Multiuser Detection of DS-CDMA Signals using Parallel Interference Cancellation in Wireless Communications

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ABSTRACT

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In a limited network resource, techniques are needed to share the channel among different users as efficiently and as fairly as possible. Among multiple access techniques. Code Division Multiple Access (CDMA) has the exclusive advantage of allowing all active users share the same channel concurrently.

When CDMA technique is used, Multi User Detection (MUD) is needed to reject or reduce the Multiple Access Interference (MAI) affecting each active user.
In this thesis, it is shown that multiuser detection using Parallel Interference Cancellation (PIC) technique provides a good compromise among the complexity, latency, and performance. This technique is suitable for Digital Video Broadcasting - Return Channel via Satellite (DVB-RSC) as well as Base Station (BS) in cellular commuincation systems. We offer a new scheme that is a combination of soft and hard PIC detectors whose performance is superior to that of the other famous sub-optimal detectors.

For most MUD schemes, a perfect knowledge of users' parameters is required. In this thesis, we apply a very simple method to estimate the parameters.

PIC detectors are usually studied in equal-power case. i.e., a perfect power control scheme is assumed. We, study PIC detector in near-far condition as well, where users arrive at receiver with different power levels. It is shown that our proposed scheme has some advantages over other schemes. First, it is much less complex than optimal and linear detectors. Second, it is much faster than sequential detector. Third, it has better performance than that of linear detectors.

Dedicated to my parents, sisters and brothers ......

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I would also like to extend my appreciation to my dearest parents, sisters and brothers for their great sacrifice, support and patience which made my study much easier to achieve and a memorable experience.

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Chapter 1

Introduction

Today, more than ever, not only tangible goods, but also, knowledge is a valuable commodity. The wealth of nations is not merely measured by their capacity to produce agricultural and industrial goods, but also, by their capability to generate, process, and transfer information. This is the driving force behind the information and telecommunication industries.

1.1 Contemporary History of Wireless Communications

The first generation personal mobile communication systems dealt with analog signals. Such systems offer a simple circuit to transmit and receive information. However, the signals used in this method are less tolerant of channel impairments due to their analog characteristics and they are less efficient in the sense of transmission power [32].

The problem of power efficiency was resolved by exploiting second generation systems that used digital communication techniques. Some examples of these systems are Global System for Mobile communications (***GSM***) and ***IS-95***. With mushrooming growth of demand for access to telecommunication networks. the second generation will fail to meet all new needs. Therefore, third generation systems with the provision of higher data rates specially for video and web services are to be sought.

Third generation mobile communication systems are referred as the *Universal Mobile Telecommunication Systems* (***UMTS***). For such an environment, the major air interface would be the *Wideband Code Division Multiple Access* (***WCDMA***). This system within the *International Telecommunications Union* (***ITU***) is called *International Mobile Telephony 2000* (***IMT-2000***). Third generation systems seem to be more deploying than their second generation counterparts in the not-so-distant future because of the following unique properties [2], [31]:

- Higher carrier spacing which means higher data rate and or higher spectral efficiency
- Higher chip rate giving rise to better multipath diversity
- Faster power control resulting in less *Multiple Access Interference* (***MAI***)
- *Multi User Detection* (***MUD***) and antenna diversity features.

1.2 Multiple Access Schemes

The main goal of using multiple access schemes is to share a limited network resource among different users as efficiently as possible. There are three major multiple access techniques each of which will be explained as follows (Figure 1.1):

The first type of multi-access techniques employed by the first generation mobile communication systems is Frequency Division Multiple Access (***FDMA***). In this method, the available spectrum is divided among the users and they are supposed to transmit their data simultaneously. Hence. the whole bandwidth consists of non-overlapping slots of frequency and each slot is assigned to one user.

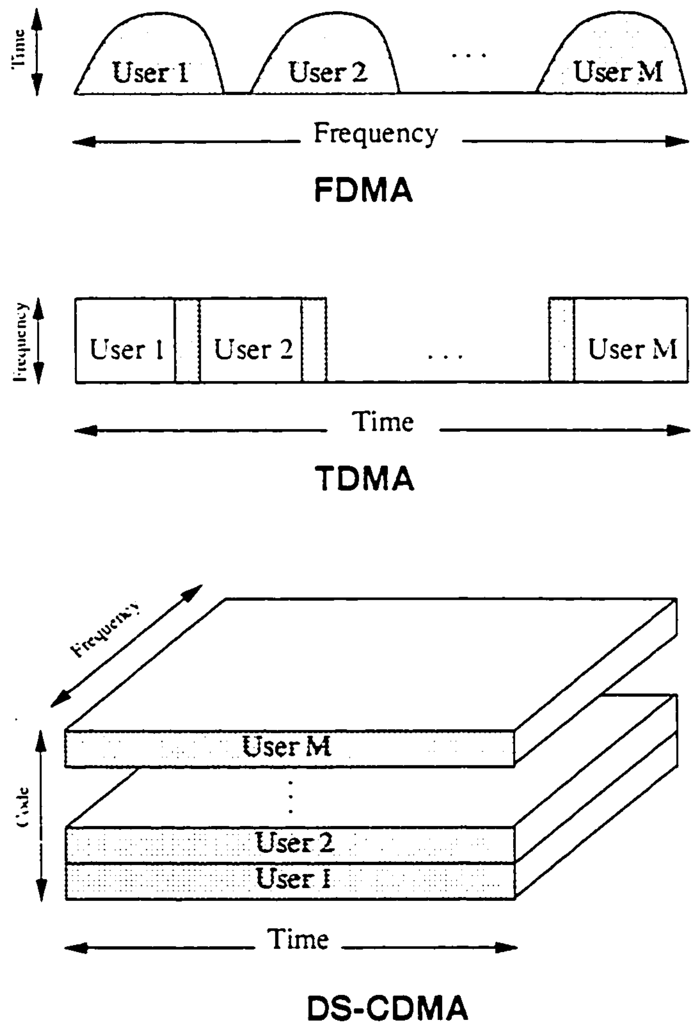


Figure 1.1: Multiple access techniques

The second type of multiple access techniques used in the second generation mobile communication systems, is called the Time Division Multiple Access (*TDMA*). In this approach, users are aligned in time slots rather than frequency slots. These time slots are non-overlapping to each other to provide no interference from one user on another.

The main drawback of both FDMA and TDMA is that they have hard capacity limit. It means that after the number of users equal to the number of frequency or time slots. adding one more user is not possible, since all the available frequency or time slots have already been allocated to the existing users. To this end, another kind of multiple access scheme called Code Division Multiple Access (*CDMA*) was proposed.

The CDMA system as a candidate for providing soft capacity limit is not a new technique. It was widely used in military applications, and recently, it has been become popular in telecommunications industry due to its exceptional properties that will be mentioned in Chapter 2 [10].

In CDMA, a unique *code* (which is also called a *Signature Sequence* or a *Signature Waveform*) is assigned to each user. Such signature sequences have a bandwidth well beyond what is required for the transmission of information. Therefore, coding the data with them results in Spread Spectrum (*SS*) communication. The number of signature sequence pulses (*chips*) in one bit duration is called the *processing gain*, N.

Signature sequences are usually Pseudo-random or Pseudo-Noise (*PN*) codes with the duration of each chip (T_c) much less than the bit duration. These PN codes are usually generated by a feedback shift register with linear feedback and are called Maximal-Length sequences. The PN codes generated in this manner, have some special characteristics such as [32]:

- The number of *1*s is one more than the number of *0*s in each period (Balance property).

- *One-half* of the runs of each kind of *1*s and *0*s are of length *one*, *one-fourth* of length *two*, *one-eighth* of length *three*, ... as far as it is applicable (Run property). The total number of runs is $(N+1)/2$ and $N = 2^m - 1$ where m is the number of shift register bits.
- The normalized auto-correlation of the generated codes is either 1 or $-1/N$.

1.3 Recent Research in Multi User Detection

Among the spread-spectrum techniques that will be discussed in Chapter 2, the most popular one is the *Direct-Sequence* CDMA (***DS-CDMA***) where each active user's data is modulated (multiplied) by a unique code. When the signature waveforms assigned to different users are not orthogonal, each user suffers from the *Multiple Access Interference* (*MAI*) emanating from the other active users.

In order to combat such an undesired matter, efforts have been made to mitigate MAI with the aim of reducing the Bit Error Rate (*BER*). Perhaps, the most prominent work has been done by Verdu [33]. His devised receiver is an optimal one as it is based on the Maximum Likelihood (ML) detection principle. This kind of detector sounds perfect as far as only a few users attempt to share the channel. Otherwise, the computational complexity grows exponentially with the number of users making this approach impractical to implement. Therefore, the goal of suppressing MAI has been compromised to find schemes that sacrifice optimality for easier-to-implement circuits while maintaining a satisfactory level of performance. As a result of such endeavors, some suboptimal multiuser detectors have been introduced.

The first class of receivers with performance relaxation via simpler structures are Linear Multi-User Detectors (LMUD) in which a linear mapping is applied to the outputs of the Matched Filters (MF). The most familiar ones under this class are the Decorrelator and Minimum Mean-Squared Error (MMSE) detectors [1]. Such receivers have less complexity than that of the optimal ML receiver, however, they suffer from a main drawback of inverse cross-correlation matrix calculation. Such a computation must be done in real time which takes a large amount of memory when the number of users is high. Moreover, the necessity to guarantee the existence of inverse of the cross-correlation matrix makes the case more problematic. Thus, another class of multiuser detectors with still a better structure in the sense of complexity were proposed.

