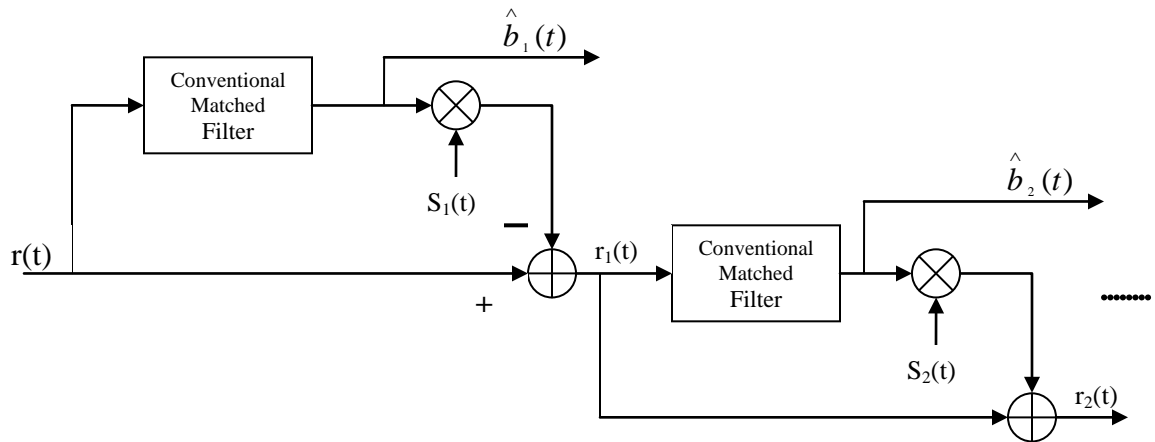


Figure 4.2: Successive Interference Cancellation

First, the strongest users cause the most interference. Thus it is most beneficial to eliminate these interferers first. Second, the strongest users provide the most reliable estimates and thus cause the least error in cancellation. The result is that each user is estimated and only cancelled once as opposed to ‘m’ times in the parallel cancellation approach. This can provide a savings in computational complexity depending on the implementation. The performance relative to parallel cancellation is dependent on the

spread of user powers. That is, for the equal power case the successive cancellation scheme performs significantly worse than the parallel approach. However, as the user powers get more widely distributed, the relative performance of the successive scheme improves.

The Acquired Knowledge from system model can be investigated using the following parameters stated in table 4.2 and 4.3.

- a: signature waveform of the desired user
- b: signature waveform of the interfering user
- c: timing of the desired user
- d: timings of each of interfering user
- e: received amplitude of interfering user

Table 4.1 Comparison of Detection Schemes (1)

Detection Scheme	Acquired Knowledge
Conventional Matched Filter	a,c
Optimum Detector	a,b,c,d,e
Linear decorrelating Detector	a,b,c,d
MMSE Linear Multiuser Detector	a,b,c,d,e
Parallel Interference Cancellation	a,b,c,d,e
Successive Interference Cancellation	a,b,c,d,e

Table 4.2 Comparison of Detection Schemes (2)

<b>Detection Scheme</b>	<b>Advantage</b>	<b>Disadvantage</b>
Conventional Matched Filter	Simplicity	Low Capacity
Optimum Detector	High Capacity	Complexity
Decorrelating Detector	Near-Far resistance Substantial capacity gain	Noise Enhancement, correlation matrix inversion complexity
MMSE Linear Multiuser	Better BER than	Received Amplitude

Detector	Decorrelating detector	Estimation, Near-far problem
Successive Interference Cancellation (SIC)	Near-Far resistance, complexity lower than PIC	Bit Delay, Initial data estimate should be accurate, lower performance under equal-power control.
Parallel Interference Cancellation (PIC)	High capacity gain under equal-power control	Complexity Higher than SIC

## 4.2 Performance Comparison Based on Computational Complexity

This work presents mainly a comparison of Successive and Parallel interference cancellation multiuser receivers and their usefulness for CDMA, particularly at the base station. Cellular or Personal Communication System (PCS) design consists of two distinct problems, namely the design of the forward link from the base station to the mobile and the design of the reverse link from the mobile to the base station. The forward link can be designed so that users transmit with orthogonal spreading codes with signals arriving at the mobile receiver with identical energy. To assure marketability the receiver must be inexpensive and have low power requirements. The reverse channel is harsher, but can support a more sophisticated receiver. User signals arrive at the receiver asynchronously and may have differing energies, resulting in the near-far problem. The base station receiver can be larger and more complex, have higher power consumption and use information about the interfering signals. We focus on this latter situation where the receiver jointly detects signals from all users. One may observe that many of the problems observed in CDMA are the result of the approach used by the conventional receiver, rather than being inherent to CDMA. Receiver structures with high computational complexity require extremely high speed processors for implementation as well as extremely long run times for simulation.

### 4.2.1 Successive Interference Cancellation

Parallel interference cancellation scheme suggests a cancellation of interference is done in parallel and in multiple stages, a somewhat simpler approach is to estimate and cancel interference successively using feedback. In this approach users are first ranked according to their received powers, and then estimated and cancelled in order from strongest to weakest.

The performance of the Successive Interference Cancellation detector in AWGN channel can be predicted by using the probability of symbol error (equivalent to bit error in BPSK) of the  $k^{\text{th}}$  user as:

$$P_{k,i}(E) = Q\left(\sqrt{\frac{E[y_{k,i}]^2}{\text{var}[y_{k,i}]}}\right) \quad [4.1]$$

where,  $y$  is the decision matrix, the mean,  $E[y] = \omega b$ , and the variance,  $\text{var}(y)$  needs to be determined and  $Q(\cdot)$  is the standard Q function.

$\omega$  is a  $KN_b \times KN_b$  diagonal matrix of the square root of user received energies;

$N_b$  is number of bits in the sequence under consideration,

$$\text{we define, } \sum_y = \text{var}[y]$$

and,

$$\begin{aligned} \sum_y &= E[yy^T] - E[y]E[y^T] \\ &= E[(\omega b + R^{-1}n) + (\omega b + R^{-1}n)^T] - (\omega b)(\omega b)^T \\ &= R^{-1}\sigma^2 R(R^{-1})^T \\ &= \sigma^2(R^{-1})^T \end{aligned} \quad [4.2]$$

where, we have used  $E[n]=0$ ,  $E[nn^T] = \sigma_n = \sigma^2 R$  and  $\sigma^2$  is the power of the AWGN at the receiver, and results in:

$$P_{k,i}(E) = Q\left(\sqrt{\frac{\omega_{i,j}}{(R^{-1})_{i,j} N_o}}\right) \quad [4.3]$$

Where,  $j = (i-1)K + k$ ,  $N_o$  is the one sided noise power spectral density of the AWGN.

## 4.2.2 Parallel Interference Cancellation

The estimates for each user can be used to reduce the interference of the other users by subtracting the estimate of each interferer from the desired user's signal. Ideally, this would allow the elimination of all interfering signals from the desired user. However, due to the inaccuracy of the estimates, the interference will be subtracted imperfectly. Thus to overcome this, the entire process can be repeated in several stages. At each stage, better estimates of each user are produced, allowing more effective interference cancellation. In this work, we assume the use of matched filters at each stage for estimation. This allows a single estimate (the matched filter output) to be used for both the data symbol and the channel gain and alleviates the need for any outside estimates. While more robust receivers could be used in the first stage to improve performance, this approach is the most straightforward and allows reasonable complexity.