The second suboptimal class of detectors are subtractive or interference cancellation based multiuser detectors. In this case, the interference of each user on the others is estimated, re-spread, and cancelled from the received signal. This process is usually done through a multitude of stages giving these schemes the name multistage detectors. Successive Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) detectors are well-known examples of this class of detectors. In the case of SIC, interferences are cancelled sequentially, while, in PIC the interferences of all other users on each one are removed at once, which makes this scheme more attractive due to its higher speed. Recently, another kind of PIC called Partial Parallel Interference Cancellation (*PPIC*) has been proposed by Divsalar *et al* [3], [4]. In this scheme, instead of complete cancellation of the interferences, the cancellation is done partially by introducing a partial cancellation coefficient λ that is always less than unity. It has been proven that the performance of PPIC is drastically better than that of the pure PIC.

It is worth noting that although all kinds of subtractive multiuser detectors offer less complex structures compared to LMUDs, their efficiency is inferior to that of the Linear Multi-User Detectors (LMUD). Consequently, the latter receivers and specially the Decorrelator Detector (DD), serves as a reference to quantify the performance degradation of any newly-proposed receiver. Henceforth, any step which is taken to raise the performance of SIC, PIC, and PPIC in each stage without adding any remarkable complexity, merit special attention. As a result, such a performance enhancement results in less stages of iteration which makes interference-cancellation-based detectors more promising for the third generation wireless receivers.

1.4 Objective

The objective of this thesis is to devise a new scheme for Multi User Detection (MUD) that results in less performance degradation with a reasonable complexity.

1.5 Research Contributions

Some of the main contributions to this thesis are as follows:

- Derived a closed form equation, analyzed, and simulated the outputs of a multistage Soft Partial Parallel Interference Cancellation (PPIC).
- Analyzed and simulated multistage Hard Partial Parallel Interference Cancellation (PPIC).
- Amplitude and phase estimation for all active users.
- Proposed a new MUD scheme based on the combination of multistage Soft and Hard PPIC with parameter estimation: simulated and compared the proposed scheme with the case where perfect knowledge of the parameters is assumed, Decorrelator, SIC, and single user cases.
- Simulated the near-far problem by splitting users into groups with each group having a different power level.
- Applied the proposed scheme to UMTS (BPSK and QPSK modulations, PN codes).
- Compared the complexity issue of the proposed method with some other known detectors.

1.6 Organization of the Thesis

This thesis is continued as follows

Chapter 2 presents the spread spectrum techniques that have been proposed so far. The spread spectrum technique is discussed under two major groups of pure and hybrid CDMA. Under pure CDMA group, Frequency-Hopping, Time-Hopping, and Direct-Sequence CDMA are introduced. For those under hybrid CDMA group, some combinations of pure CDMA as well as some combinations with other techniques such as TDMA are presented.

Chapter 3 addresses some MUD techniques. Optimum and sub-optimum detectors with their benefits and drawbacks are discussed. Under sub-optimum group of multiuser detectors, two major groups of linear and subtractive detectors are introduced.

Chapter 4 covers the new method that we have proposed for MUD. In this new method, a combination of Soft and Hard PPIC detectors with parameter estimation is introduced. Through simulation, it is shown that our proposed scheme surpasses the performance of the linear detectors.

Chapter 5 contains some trends in MUD that are of special interest. These trends are studied in two distinct sections of near-far problem and application of our proposed method to some newly-proposed standards for the third generation systems.

Finally, Chapter 6 concludes this thesis and some suggestions for future work are included.

Chapter 2

Spread Spectrum Techniques

Some well-known CDMA techniques are introduced in this chapter. In addition to the general capabilities of CDMA, there are some exclusive properties attributed to each of these techniques, which will be reviewed briefly. The most well-known available CDMA technique can be divided into two groups of pure and hybrid CDMA [2], [10]. Under pure CDMA group, *Direct-Sequence* (*DS*), *Frequency-Hopping* (*FH*), and *Time-Hopping* (*TH*) techniques will be discussed. For those under hybrid CDMA group, some combinations of pure techniques as well as a combination of CDMA and TDMA (*CTDMA*) and Multi-Code CDMA (*MC-CDMA*) will be presented.

2.1 Direct-Sequence CDMA

This technique is the most popular technique. In this technique, the information symbols are directly modulated (multiplied) by the signature sequences (codes). Figure 2.1 shows a simple block diagram of a transmitter and a receiver used for such a technique. As it is seen, before carrier modulation, the users' information data are spread with the codes assigned exclusively to each user.

Figure 2.2 shows a binary antipodal signal which is spread by a signature

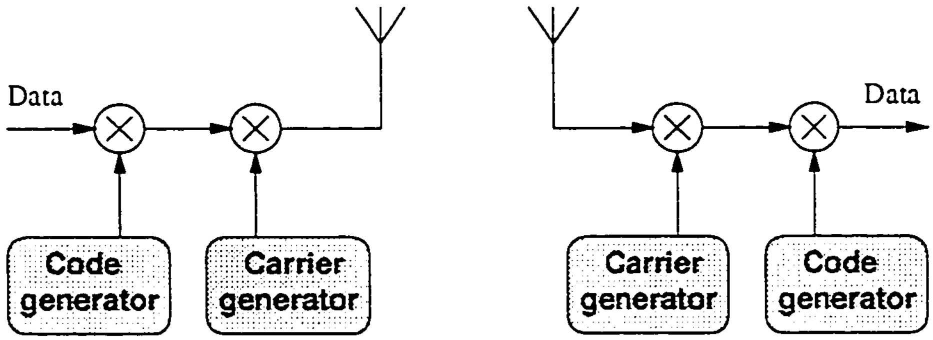


Figure 2.1: Transmitter and receiver of a DS-CDMA system [2].

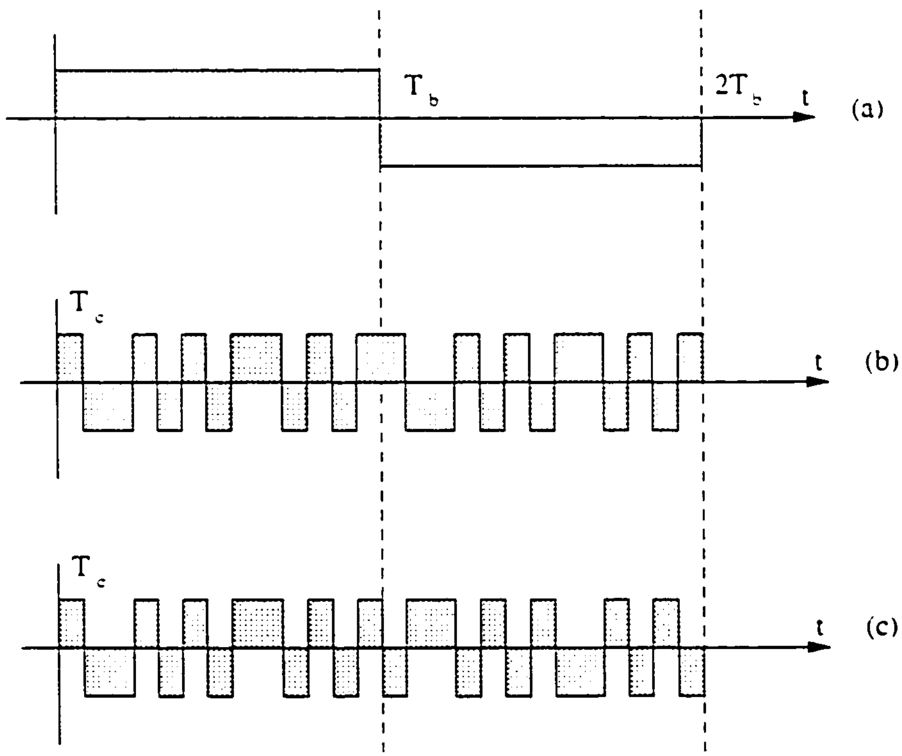


Figure 2.2: Spreading a binary data using DS-CDMA technique. (a) Original data, (b) Signature sequence with $N = 13$, and (c) Spread data.

waveform.

The spreading codes used to spread the information data can be in the form of either short or long codes. In the former case, the period of the signature sequence is equal to the symbol period, whereas in the latter case, more than one symbol occur in one period of the signature waveform. Both of these codes have their own benefits and drawbacks. For example, when short codes are used, the circuitry will be simpler, while giving a fixed interference to each user. Therefore, some users suffer from a larger amount of interference than the others. For the long code case, the interference on each user is more random-like, although the complexity will be higher.

2.1.1 General Capabilities

Due to its simplicity, DS-CDMA is suitable as an air interface in satellite and cellular communication systems. In what follows, some of the main attributes of such a technique will be explained briefly [2], [13].

Multiple access: Since each user is assigned a specific code, as far as the cross-correlation between the codes is good (low) enough, each user's data can be recovered with high reliability. Therefore, multiaccess requirement is met.

Multipath diversity: Since in a mobile environment, there are more than one path for signals to travel, if the signals received from different paths are combined, we may have constructive and destructive combination. When DS-CDMA is used, all the signals arrived at the receiver with the time difference of more than one chip duration can be treated as different users provided that the autocorrelation of codes is good (high) enough and, they can be combined through a Rake receiver [31]. Therefore, multipath diversity is possible.

Narrowband interference rejection: While DS-CDMA signal is considered as a wideband signal, it will not be contaminated by a narrowband noise interference. This is because when the arrived signal at the receiver is decoded (despread), the useful wideband signal will turn out as a narrowband signal; while the narrowband disturbance would be in the form of a wideband signal with low power density.

Low probability of interception: Due to their wideband nature, CDMA signals have low power density. This desirable feature prevents their signal to be heard by the other listeners.

2.1.2 Specific Properties

There are some advantages and disadvantages exclusively contributed to the DS-CDMA technique which are mentioned in what follows.

Advantages

- DS-CDMA technique is usually called a soft-interference-limited technique. It means that the more the number of active users, the lower is the link performance, but the whole information is seldom lost. This is against FDMA and TDMA where in the addition of an extra user leads to destroy the information originating from the aliased users.
- The spreading operation is easy because it is a simple multiplication (modulation). Since the signals are digital, this multiplication can be done through logical additions (Exclusive OR circuits) that makes it much easier to implement.
- The system is based on a single carrier.

Disadvantages

- Each user suffers from the Multiple Access Interference (MAI) emanating from other users that attempt to share the channel concurrently. Ideally, when all codes assigned to different users are orthogonal to each other, there would be no MAI. However, since the number of orthogonal codes is low, the capacity will be reduced. In addition, even the codes are assumed to be orthogonal. such an orthogonality can not be guaranteed in an asynchronous condition. Therefore, although it can be mitigated by choosing the signature sequences with good (low) cross-correlations, MAI will be an inevitable part of DS-CDMA technique.

- When the mobile users are at different distances to hub or base station, the MAI coming from the closer user will exacerbate the situation of the weak users' data which are more distant. This issue is called the *Near-Far* problem. To avoid this issue, power control should be applied on all transmitters in order to receive all signals at almost the same power level. It is noteworthy that perfect power control is hard to achieve in practice.

- The synchronization between signature sequences is difficult, because the synchronization error is needed to be kept within a fraction of a chip duration.

2.2 Frequency-Hopping CDMA

In this technique. the data will be modulated with a carrier whose frequency changes according to the signature sequence. The basic diagram of such a technique is shown in Figure 2.3.

The main difference between the FH-CDMA and DS-CDMA techniques is that in the former case in each time interval, only a portion of the bandwidth is used with higher power, while in the latter case, the whole bandwidth is used simultaneously. Figure 2.4 shows this difference.

There are two types of frequency hopping technique. If the hope rate is greater than the symbol rate, then it is called *Fast Hopping* where a symbol is transmitted through different carriers. On the other hand, if numerous symbols are sent with

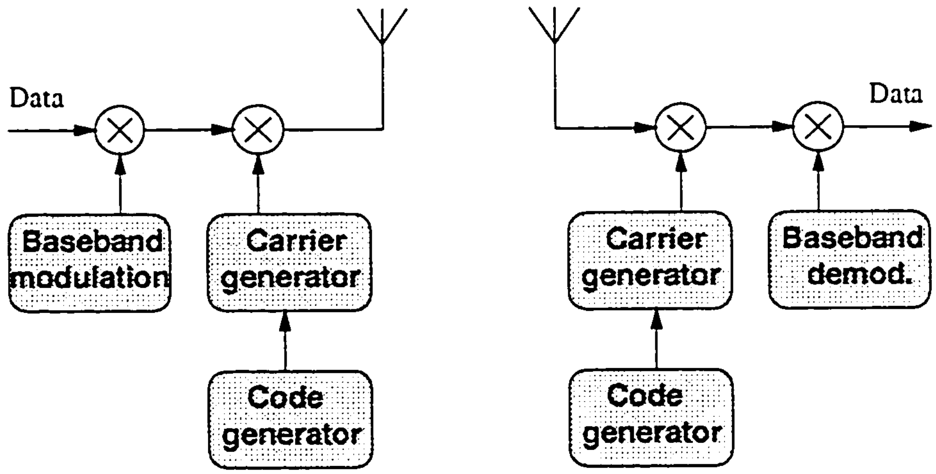


Figure 2.3: **Transmitter and receiver of an FH-CDMA system.**

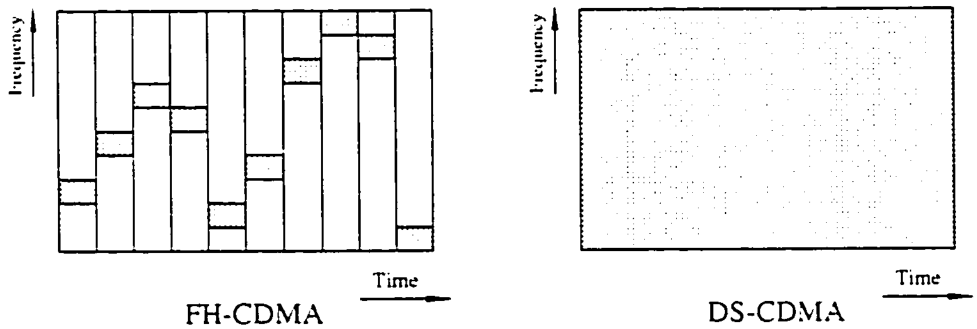


Figure 2.4: **Comparison of the FH-CDMA with DS-CDMA system (N = 10).**

the same carrier, the technique is called *Slow Hopping.*

2.2.1 General Capabilities

The general capabilities can be expressed in the same way as it was done for the DS-CDMA technique.

Multiple access: While one user occupies a portion of the bandwidth, other users can use the remaining bandwidth simultaneously.

Multipath diversity: Since in each time interval, each user is transmitted through a distinct carrier frequency, the received signal will experience different fadings. Therefore, if it is averaged over different paths, multipath fading will be resolved, although it is not as efficient as DS-CDMA.

Narrowband interference rejection: In this case, narrowband interference will occur in one or some of the transmitting bands, while the others will be clear of such a disturbance.

Low probability of interception: If the frequency of the signal that is going to be transmitted is unknown, it will be hard to detect the information by other listeners.

2.2.2 Specific Properties

Advantages

- Synchronization is easier, because it needs to be done in a fraction of hopping interval (Instead of chip interval in the case of DS-CDMA).
- The near-far problem is less serious since the probability that two or more users sharing the same bandwidth is less.

Disadvantages

- The system is based on a multicarrier technique. Therefore, the complexity is higher than the single-carrier case.
- Switching between the carriers occurs very frequently. Therefore, it needs more bandwidth than in the DS-CDMA case.

2.3 Time-Hopping CDMA

The last technique in pure CDMA class to be discussed is Time-Hopping CDMA (TH-CDMA) in which, each user transmits its data in a short time at the intervals that are defined by each user's code. Figures 2.5 and 2.6 show the block diagram and the time-frequency sharing of such a scheme, respectively. As it is seen, in a short burst, the information of each user is transmitted using the whole available spectrum. This is against the FH-CDMA technique where, in each time slot only a portion of the available bandwidth is occupied by each user.

2.3.1 General Capabilities

Multiple access: Since a unique signature sequence (code) is assigned to each user, each user shares the channel with the others in time division format where the time intervals are determined by the signature waveforms. These time intervals are random-like. Therefore, the probability of time aliasing would be low.

Narrowband interference rejection: Since the signal is transmitted in short bursts, it is only contaminated by a narrowband interference in those short intervals.

Low probability of interception: When the time intervals in which the signals are transmitted are unknown, it will be hard for a third party to realize and detect any information pertaining to users.

2.3.2 Specific Properties

Advantages

- It is simpler than the FH-CDMA because it has a single carrier.
- It is good for near-far cases, because, in most intervals, users do not have any overlap. Therefore, even weak users can be detected since there is no interference coming from strong users.

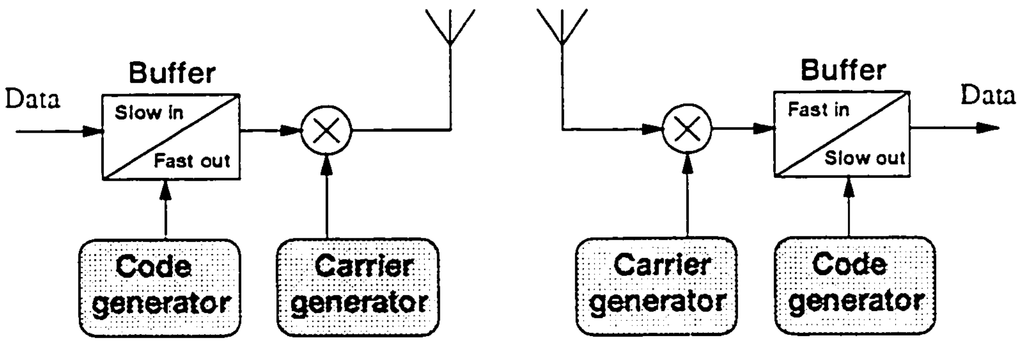


Figure 2.5: **Transmitter and receiver of a TH-CDMA based system.**

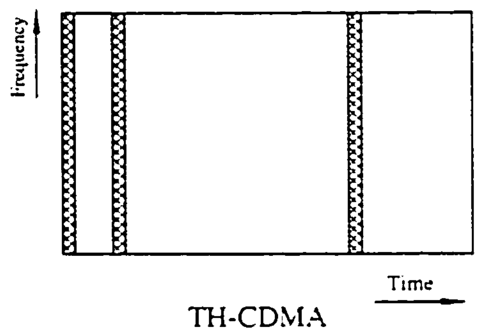


Figure 2.6: **Time-frequency sharing between the TH-CDMA users.**

Disadvantages

- This technique is more vulnerable to multipath fading problem. since the signal is transmitted in a short time while employing the whole available spectrum.
- Synchronization is difficult, because it has to be achieved in a short time.
- When overlapping occurs, like in TDMA, all concurrent data will be lost.

2.4 Hybrid Techniques

The objective of using hybrid techniques is to combine the advantages carried by each technique individually. Obviously, a possible disadvantage can be the complexity increase. The most well-known combinations of CDMA techniques are Direct-Sequence Frequency-Hopping (DS/FH), Direct-Sequence/Time-Hopping (DS/TH), CDMA/TDMA (CTDMA), and Multi-Code CDMA (MC-CDMA). In what follows, a brief explanation of each technique is given.

2.4.1 Direct-Sequence/Frequency-Hopping CDMA

In this technique, first of all, the data stream is spread by the signature sequence. After this stage, the spread data is modulated with different carriers whose frequencies are defined by a different code generator. Figure 2.7 shows the block diagram of DS/FH-CDMA transmitter. The resultant system has the advantages of soft interference limit from DS-CDMA and near-far resilience from the FH-CDMA techniques.

2.4.2 Direct-Sequence/Time-Hopping CDMA

In this technique, the spread data will be transmitted in random-like intervals defined by another code generator (Figure 2.8).