In an AWGN channel the bit error rate (BER) of the receiver employing the standard Gaussian approximation for MAI at stage 's' is:

$$P_k^s(E) = Q \left( \left[ \frac{1}{2E_b/N_0} \left( \frac{1 - \left(\frac{K-1}{3N}\right)^s}{1 - \frac{K-1}{3N}} \right) + \frac{1}{(3N)^s} \left( \frac{(K-1)^s - (-1)^s}{K} \sum_j P_j + (-1)^s \right) \right]^{-1/2} \right) \quad [4.4]$$

where, K is the number of users and N is the processing gain.

Table 4.3 Key general trends of different multiuser receivers, with spreading factor N, number of users K, and S receiver stages.

MUD type	Complexity order	Latency	Error Correcting Code (ECC)	K>N allowed?
Optimal maximum likelihood	$2^K$	1	Separate	Yes
MMSE	K to $K^3$	1	Separate	Yes
PIC	SK	S	Integrated	Yes
SIC	K	K	Integrated	Yes
Non orthogonal Matched	K	1	Separate	Yes

Filter				
Orthogonal Matched Filter	K	1	Separate	No

Latency: the time it takes for a packet to travel from a client to server and back again, which signifies packet transmission time.

Table 4.3 gives a high-level comparison of some of the different types of multi-user receivers. Due to the vast number of different subtypes for each of these receivers in the literature, these values should be interpreted as general trends. The different types of multi-user receivers have dramatically different scaling for complexity, which generally depends on the number of users and the number of receiver iterations. They also incorporate error correction codes (ECC) in different ways: in systems like SIC, ECCs are directly integrated into the receiver structure, whereas in other systems they must form a separate block independent of user separation, which generally reduces performance since the coding redundancy competes with the spreading gain,  $N$  [1].

The capacity of a CDMA network is reverse link limited, and hence our study is confined to reverse link capacity. One of the principal characteristics of a CDMA network is that the capacity of the system is a function of total interference experienced by the network, and is upper bounded by the cell experiencing the most interference. Thus, it is imminent to characterize total inter-cell interference seen by a single cell in terms of the user distribution in every other cell for determining capacity in that single cell. Traditionally, the total interference contributed by a cell has been viewed as an approximation, determined by simply multiplying the number of users in that cell by the average interference offered by that cell [25]. In other words, a user placed anywhere within a cell generated the same amount of interference. Clearly, a more realistic approach will use per user interference as a function of its actual distance to the point of interest [25].

The capacity of a CDMA network is determined by maintaining a lower bound on the bit energy  $E_b$  to interference density ratio  $I_o$  which is given by:

$$\left( \frac{E_b}{I_o} \right) = \frac{E_b}{\alpha(RE_b)(n_i - 1 + I_i)/W + N_o} ; \text{ for } i=1, \dots, M \quad [4.5]$$

where the network has a spread signal bandwidth of  $W$ , total number of cells in the network  $M$ , information rate of  $R$  bits/sec, voice activity factor of  $\alpha$ , background noise spectral density of  $N_0$ , and  $n_i$  users in cell  $i$ . To achieve the required bit error rate

$\left( \frac{E_b}{I_o} \right)_i$  must be maintained above a certain threshold.

## Chapter 5

### 5 Simulation Results

The performance measure of interest is the probability of error of each user. In multiuser problems it is often more convenient and intuitively sound to give information concerning the error probability by means of the efficiency, or ratio between the effective signal-to-noise ratio (SNR) and the actual SNR, where the effective SNR is the one required to achieve the same probability of error in the absence of interfering users, and the actual SNR is the received energy of the user divided by the power spectral density level of the background thermal white Gaussian noise (not including interference from other users). Note that since the single-user error probability is a one-to-one function of the SNR, the efficiency gives the same information as the error probability. Its limit as the background Gaussian noise level goes to zero, the asymptotic efficiency, characterizes the underlying performance loss when the dominant impairment is the existence of other users rather than the additive channel noise [21].

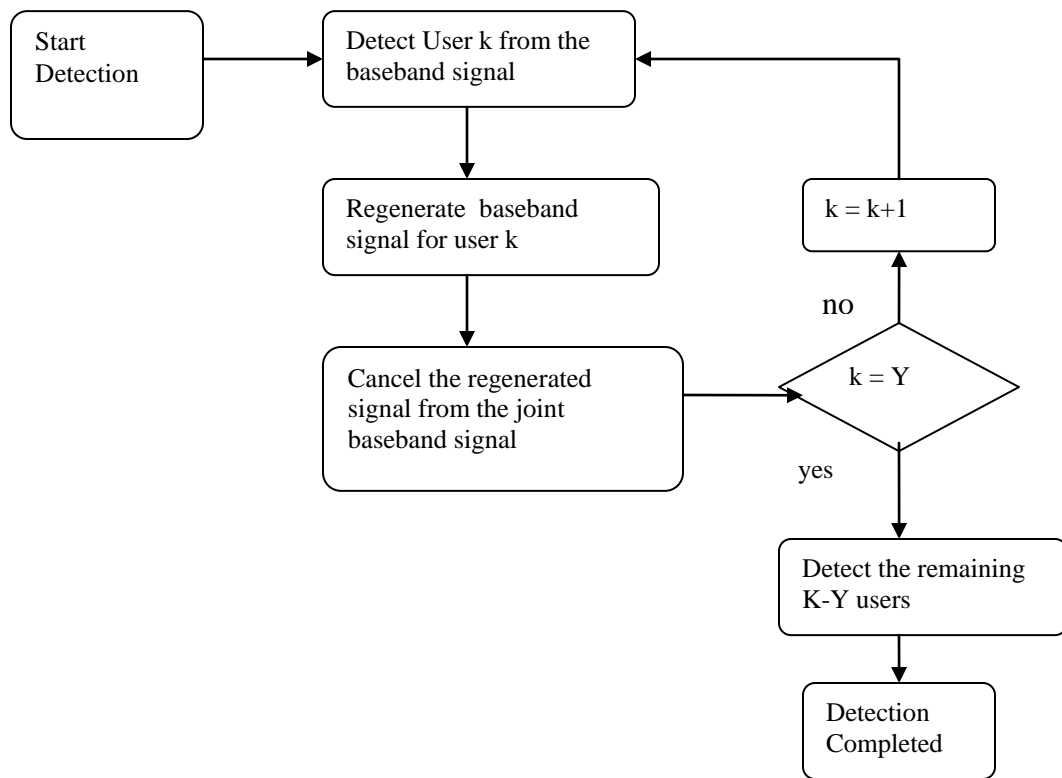


Figure 5.1: Flow chart illustrating the SIC scheme

The flow chart is for a system with  $K$  users and it is assumed that  $Y$  cancellations are performed. All cancellations are performed at baseband. The basic principle is to (i) detect one user with the conventional detector, (ii) re-generate the baseband signal for this user, and (iii) cancel the re-generated signal from the received baseband signal. This operation results in a reduced multiple-access interference (MAI) for the remaining users. To perform the interference cancellation, estimates of amplitude are required. This information is needed in order to re-generate the baseband signal before cancellation. The amplitude estimates are obtained from the linear correlation output of the conventional matched filter. Knowledge of the spreading sequences for all users is also required. This knowledge is only available at the base station.

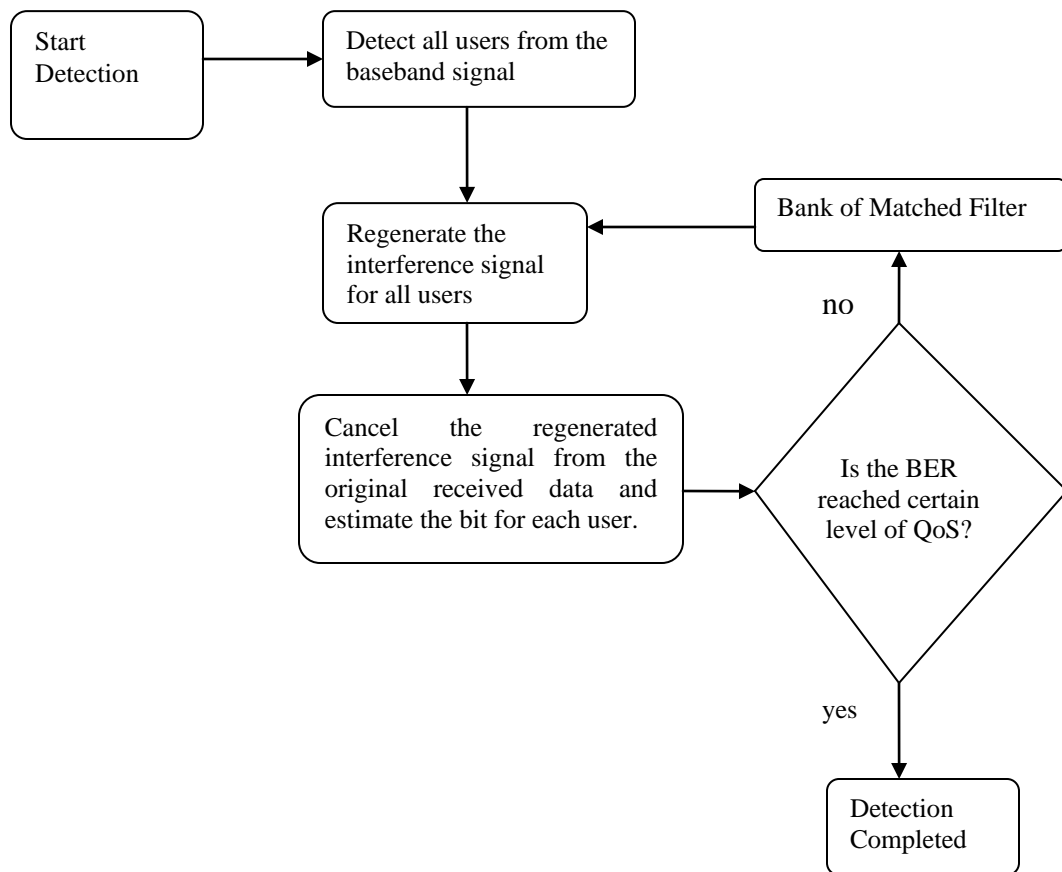


Figure 5.2: Flow chart illustrating the PIC scheme

The flow chart depicted in Fig.5.2 shows the major steps in parallel interference cancellation (PIC). (i) As the name implies in PIC all users are treated simultaneously and hence detect a symbol of all users from the original data, (ii) re-create the interference signals from all users. (iii) Subtract the re-created interference from the original received data and estimate the desired signal. Finally go to step (ii) according to the required level of BER.

## 5.1 Performance in AWGN Channel

Fig.5.1 depicts the SNR versus BER performance of interference cancellation using SIC and PIC scheme in AWGN channel for 10 users and their performance is compared with matched filter (MF). In this simulation we use a spreading gain of  $N=31$ , for data size of

1000 bits. Here, the matched filter is become an optimum detector for AWGN channel with orthogonal spreading codes assigned for each user data.

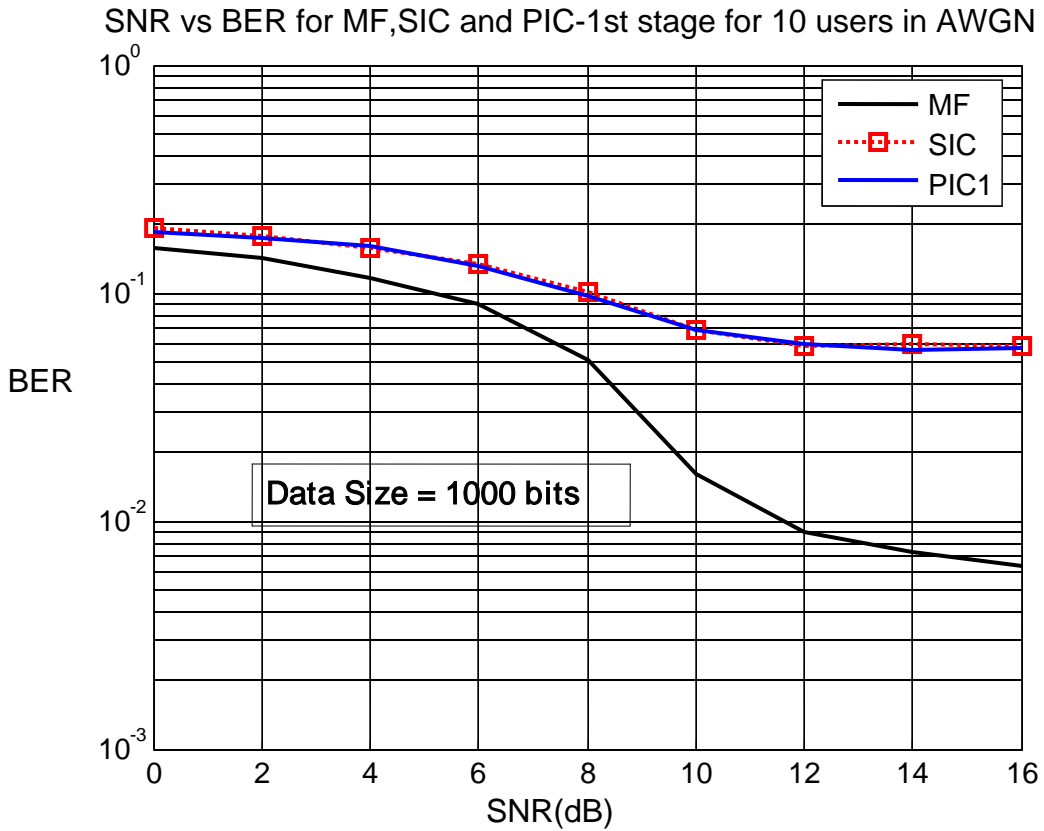


Figure 5.3: Performance of MF, SIC and PIC in AWGN channel for 10 users and data size of 1000 bits.

During simulation of Fig.5.4 and Fig.5.5 the computer processing time significantly increases due to higher data size of 10,000 bits used in both cases. In Fig.5.2 for the case of 3 users the BER sticks on  $6.4 \times 10^{-3}$  as the SNR equals to 10 dB and above. When the number of users in the network decreases the effect of noise in AWGN channel also reduced.