2.4.3 CDMA/TDMA

This hybrid technique is a combination of CDMA and TDMA. After spreading users' data, their information will be transmitted in fixed time intervals (Figure 2.9). This hybrid technique is considered as an evolutionary system, since present-day satellite communications are based on TDMA technique.

2.4.4 MC-CDMA

In this scheme, instead of a unique code assignment to each user, a variety of codes spread the data belonging to each user. These codes have different processing gains but are orthogonal to each other. The most famous codes used for this purpose are Walsh-Hadamard codes[10]. This technique is suitable when variable bit rate services are required.

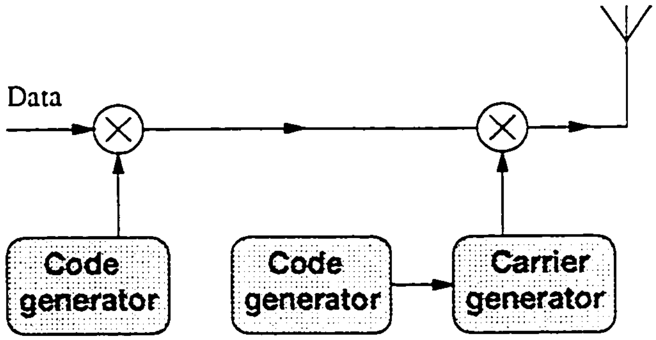


Figure 2.7: DS/FH-CDMA transmitter.

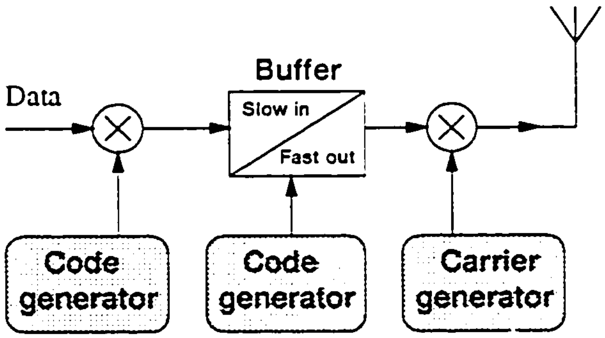


Figure 2.8: DS/TH-CDMA transmitter.

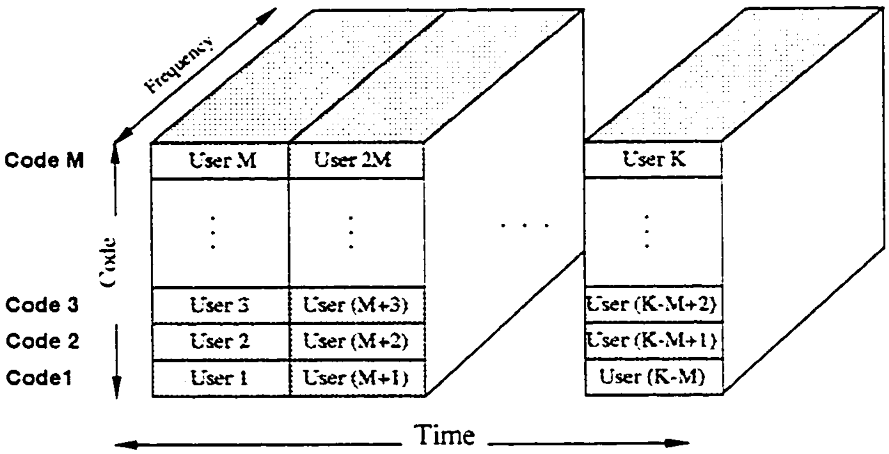


Figure 2.9: Time-frequency-code sharing in CDMA/TDMA technique.

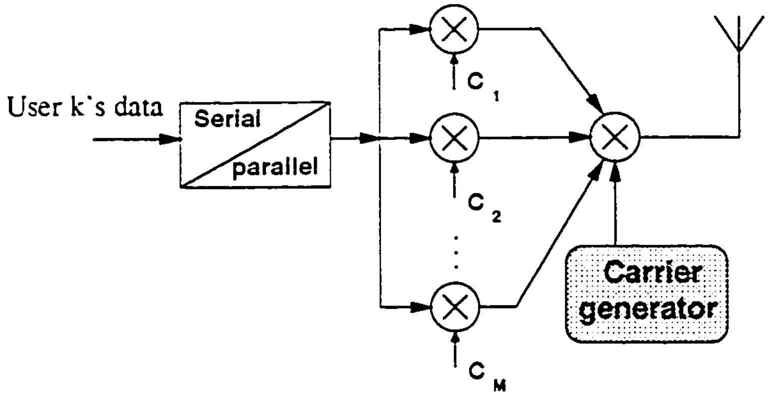


Figure 2.10: MC-CDMA **transmitter for one user.**

2.5 Spread Spectrum and Multi User Detection

As it was mentioned earlier, DS-CDMA is the most popular among the spread spectrum techniques for multiple access applications. Therefore, in the remainder of this chapter, a system model based on DS-CDMA scheme will be discussed in more detail.

2.5.1 System Model

Assuming that K users share a channel and the modulation is BPSK, the baseband model of the received signal at the receiver can be written as

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} S_k(t-\tau_k) + n(t) \\ &= \sum_{k=1}^{K} \sqrt{E_{bk}} d_k(t-\tau_k) c_k(t-\tau_k) e^{j\varphi_k} + n(t) \end{aligned}$$

where, E_{bk}, $d_k(t-\tau_k)$, $c_k(t-\tau_k)$, and φ_k are bit energy, information bit, signature waveform, and the carrier shift of kth user, respectively. The τ_k's are the time delays of users at the receiver end. Under synchronous condition, we have $\tau_1 = \tau_2 = \ldots \tau_K = 0$. The noise $n(t)$ is a complex Additive White Gaussian Noise (AWGN) with zero mean and two-sided Power Spectral Density (PSD) of $N_o/2$

W/Hz for each real and imaginary component. The d_k and $c_k \in \{+1, -1\}$ with the duration of T_b (bit duration) and T_c (chip duration), respectively, are assumed to be independent identically distributed (i.i.d.) random variables. The processing gain is N. Therefore, $N = T_b/T_c$. A simple representation of such a received signal is depicted in Figure 2.11. At the receiver end, the arrived signal is passed through a group of correlators in order to recover the information stream transmitted by each user. Hence, the output of the kth correlator under synchronous condition would be (Figure 2.12)

$$\begin{aligned} \tilde{d}_k^{(0)} &= \frac{1}{T_b}\int_o^{T_b} r(t)c_k(t)dt \\ &= \frac{1}{T_b}\int_o^{T_b} [\sum_{k'=1}^{K} \sqrt{E_{bk'}} d_{k'} c_{k'}(t) e^{j\varphi_{k'}} + n(t)] c_k(t)dt \\ &= \sum_{k'=1}^{K} \sqrt{E_{bk'}} d_{k'} \rho_{k'k} e^{j\varphi_{k'}} + n_k \end{aligned}$$

where

$$\rho_{kk'} = \rho_{k'k} = \frac{1}{T_b}\int_o^{T_b} c_{k'}(t).c_k(t)dt = \frac{1}{N}\sum_{i=1}^{N} c_{k'i}.c_{ki} \quad ,$$

$$n_k = \frac{1}{T_b}\int_o^{T_b} n(t).c_k(t)dt$$

It is easy to see that n_k is a complex Gaussian random variable with zero mean and variance of $N_o/2$ W/Hz. For the sake of simplicity in notation, hereafter, we will consider the first user as the one of interest, and also, all notations are based on

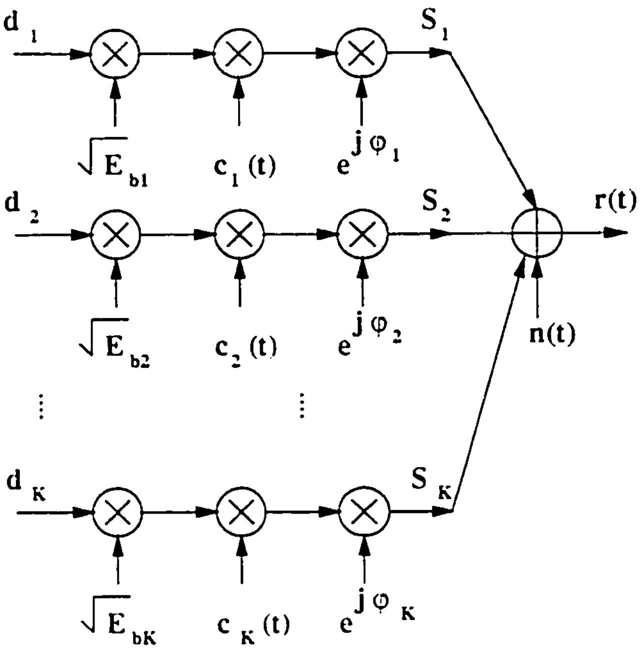


Figure 2.11: **DS-CDMA channel and receiver model.**

one bit duration (T_b). Hence, the soft output of the first correlator will turn out as

$$
\begin{aligned}
\tilde{d}_1^{(0)} &= \frac{1}{T_b}\int_o^{T_b} r(t)c_1(t)dt \\
&= \frac{1}{T_b}\int_o^{T_b} [\sum_{k=1}^{K} \sqrt{E_{bk}} d_k c_k(t) e^{j\varphi_k} + n(t)] c_1(t)dt \\
&= \sum_{k=1}^{K} \sqrt{E_{bk}} d_k \rho_{1k} e^{j\varphi_k} + n_1 \\
&= \sqrt{E_{b1}} d_1 e^{j\varphi_1} + \sum_{k=2}^{K} \sqrt{E_{bk}} d_k \rho_{1k} e^{j\varphi_k} + n_1
\end{aligned}
$$

where the first, second, and the third terms denote the useful information, the MAI, and the noise component, respectively.

Now, if the signal pertaining to each user is detected without any regard of other users', the procedure is called Single User Detection (SUD). The quality of the output of such a detector depends strongly on the cross-correlation between the codes of different users.

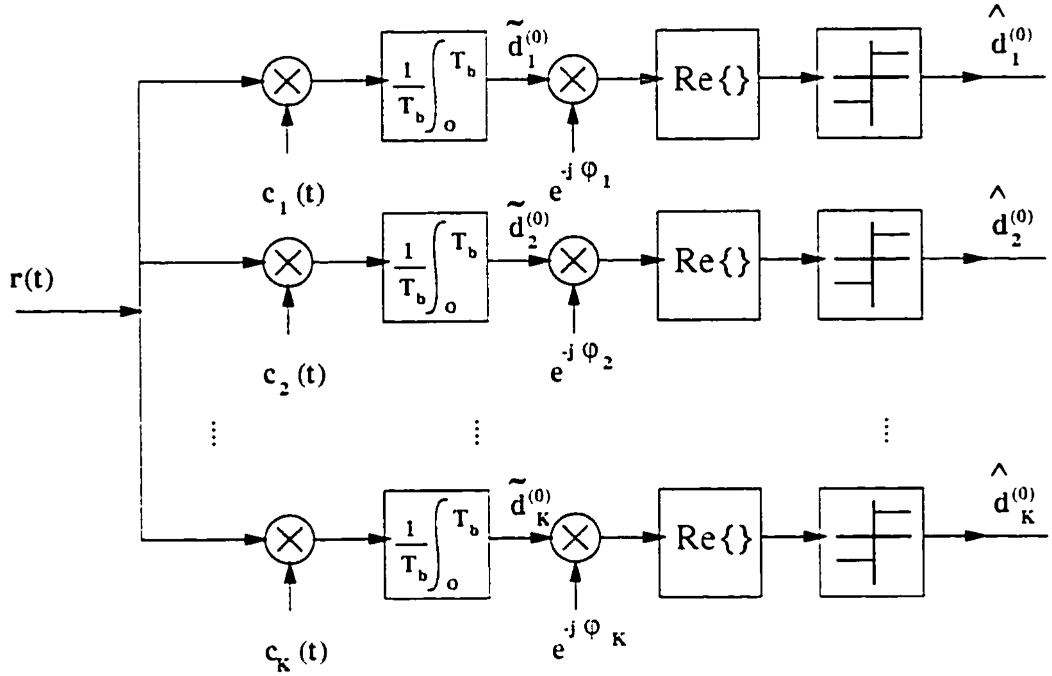


Figure 2.12: **Soft and hard outputs of correlators at the receiver.**

In order to mitigate the effect of MAI, some suggestions have been made in [1]:

- employing codes whose cross-correlation is good (low) enough in order to recover each user's information with a good accuracy.
- applying power control on each transmitter such that all users are received at almost the same power level.
- use of antenna diversity where the data of each user is transmitted and/or received through a multitude of antenna arrays, and
- use *Multi User Detection (MUD)*, i.e., take advantage of the information of all users when recovering the data transmitted by each user.

2.6 Summary

In this chapter, a brief introduction of different types of spread spectrum technique was presented. The most popular one for multiuser detection purposes is the DS-CDMA technique. In Chapter 3, we discuss different kinds of DS-CDMA based multiuser detectors that have been proposed recently.

Chapter 3

Multi User Detection Technology

Some well-known multiuser detectors will be introduced in this chapter. As it was mentioned in Chapter 2, the spread spectrum technique widely used, is DS-CDMA. In general, any type of multiuser detector is either optimum or sub-optimum. Under sub-optimum group, two classes of Linear and interference-cancellation-based detectors are addressed.

3.1 Optimum Multiuser Detector

The optimum multiuser detector is based on the Maximum-Likelihood (ML) detection. As it is known from Chapter 2, the received signal (synchronous case) is

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} S_k(t) + n(t) \\ &= \sum_{k=1}^{K} \sqrt{E_{bk}} d_k(t) c_k(t) e^{j\varphi_k} + n(t) \end{aligned}$$

where, $n(t)$ is an AWGN. In each bit interval, optimal detector, selects the bit sequences d_1, d_2, d_3, ... , d_K such that the

$$exp\left(-\frac{1}{2\sigma^2}\int_0^{T_b}\left[r(t)-\sum_{k=1}^{K}S_k(t)\right]^2 dt\right) \tag{3.1}$$

is maximum [33].

In order to maximize (3.1), the squared Euclidean distance of $\int_0^{T_b}|r(t) - \sum S_k(t)|^2 dt$ needs to be minimized.

The Euclidean distance is defined as [4]

$$\begin{aligned} D &= \int_0^{T_b}\left|r(t)-\sum_{k=1}^{K}S_k(t)\right|^2 dt \\ &= \int_0^{T_b}\left|r(t)-\sum_{k=1}^{K}\sqrt{E_{bk}}d_k(t)c_k(t)e^{j\varphi_k}\right|^2 dt \\ &= \int_0^{T_b}|r(t)|^2 dt \\ &\quad -2Re\left\{\int_0^{T_b} r(t)\sum_{k=1}^{K}\sqrt{E_{bk}}d_k(t)c_k(t)e^{-j\varphi_k}\right\}dt \\ &\quad +\int_0^{T_b}\left[\sum_{k=1}^{K}\sqrt{E_{bk}}d_k(t)c_k(t)e^{j\varphi_k}\right]\left[\sum_{l=1}^{K}\sqrt{E_{bl}}d_l(t)c_l(t)e^{-j\varphi_l}\right]dt \end{aligned} \tag{3.2}$$

Discarding the common term, i.e., the first term in (3.2), the minimization is equivalent to maximizing,

$$\begin{aligned} \Omega &= Re\left\{\int_0^{T_b} r(t)\sum_{k=1}^{K}\sqrt{E_{bk}}d_k(t)c_k(t)e^{-j\varphi_k}\right\}dt \\ &\quad -\frac{1}{2}\int_0^{T_b}\left[\sum_{k=1}^{K}\sqrt{E_{bk}}d_k(t)c_k(t)e^{j\varphi_k}\right]\left[\sum_{l=1}^{K}\sqrt{E_{bl}}d_l(t)c_l(t)e^{-j\varphi_l}\right]dt \end{aligned}$$

Since

$$\tilde{d}_k^{(0)} = \frac{1}{T_b}\int_0^{T_b} r(t)c_k(t)dt \ , \ \rho_{kl} = \frac{1}{T_b}\int_0^{T_b} c_k(t)c_l(t)dt$$

we get

$$\Omega = Re\left\{\sum_{k=1}^{K}\sqrt{E_{bk}}d_k\tilde{d}_k^{(0)}e^{-j\varphi_k}\right\}dt - \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{K}\sqrt{E_{bk}E_{bl}}d_k d_l \rho_{kl} e^{j(\varphi_k-\varphi_l)}$$

This kind of multiuser detector provides the most reliable outputs and rejects the effect of MAI. Therefore, its performance is superior to all other detectors. In spite of its great performance, the complexity of ML detector is subject to an exponential growth in the number of users, since it is based on a full search, performed, e.g., using the Viterbi algorithm [1]. Hence, when the number of active users is large, this approach turns out to be too complex to implement. As a result, some sub-optimum multiuser detectors that are less complex while causing a reasonable performance degradation have been proposed.

Sub-optimum detectors are divided into two major groups of Linear and interference cancellation based detectors [1] which will be discussed in the remainder of this chapter.

3.2 Linear Multiuser Detectors

In any detector under this group, a linear mapping is applied to the outputs of the Matched Filters (MF) [1]. Some well-known examples of such detectors are Decorrelator Detector (DD) and Minimum Mean-Squared Error (MMSE) detector.

3.2.1 Decorrelator Detector

As a linear mapping, this type of detector applies the inverse of the cross-correlation matrix to the outputs of MFs. Figure 3.1 shows the block diagram of such a detector. If matrix notation is used, we get

$$\begin{aligned} r &= S + n \\ &= A.D.C + n \end{aligned} \tag{3.3}$$

$$d_{MF} = A.D.R + N \tag{3.4}$$

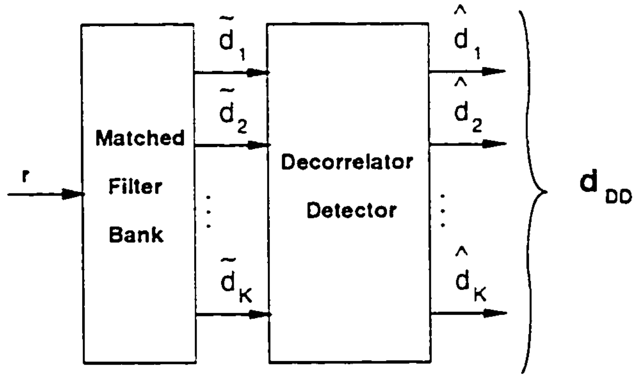


Figure 3.1: **Decorrelator multiuser detector.**

$$\begin{aligned} d_{DD} &= d_{MF}.R^{-1} \\ &= A.D + N.R^{-1} \end{aligned} \quad (3.5)$$

where, the symbols are defined as follows

r : Received signal

S : Total transmitted signal

n : Addiditve White Gaussian Noise (AWGN)

A : User's amplitudes matrix

D : Users' information data

C : Signature waveforms vector

$\tilde{d}$: Outputs of Matched Filters (MF)

R : Cross-correlation matrix

N : Noise component of Matched Filters (MF) outputs

d_{DD} : Outputs of Decorrelator Detector (DD)

Advantages

- It does not require any knowledge about the amplitude of users. Therefore, it is near-far resistant.

- The computational complexity is much less than that of ML detector.
- Eliminates the effect of MAI completely.