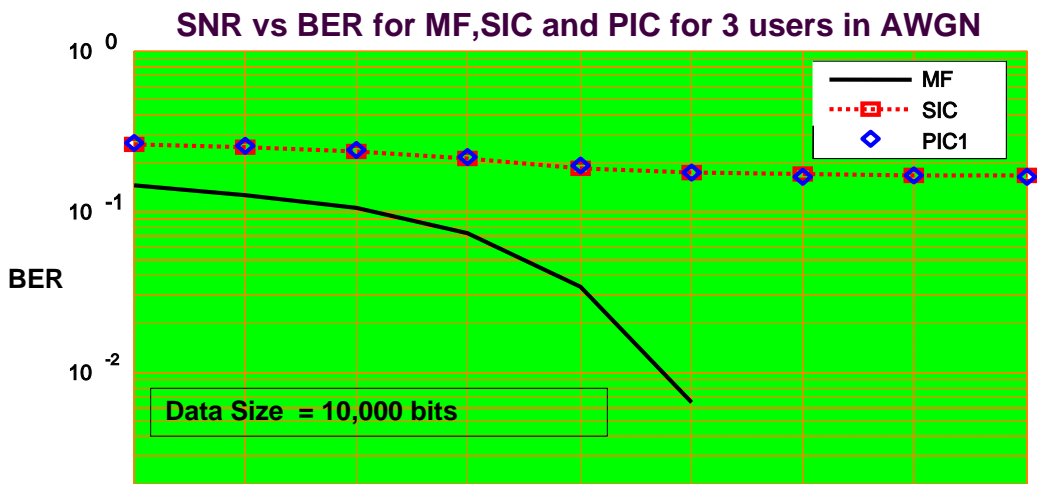


Figure 5.4: Performance of MF, SIC and PIC in AWGN channel for 3 users, when the data size is 10,000 bits.

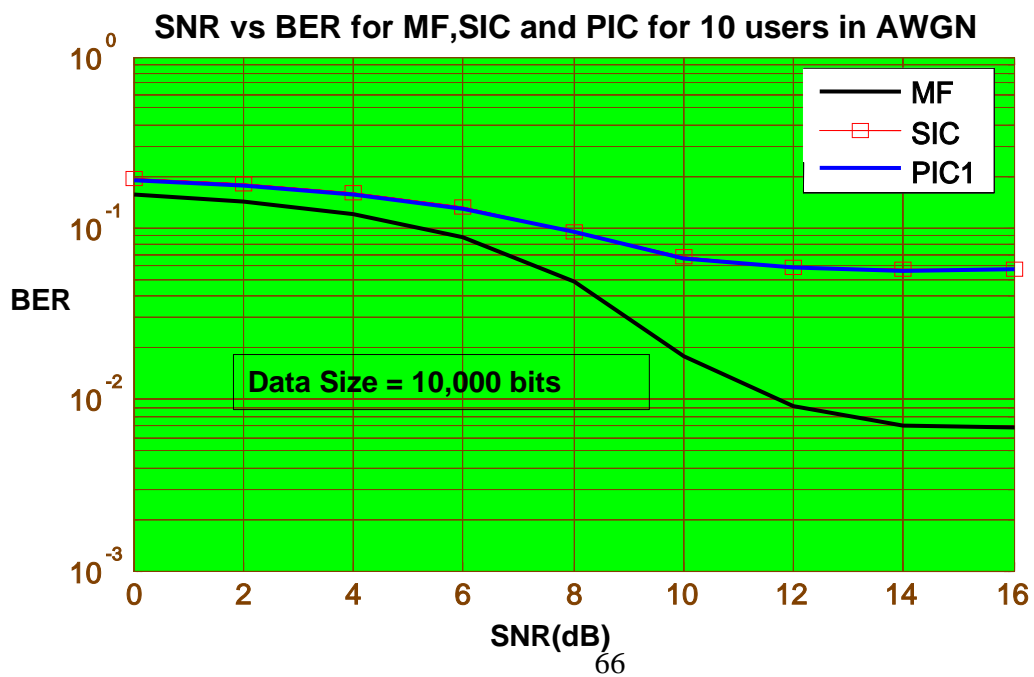


Figure 5.5: Performance of SIC and PIC in AWGN channel for 10 users, when the data size is 10,000 bits.

As shown from Fig.5.3, Fig.5.4 and Fig.5.5, the matched filter (MF) has shown significant performance improvement over SIC and PIC in AWGN channel, therefore matched filter is become an optimum detector for AWGN channel with orthogonal spreading codes assigned for each user data.

## **5.2 Performance in multipath fading channel**

The performance SIC and PIC in multipath fading channel when the number of paths  $P=3$ , spreading gain  $N=31$  and for the number of user  $K=10$  is depicted in Fig. 5.6. In this case the performance of PIC for all three stages has shown significant performance improvement over the conventional matched filter. In each stage of iteration in ascending order the performance of PIC is becoming progressive. The improvement in each cancellation stage is due to the result of improved interference cancellation.

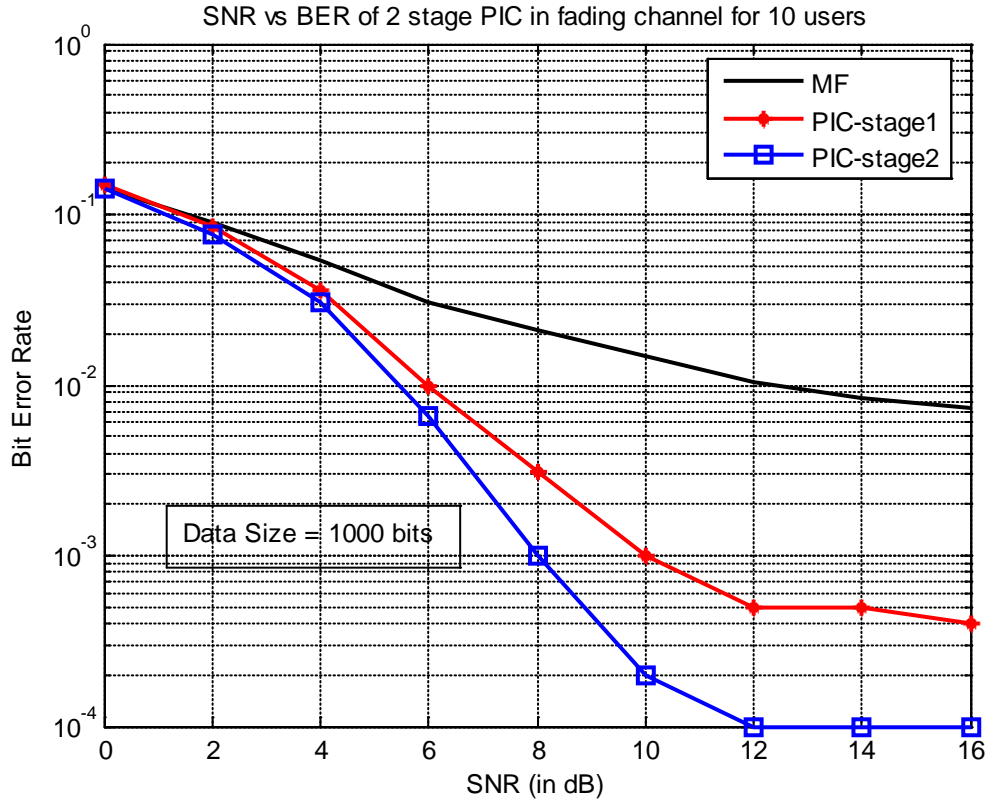


Figure 5.6: SNR vs BER of 2 stage PIC in fading channel for 10 users, in perfect power control condition for a data size of 1000 bits

Fig.5.7. shows the performance of 3 stage PIC for 3 users case in multipath fading channel, and here at the SNR value of 8 dB and above the lowest bit error rate (BER) about  $2.8 \times 10^{-4}$  is registered. Because, as the number of users in the network decreases the multi access interference (MAI) in the network also decreases, hence for the required level of quality of service (QoS) the level of SNR value will also be minimized.