Disadvantages

- As it is seen from (3.5), this type of detector enhances the background noise.
- The computation of the inverse cross-correlation matrix (R^{-1}) has to be done in real-time specially in an asynchronous environment.
- In some special cases, R^{-1} does not exist.

In spite of these disadvantages, this type of detector provides a good performance which in most cases is used as a reference to gauge other kinds of detectors which will be explained later in this chapter. It is noted that Decorrelator Detector will correspond to the optimum detector if either the amplitudes of users are unknown or users are time independent.

3.2.2 MMSE Detector

This kind of detector, tries to minimize the mean-squared error between the transmitted data and MF output. This kind of detector is same as the DD type except the linear mapping used here takes the effect of noise into consideration. Using matrix notation, we get [1]

$$\begin{aligned} r &= A.D.C + n \\ \tilde{d} &= A.D.R + N \\ d_{MMSE} &= d_{MF}.L_{MMSE} \end{aligned}$$

where

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

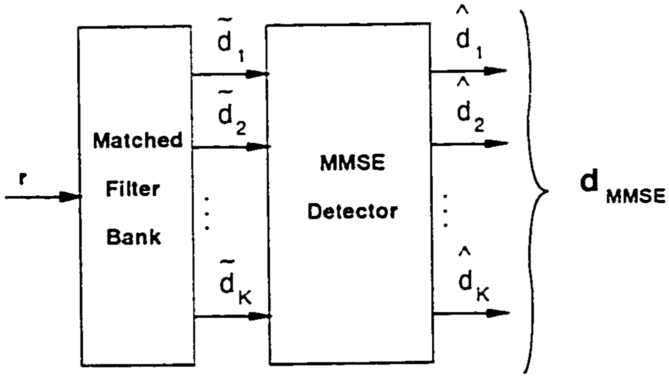


Figure 3.2: MMSE multiuser detector.

A simple block diagram for this case is shown through Figure 3.2

Advantage

- It provides a better performance than the DD since it takes into account the effect of noise.

Disadvantage

- It requires the knowledge of users' parameters (amplitude, phase, delay). Therefore, it is less resistant to the near-far issue.

3.3 Subtractive Multiuser Detectors

In these kinds of detectors which are also called the interference-cancellation-based detectors, the MAI affecting each user is estimated, re-spread, and cancelled from that user. This process is usually done through a number of stages giving rise to multistage detectors. Under this group, the most cited types are Successive Interference Cancellation (SIC) and Parallel Interference Cancellation (PIC) detectors.

3.3.1 Successive (Serial) Interference Cancellation

By applying this approach, users are detected one after the other. At the receiver end, users are ranked according to their received power in order to detect the strongest user first, since this user can be detected most reliably. Soon after the detection of the strongest user, the second strongest user will be detected. This procedure is continued until all users' data become ready.

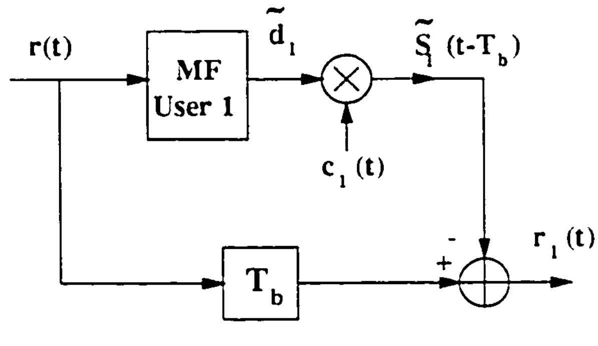
If the soft decision of each user's data is used to estimate the interferences, the detector is called *Soft* SIC detector, and if hard decision is used the approach would be a *Hard* SIC detector. Each of the soft and hard SIC detectors have their own benefits and drawbacks. Soft SIC detector is simple because it does not require any estimate of the amplitude and the phase of each user. However, because it enhances the noise, does not provide high performance. On the other hand, hard SIC detector will offer better performance given that a good approximation of the users' parameters is available. This means that this kind of SIC detector requires a more complex circuitry. Figure 3.3 shows the block diagram of such a detector for the first user as the desired user.

Advantages

- It offers a simple circuitry in comparison to all other types of multiuser detectors.
- Since users are detected according to their receiving power, it is more resilient to the near-far problem.

Disadvantages

- There is a delay of about one bit duration to detect each user which makes this scheme less efficient for the cases of high-load systems.
- The detection of all other users depends strongly on the quality of the detection of the strong users such that any erroneous decision will be propagated through the decision of all other users.
- When the users are changed, a process is needed to reorder users according to their receiving power.



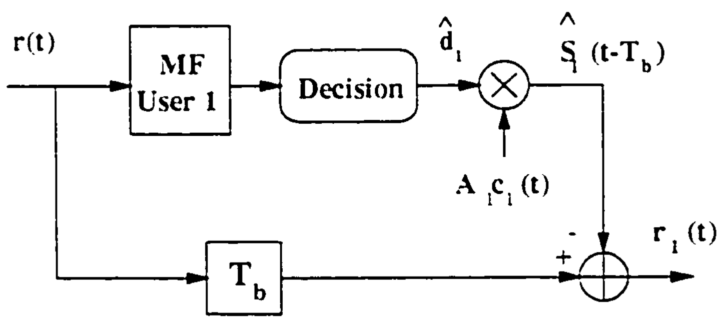


Figure 3.3: (a) Soft and (b) hard SIC detector for the first user.

3.3.2 Parallel Interference Cancellation

This type of detector takes a parallel approach to cancel the MAI affecting each user. In other words, the MAI originating from other users is estimated, re-spread, and cancelled from the received signal at once. Again, same as the SIC scheme, PIC process can be done in a multistage architecture. Figure 3.4 shows a block diagram for a single stage PIC detector.

Advantages

- It is fast since the output for all users would be ready in parallel format which takes around one bit duration per stage.
- It is much simpler than the ML and DD detectors.

Disadvantages

- It provides more complex circuitry than the SIC detector.
- It is more vulnerable to near-far issue compared to SIC detector. because strong and weak users are detected at the same time.

3.3.2.1 PIC Detector Analysis

As it was discussed in Chapter 2, the soft output of MF (correlator) for the first user is

$$\tilde{d}_1^{(0)} = \sqrt{E_{b1}}\, d_1\, e^{j\varphi_1} + \sum_{k=2}^{K} \sqrt{E_{bk}}\, d_k\, \rho_{k1}\, e^{j\varphi_k} + n_1$$

So,

$$\tilde{d}_1^{(0)} e^{-j\varphi_1} = \sqrt{E_{b1}}\, d_1 + \sum_{k=2}^{K} \sqrt{E_{bk}}\, d_k\, \rho_{k1}\, e^{j(\varphi_k - \varphi_1)} + n_1 e^{-j\varphi_1}$$

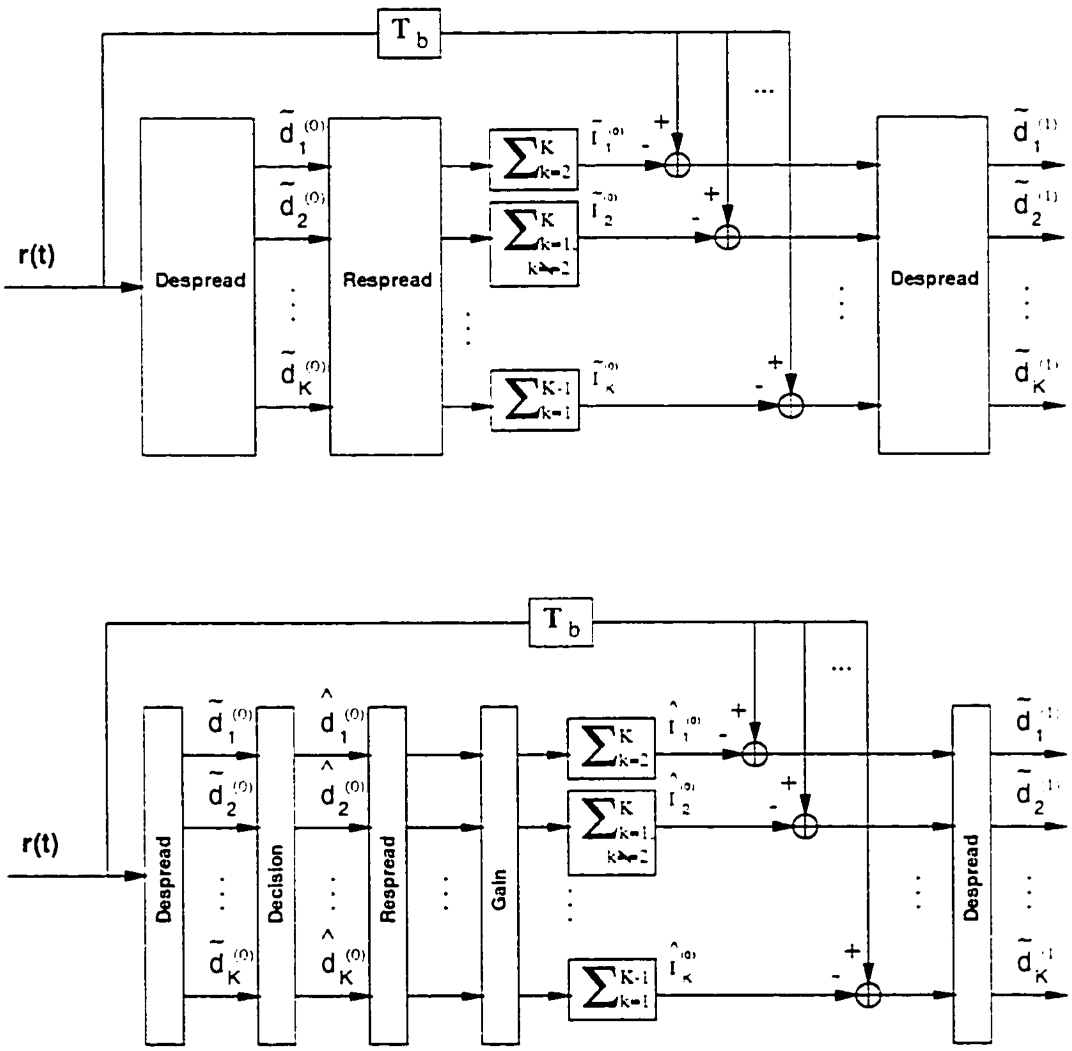


Figure 3.4: One stage of (a) soft and (b) hard PIC detector.

and

$$\widehat{d}_1^{(0)} = sgn\left\{Re\left[\widetilde{d}_1^{(0)}e^{-j(\varphi_1)}\right]\right\}$$

where $\widehat{d}_1^{(0)}$ denotes the hard decision output of the conventional (MF) detector for the first user.

Now, by taking one step further to remove all the interference contaminating the first user we get

$$\begin{aligned}
\widetilde{d}_1^{(1)} &= \widetilde{d}_1^{(0)} - \sum_{k=2}^{K} \widetilde{I}_k^{(0)} \\
&= \sqrt{E_{b1}}\, d_1\, e^{j\varphi_1} + \sum_{k=2}^{K} \sqrt{E_{bk}}\, d_k\, \rho_{k1}\, e^{j\varphi_k} + n_1 - \sum_{k=2}^{K} \sqrt{E_{bk}}\, \widehat{d}_k^{(0)}\, \rho_{k1}\, e^{j\varphi_k} \\
\widetilde{d}_1^{(1)} e^{-j\varphi_1} &= \sqrt{E_{b1}}\, d_1 + \sum_{k=2}^{K} \sqrt{E_{bk}} \left[d_k - \widehat{d}_k^{(0)}\right] \rho_{k1}\, e^{j(\varphi_k - \varphi_1)} + n_1 e^{-j\varphi_1}
\end{aligned}$$

where

$$\widehat{d}_1^{(1)} = sgn\left\{Re\left[\widetilde{d}_1^{(1)}e^{-j\varphi_1}\right]\right\}$$

The probability of error for the first user will turn out as [4]

$$\begin{aligned}
P_b(e) &= \frac{1}{2}P\left\{Re\left[\left(\widetilde{d}_1^{(1)}e^{-j\varphi_1}\right) > 0\right] |d_1 = -1\right\} + \frac{1}{2}P\left\{Re\left[\left(\widetilde{d}_1^{(1)}e^{-j\varphi_1}\right) < 0\right] \mid d_1 = 1\right\} \\
&= P\left\{Re\left[\left(\widetilde{d}_1^{(1)}e^{-j\varphi_1}\right) > 0\right] \mid d_1 = -1\right\}
\end{aligned}$$

It has been proven in [4] that the average probability of error for an equal power case is in the form of

$$P_b(e) = Q\left(\sqrt{\frac{2E_b}{N_o}\Lambda}\right)$$

where,

$$\Lambda = \frac{\left[1 + (k-1)\,\overline{\xi}_{1k}^{2}\right]}{1 + 2\frac{E_b}{N_o}(k-1)\left[\overline{\xi^2}_{1k} - (k-1)\,\overline{\xi}_{1k}^{2} + (k-2)\,\overline{\xi_{1k}\xi_{1l}} + \frac{2}{\sqrt{E_b}}\overline{N_1\xi_{1k}}\right]}$$

and

$$\xi_{1k} = \left(d_k - \hat{d}_k^{(0)}\right) \rho_{k1} \cos\left(\varphi_k - \varphi_1\right) ,$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-t^2/2} dt$$

Figure 3.5 compares the degradation factor of conventional receiver where there is no interference cancellation with soft and hard PIC detectors for different numbers of active users. The degradation factor is defined as the difference of the E_b/N_o in dB needed to meet a specific level of BER to that of single user case.

Figure 3.6 shows the performance of a soft and hard PIC detectors against that of conventional detector for upto three stages. As it is seen, these two figures show that the performance of hard PIC is better than that of soft PIC detector, where a perfect knowledge of users' parameters is assumed.

3.3.3 Improved Parallel Interference Cancellation Detector

As it is seen from Figure 3.6, for a large number of users, when multistage PIC scheme is used, performance improves very slowly as the number of stages goes higher. Specifically, when users' parameters are not available and soft PIC detector would be the only alternative to apply. In this case, even the performance gets worse for high system load. Divsalar *et al* [3] showed that the cancellation of the entire interferences from each user is not necessarily the best approach. Instead, partial removal of interference enhances the performance drastically. This kind of detector was named Partial Parallel Interference Cancellation (PPIC) detector where a small portion of the interference is cancelled in early stages since the decisions are not that reliable. Consequently, as the number of stages increases, the amount of the partial cancellation is increased since it is assumed that more stages result in better quality of data in the sense of BER. In PPIC detector, the output of the mth stage

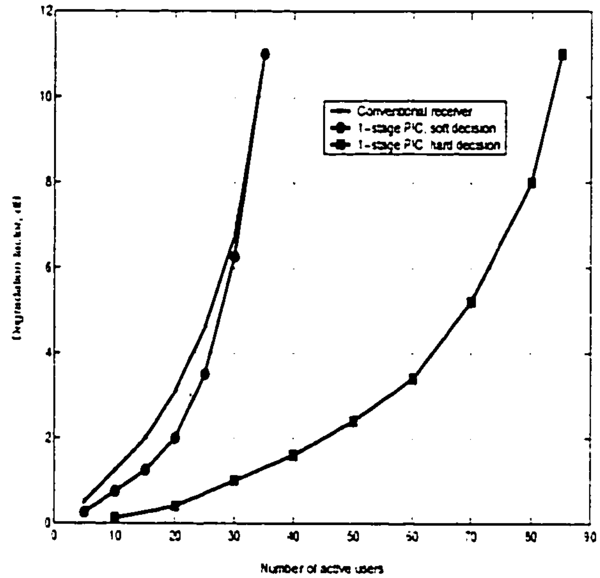


Figure 3.5: **A comparison of degradation factor of a conventional receiver with soft and hard PIC detectors($N = 100$, $P_b = 10^{-2}$, $0 \leq \varphi_k \leq 2\pi$, and equal power) [3, 4].**

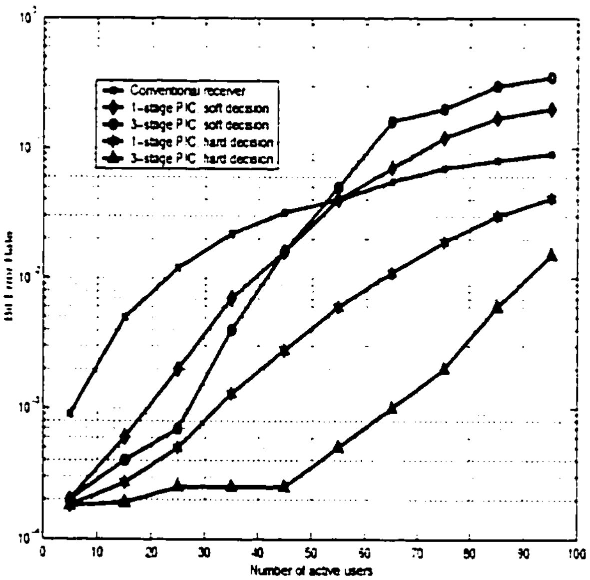


Figure 3.6: **Performance comparison of multistage soft and hard PIC detectors with conventional receiver ($N = 100, E_b/N_o = 8dB$, and equal power) [5].**

is based on a *weighted sum* of the output of the $(m-1)$th stage $(\tilde{d}_1^{(m-1)})$ and the interference canceled version of Matched Filter (MF) output at the $(m-1)$th stage $(\tilde{d}_1^{(0)} - I_1^{(m-1)})$. The idea to use weighted sum originates from the joint observation of $\tilde{d}_1^{(0)}$ and $\tilde{d}_1^{(m-1)}$ [3]. Therefore, the output of the mth stage of a PPIC detector is

$$\tilde{d}_1^{(m)} = \lambda_m \left[\tilde{d}_1^{(0)} - \hat{I}_1^{(m-1)}\right] + (1-\lambda_m)\, \tilde{d}_1^{(m-1)}$$

where λ_m, $\tilde{d}_1^{(0)}$, $\hat{I}_1^{(m)}$, and $\tilde{d}_1^{(m-1)}$ are the partial cancellation coefficient, MF output, interference affecting the first user, and the output of the soft $(m-1)$th stage of a PPIC detector, respectively. It is noted that in this equation the hard estimates of interferences $(\hat{I}_1^{(m)})$ are used, since it is assumed that a perfect knowledge of the users' parameters is available. Whenever this is not the case, a soft estimate of interference $(\tilde{I}_1^{(m)})$ should be replaced by its hard counterpart which results in lower quality of performance. Figure 3.7 shows the block diagram of the soft and hard PPIC detectors, respectively.

Figures 3.8 and 3.9 compare the degradation factors of soft and hard multistage PPIC detectors with conventional and PIC detectors.

Figures 3.10 and 3.11 compare the performances of soft and hard multistage PPIC detectors with conventional and PIC detectors.

It is easily seen from these four figures that in both cases of soft and hard cancellation, the PPIC detector is superior to the PIC detector; especially, when the number of active users is high.

3.3.4 Hybrid Interference Cancellation

In order to combine the advantages of SIC and PIC detectors, a combination of them is of special interest. The new scheme is called Hybrid Interference Cancellation (HIC) detector. Two kinds of such detectors have been introduced in [12]. Obviously, the new scheme is more resilient than PIC scheme in near-far conditions and faster than SIC scheme. Figure 3.12 shows the block diagram of such a detector.