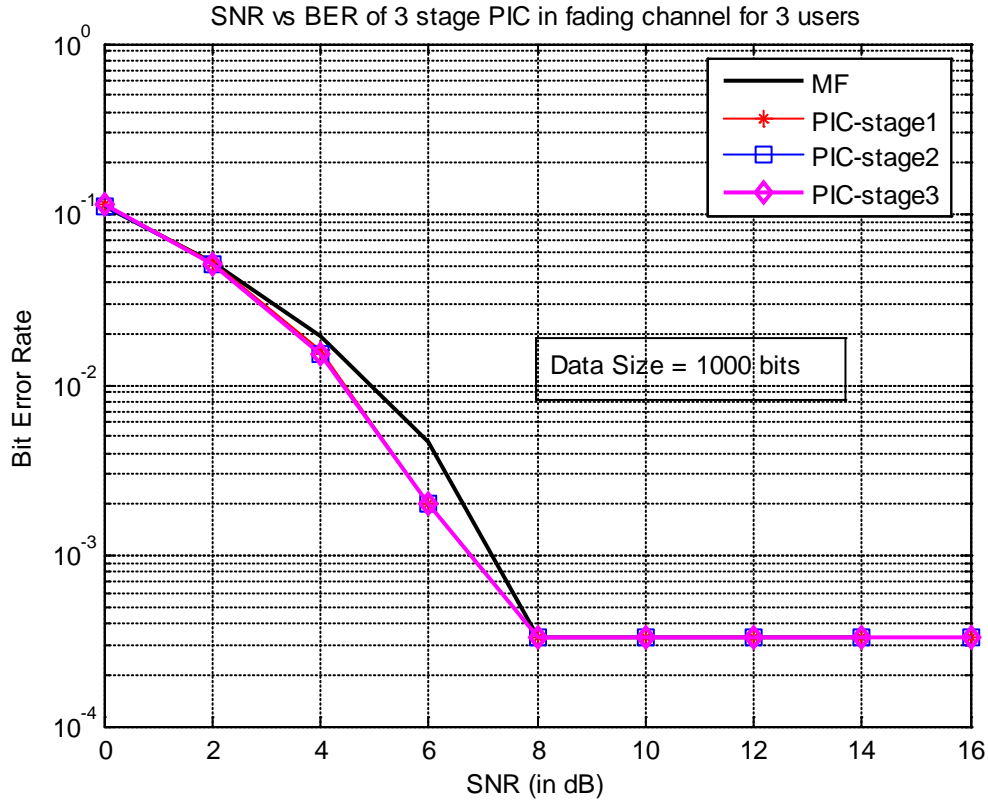


Figure 5.7: SNR vs BER of 3 stage PIC in fading channel for 3 users and a data size of 1000 bits/sec

Fig.5.8 shows the performance of PIC in multipath fading channel for a data size of 10,000 bits. The performance of PIC at 2<sup>nd</sup> and 3<sup>rd</sup> stage has shown similar characteristics and the lowest and constant BER is registered for the SNR value of 12 dB and above. Hence, using the 2<sup>nd</sup> stage PIC multiuser detector for 10 users high performance is achieved at SNR is equal to 12 dB.

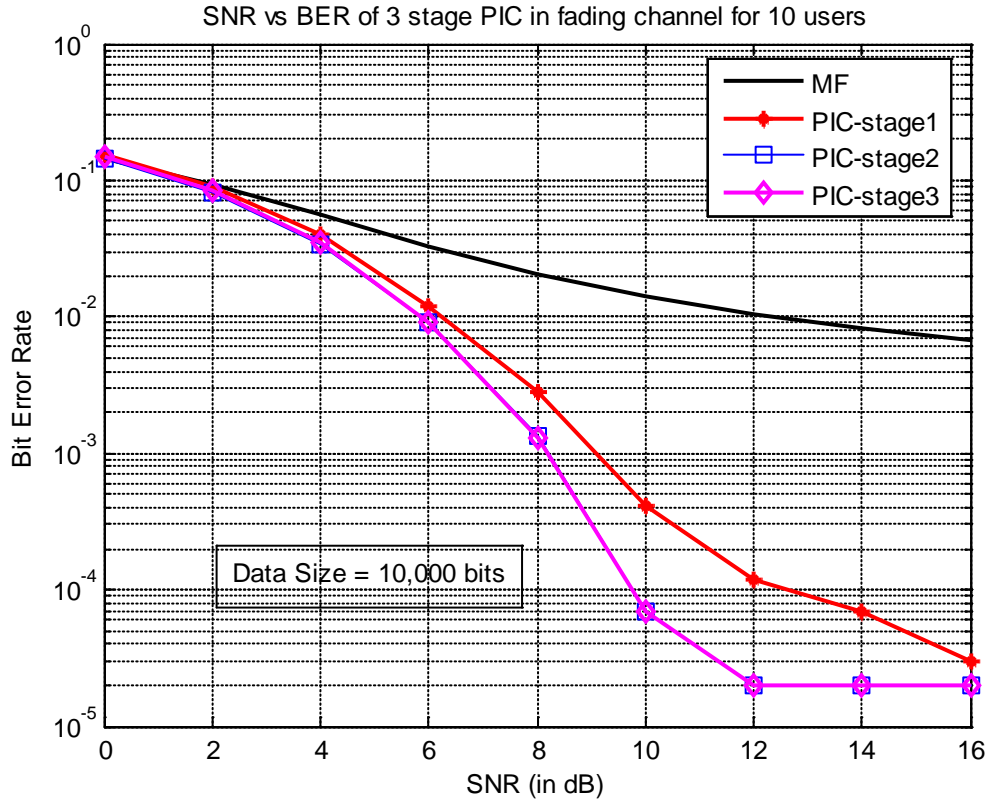


Figure 5.8: SNR vs BER of 3 stage PIC in fading channel for 10 users for a data size of 10,000 bits.

Fig.5.9 depicts the performance of SIC in perfect power control condition deteriorates as compared to PIC; and PIC has shown significant improvement as the number of cancellation stage increases.

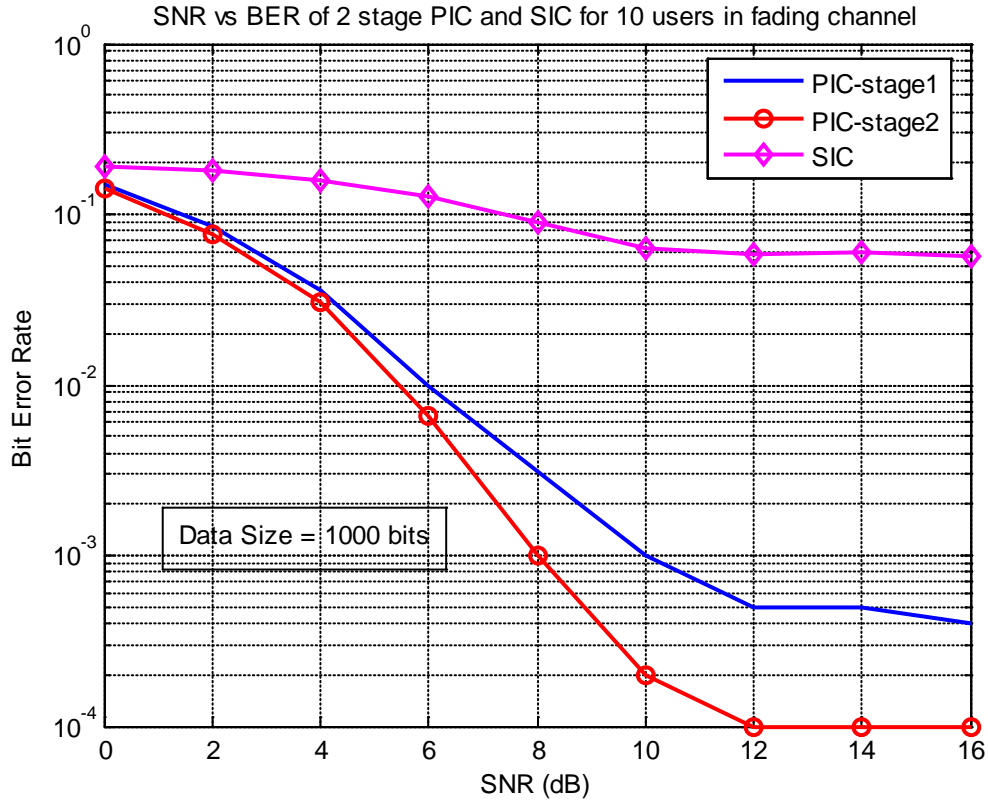


Figure 5.9: SNR vs BER of 2 stage PIC and SIC in fading channel for 10 users, in perfect power control condition for a data size of 1000 bits.

Fig.5.10. shows as the number of users increases from  $K=10$  to  $K=20$  users, the performance of 3 stage PIC improved in ascending order. All the figures from Fig.5.6 to Fig.5.10 confirm that PIC has shown significant performance capability over conventional matched filter in multipath fading channel.

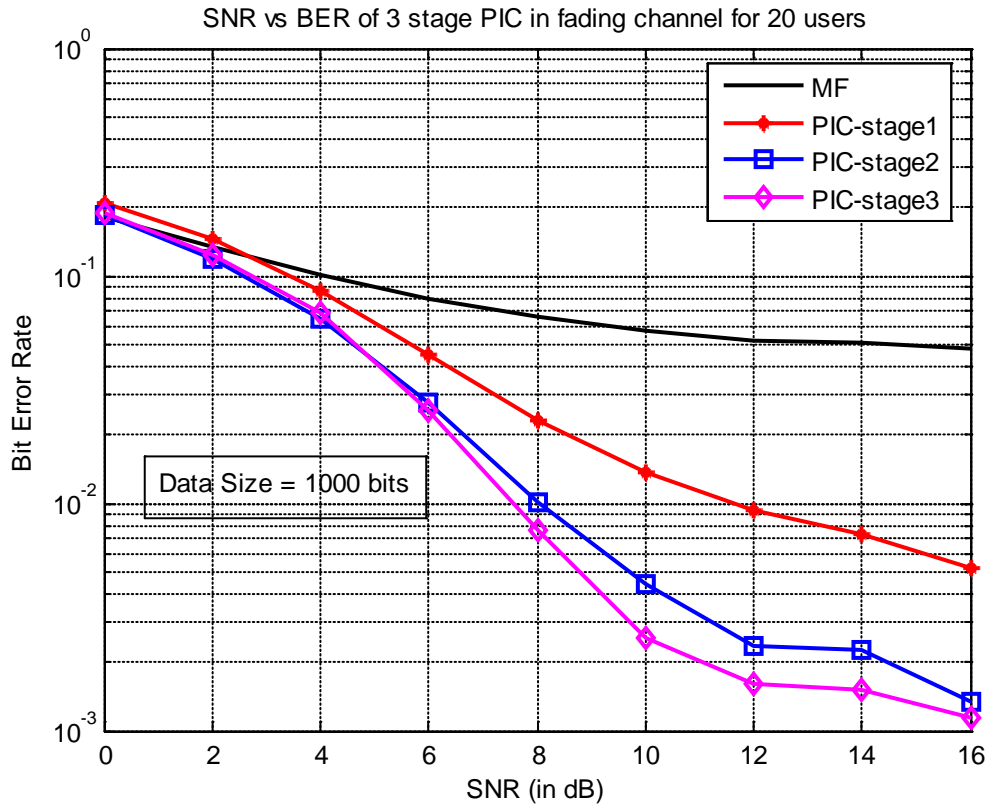


Figure 5.10: SNR vs BER of MF and 3 stage PIC for 20 users in multipath fading channel for a data size of 1000 bits and number of path, P=3.

As shown in Fig.5.9 the performance of SIC in perfect power control condition is deteriorates. SIC needs the power level information of each user in order to give priority for the higher power level signals in ascending order during detection, since users having high power level signal can interfere the rest of the users in the network dominantly. Therefore, these users are prioritized during detection in order to reduce the multi access interference in the network significantly. PIC multiuser detector has shown remarkable improvement over SIC multiuser detector in perfect power control condition, since each user in PIC are detected simultaneously.

Fig.5.11 and Fig.5.12 are showing the characteristics of data size in bits versus bit error rate (BER) for 10 users at SNR=10 dB and SNR=12 dB respectively. From the given figures it is also possible to deduce that as the data size increases the BER also improved.

Besides that, the computer simulation shows when the data size increases the processing time of the computer increases and the computational complexity will be higher.

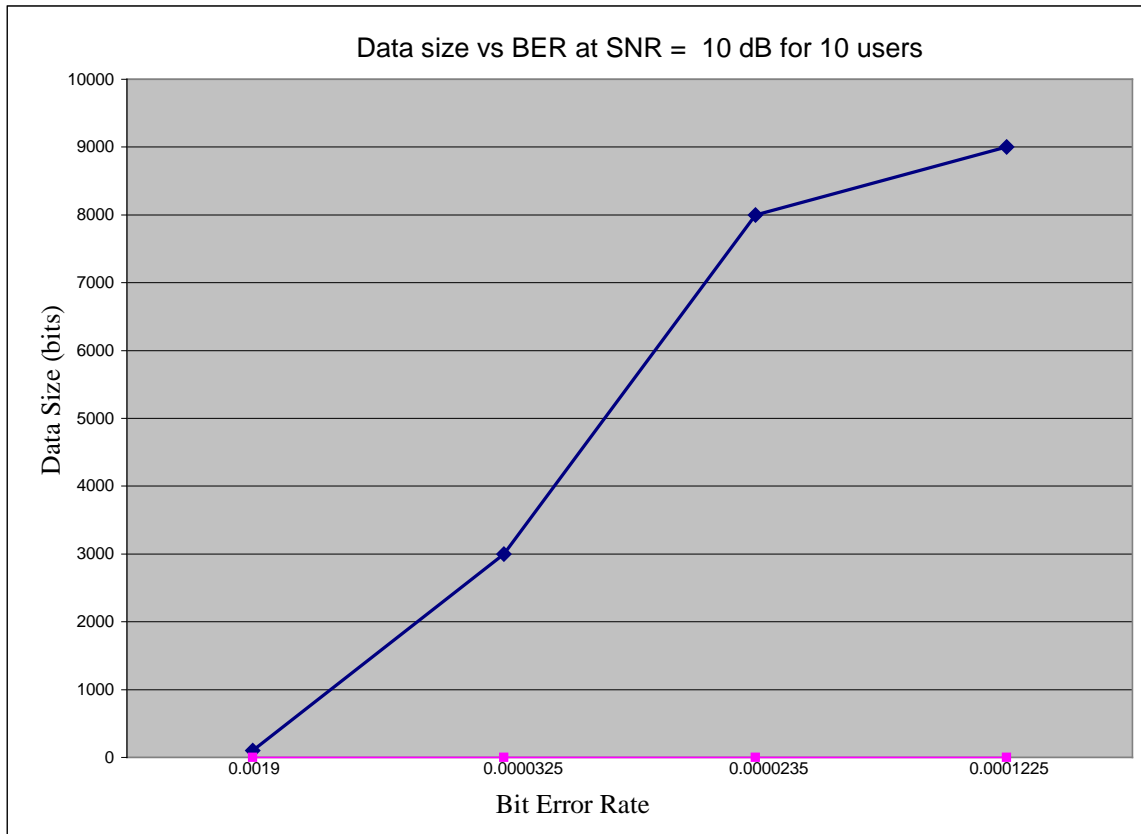


Figure 5.11: Data size vs BER at SNR=10 dB for 10 users.

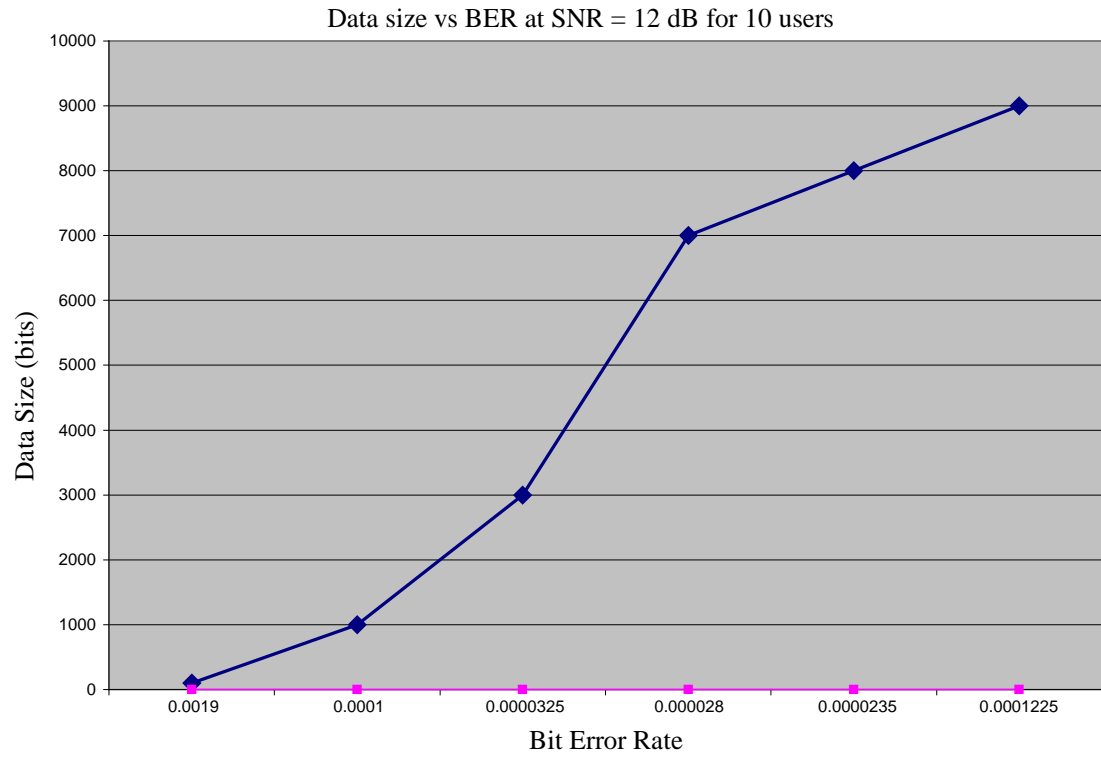


Figure 5.12: Data size vs BER at SNR=12 dB for 10 users.

# Chapter 6

## 6. Conclusion and Future Research

In this paper, we have provided a description on performance evaluation of interference cancellation using successive and parallel interference cancellation receivers which are primarily proposed for the implementation 3G systems. The issues discussed supported with basic merits of multiuser detection systems from different literature survey, and simulation results based on system model and computational complexity are explained.

Mathematical analysis and simulation results reveal that subtractive interference cancellation detectors have significant performance to mitigate the multi access interference (MAI) over the conventional matched filter; in IS-95 CDMA system MAI is treated as additive white Gaussian noise (AWGN).

Major obstacles to the application of multiuser detectors in wireless systems are processing complexity and possible processing delay. Simulation results reveal that as the number of users and data size increases the computational complexity is also increases. However, as the number of users increases the performance of parallel interference cancellation (PIC) significantly increases as the number of PIC stage increases. Besides that the higher the data sizes from the transmitting end has shown considerably lower bit error rate (BER) at the reception of the receiver.

The successive cancellation must operate fast enough to keep up with the bit rate and not introduce intolerable delay. For this reason, it will presumably be necessary to limit the number of cancellations. The ability to limit the number of cancellations is consistent with the objective of controlling complexity by choosing an appropriate performance/complexity tradeoff.

Successive cancellation works by successively subtracting off the strongest remaining signal. An alternative (the parallel method) is to simultaneously subtract off all the user's signals from all of the others. It is found that when all of the users are received with equal strength, the parallel method outperforms the successive scheme. When the received signals are of distinctly different strengths, the successive method is superior in

performance. The important thing to note is that in both cases, both the successive and parallel interference cancellers outperform the conventional matched filter.

Although the key issues thus far enumerated are technical or implementation issues, there is no question that politics and technical misunderstandings have also contributed to MUD's underwhelming impact on current systems [1]. In order to make use of most new cutting edge technologies, the entire system should be designed in an integrated fashion with the new technologies in mind. For example, no one plans to simply put extra antennas at the transmitter and receiver, expecting MIMO to work: there need to be special pilot signals, coding techniques, receiver architectures, and a specialized medium access control (MAC) layer to effectively take advantage of the multiple antennas. On the other hand, CDMA and other cellular standards have considered MUD to simply be an optional receiver implementation, and have made very minimal effort to accommodate MUD in the standards (e.g., by including an optional provision for short period spreading codes [30]). It is not altogether clear why this has happened, but it is reasonable to believe that a different design approach could have yielded a far more important and profitable role for multi-user receivers in current cellular systems.

Despite the bleak picture for multi-user receivers that unfolded in the previous study, the future appears much brighter. The methodology and application of future wireless networks (beyond 3G) may change dramatically from the current voice-centric circuit-switched paradigm, and other recent technical developments give new hope for certain classes of multi-user receivers. Many researchers have begun to recognize that the important remaining challenges for multi-user receivers are no longer information theoretic, but rather of system design and implementation, as enumerated earlier. Some encouraging recent trends are now highlighted, in rebuttal to the arguments of the previous studies.

As the literature on multi-user receivers has become increasingly comprehensive in recent years, the bottleneck for the adoption of multiuser receivers has increasingly become issues relating to complexity and implementation. Many of these implementation issues are not simply a matter of efficient integrated circuit design, but rather require system-level thinking about the crucial features of multi-user receivers. Therefore, the

signal processing algorithms for multi-user and multi-antenna suppression are in essence indistinguishable, implementation progress in MIMO receivers can be immediately applied to advance the implementation of multiuser receivers.

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## Simulation Program

```
% Program for Performance Evaluation of Interference Cancellation
% using SIC and PIC for WCDMA Systems.
snr = [0 2 4 6 8 10 12 14 16]; % Signal-to-Noise-Ratio
K = 20*ones(1,9);
for k = 1:length(snr)
    N = 32; L = 128; sinr = 0; P = 3;
% N= Spreading Gain, L=Preamble Length (used for separating user symbol
    % and known at the receiver), P=Number of
    % paths, K=number of users

    rand('state',0);
    randn('state',0)

% Estimation part

[r, codes, bits, atau, aamp] = gendata(N, K(k), sinr, snr(k), L, P); % gendata = generate DS-
CDMA data

bt = kron(bits(:, 1:L), [1; 0]) + kron(bits(:, 2:L+1), [0; 1]);
Yest = zeros(2*K(k), N);
Rbb = zeros(2*K(k), 2*K(k)); % Rbb = autocorrelation of a sequence of bits
Rbr = zeros(2*K(k), N); % Rbr = cross correlation of sequence of bits and observation
vector
Window size = L+1;
mu = 1/256;
for (i = 1:L)

    if (i < Window size)
        Rbb = Rbb + (bt(:, i)*bt(:, i)');
        Rbr = Rbr + (bt(:, i)*r(:, i)');
    else
        Rbb = Rbb + bt(i)*bt(i)' - bt(i-Window size)*bt(i-Window size)';
        Rbr = Rbr + (bt(i)*r(i)' - bt(i-Window size)*r(i-Window size)');
    end;
end;
```

```

        Yest = Yest - mu*(Rbb*Yest - Rbr); % ML channel estimate A(i)
        % A(i)=A(i-1)-mu(Rbb(i)*A(i-1)-Rbr(i))

end;

Y= Yest';
% Y = Rbr';
size(Y)
A0 = [];A1 = [];
    for i= 1:2*K(k)
        a = mod(i,2);
            if(a ~= 0)
                A0 = [A0 Y(:,i)];
            else
                A1 = [A1 Y(:,i)];
            end;
        end;

Rbr = Rbr'; % Comparison with sliding correlator
A0sl = [];A1sl = [];
    for i= 1:2*K(k)
        a = mod(i,2);
            if(a ~= 0)
                A0sl = [A0sl (Rbr(:,i))/L];
            else
                A1sl = [A1sl (Rbr(:,i))/L];
            end;
        end;

Lmat = real(A1'*A0);
C = real(A0'*A0 + A1'*A1 -diag(diag(A0'*A0 + A1'*A1 )));
error = 0;
err1 = 0;
err2 = 0;
errors1 = 0;

```

```

Ld = round(1000);
y = zeros(K(k),Ld);
d = y;
dsl = y;
ytemp = y;
ysl = y;

% Detection part
rand('state',0);
randn('state',0)
[r, codes, bits, atau, aamp] = gendata(N, K(k), sinr, snr(k), Ld, P);
r = reshape(r, N, Ld);

% Matched Filter - MF
%%%%%code for generating the matched filter (3users) %%%%%%%%%%
clear all;
clc;
N=31;
K=3; %%%% no of users
No=0.6;
Nodb=10*log10(1/No)
%No=N*No;
no_of_bits=1000;

%%%%%get signature sequences
a1=charphase;
a2=charphase;
a3=charphase;

%%%%%%%%%generate the anitpodal sequence
a1=2*a1-1;
a2=2*a2-1;
a3=2*a3-1;

```

```

%%%%%% normalize energy of signature waveforms
% a1=a1/sqrt(sum(a1.*a1));
% a2=a2/sqrt(sum(a2.*a2));
% a3=a3/sqrt(sum(a3.*a3));

A=[1 0 0;0 1 0;0 0 1];
rho12=sum(a1.*a2);
rho13=sum(a1.*a3);
rho21=sum(a2.*a1);
rho23=sum(a2.*a3);
rho31=sum(a3.*a1);
rho32=sum(a3.*a2);

R=[1 rho21 rho31;rho12 1 rho32; rho13 rho23 1];

bits=round(rand(K,no_of_bits));
b=2*bits-1;
n=sqrt(No)*randn(K,no_of_bits);
y=sign(R*A*b + n);
%convert to ones and
b_hat=(y+ones(K,no_of_bits))/2;
ber1=sum(xor(bits(1,:),b_hat(1,:)))/no_of_bits
ber2=sum(xor(bits(2,:),b_hat(2,:)))/no_of_bits

avg_ber=0.5*(ber1+ber2)
ber=sum(sum(xor(bits(1:K,:),b_hat(1:K,:)))/no_of_bits)/K

% PIC - Stage 1
for(i=1:Ld)
    if(i==1)
        ytemp(:,i) = y(:,i) -C*d(:,i) - Lmat'*d(:,i+1);
    elseif (i ==Ld)
        ytemp(:,i) = y(:,i) - Lmat*d(:,i-1) -C*d(:,i);
    else
        ytemp(:,i) = y(:,i) - Lmat*d(:,i-1) -C*d(:,i) - Lmat'*d(:,i+1);
    end;
end;

```

```

d(:,i) = sign(ytemp(:,i));
for(j =1:K)
    if( d(j,i) ~= bits(j,i))
        err1 = err1 +1;
    end;
end;
end;

% PIC - Stage 2
p=zeros(K,N1);
for i=1:N1
    for j=1:K
        for k=1:K
            if (j~=k)
                p=p+A(j)*R(j,k)*b_hat(j);
            else
                p;
            end;
        end;
    end;
end;
z=y1-p;
b_hat(j,i)=sign(z(j,i));

for j=1:K
    if (b_hat(j,i)~=b_bits(j,i));
        errpic2=errpic2+1;
    end;
end;
end;

error_slvec(k) = errorsl/(K(k)*Ld);
error_vec(k) = error/(K(k)*Ld);
err1_vec(k) = err1/(K(k)*Ld) ;
err2_vec(k) = err2/(K(k)*Ld) ;
end;

```

```

%code for generating the m-sequence of length 31%%
% enter tap weights as an array h=[h1,h2,..h6]
%h=[0 0 0 1 1];% 103 ---this is the primitive polynomial <103>
%h=[1 0 0 1 1 1];% 147
%h=[1 1 1 0 1];% 75
%h=[0 0 1 0 1];% 45
%h=[1 1 0 0 1 1];% 163
h=[0 1 1 0 0 1];% 145

%%%%%%%% enter intial state of the register as an array u=[u1 u2 u3 u4 u5 u6]
%%%%%%%%
%fid=fopen('/home/users/arun/sscdma/project/mseq31_primpoly45.txt','a');
for i=1:31
u=dec2bin(i,5);
u=u-48;
u(6)=0;
output=[];
for shift=1:31
output=[output,u(1)];
temp=u(1);
for n=2:6
u(n-1)=xor( u(n),(h(n-1)*temp) );
end
%u(1:6)
end
%output
t=[output,output];
if t(1,2:31)==t(1,2*(2:31)-1)
charphase=output;
end
end
save mseq31primpoly145.mat charphase;
u=charphase;

%%% semilogy(snr,error_slvec,'-+');

```

```
%%% hold on;
semilogy(snr,error_vec,'-v');
hold on;
semilogy(snr,err1_vec,'-x');
hold on;
semilogy(snr,err2_vec,'-r');
hold on;
%%% semilogy(snr,err3_vec,'-o');
%%% hold on;
title('Error rate vs SNR');
xlabel('SNR (in dB)');
ylabel('Bit Error Rate');
%%% legend('Sliding corr - MF','MF','PIC-stage1','PIC-stage2','PIC-stage3');
legend('MF','PIC-stage1','PIC-stage2');
% End of working program %
```