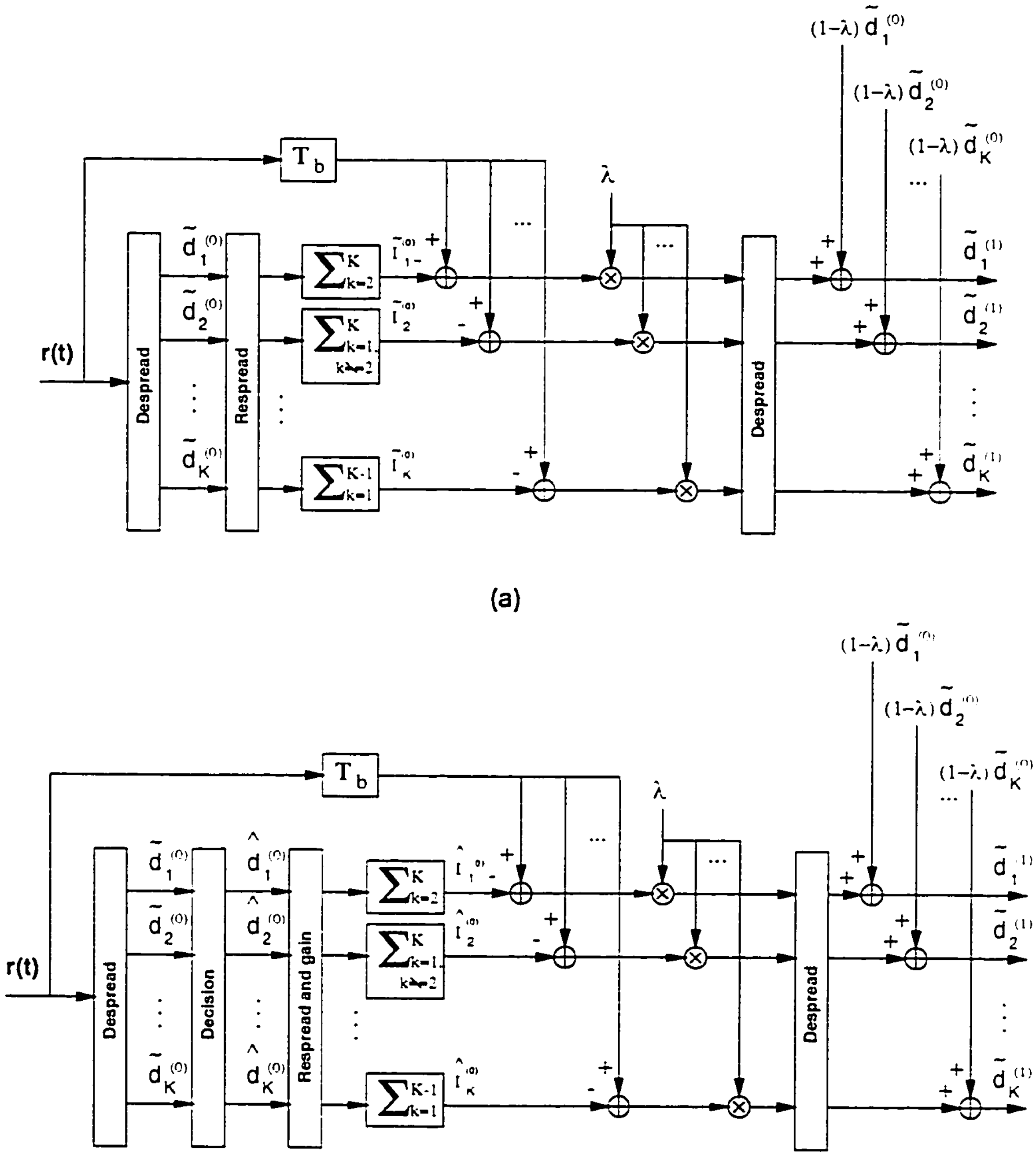


Figure 3.7: One stage of (a) soft and (b) hard PPIC detector.

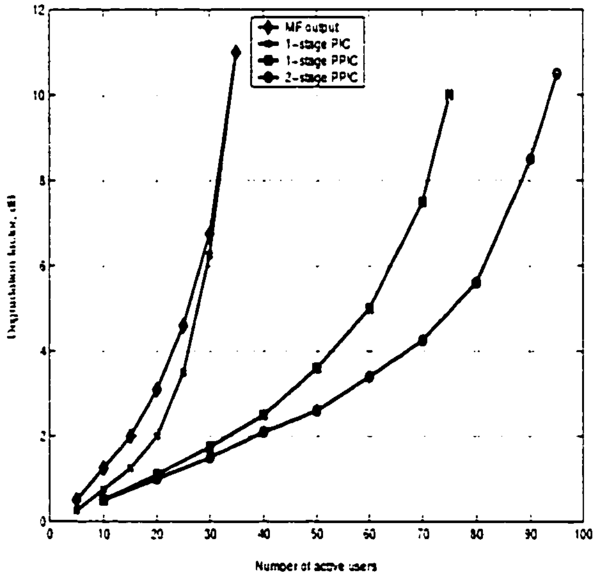


Figure 3.8: A comparison of the degradation factor of soft PPIC detector with conventional and soft PIC detectors ($N = 100$, $P_b = 10^{-2}$, and equal power. One-stage PPIC with $\lambda_1 = 0.4$, and two-stage PPIC with $\lambda_1 = 0.3$, $\lambda_2 = 0.8$) [3, 4].

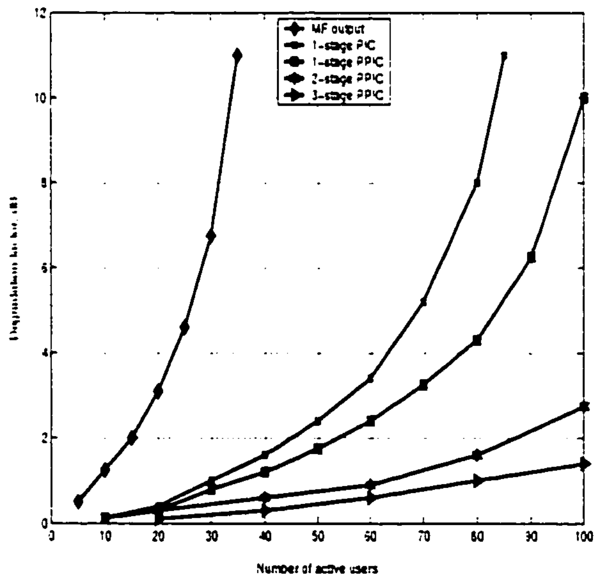


Figure 3.9: A comparison of the degradation factor of hard PPIC detector with conventional and hard PIC detectors ($N = 100$, $P_b = 10^{-2}$, and equal power. One-stage PPIC with $\lambda_1 = 0.7$, two-stage PPIC with $\lambda_1 = 0.6$, $\lambda_2 = 0.8$, and three-stage PPIC with $\lambda_1 = 0.5$, $\lambda_2 = 0.7$, $\lambda_3 = 0.9$) [3, 4].

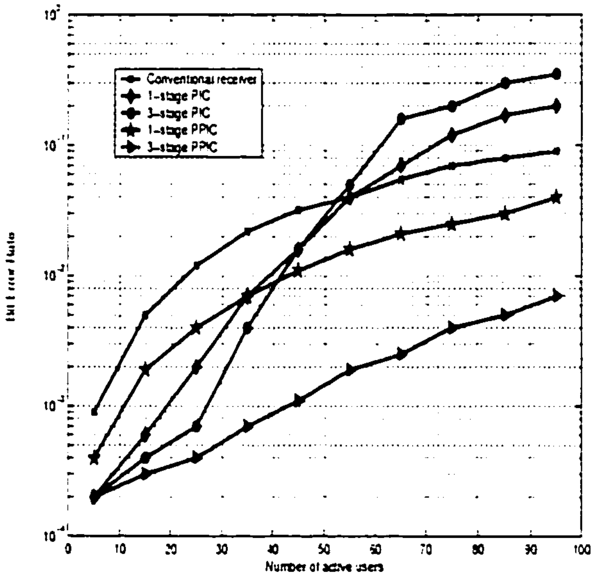


Figure 3.10: Performance comparison of soft PPIC detector with conventional and soft PIC detectors ($N = 100$, $E_b/N_o = 8dB$, equal power. One-stage PPIC with $\lambda_1 = 0.3$, and three-stage PPIC with $\lambda_1 = 0.3$, $\lambda_2 = 0.8$, $\lambda_3 = 1.0$) [5].

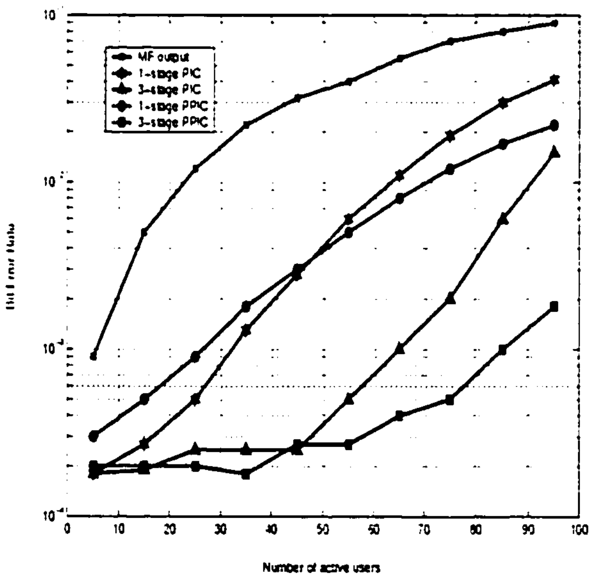


Figure 3.11: Performance comparison of hard PPIC detector with conventional and hard PIC detectors ($N = 100$, $E_b/N_o = 8dB$, equal power. One-stage PPIC with $\lambda_1 = 0.6$, and three-stage PPIC with $\lambda_1 = 0.6$, $\lambda_2 = 0.8$, $\lambda_3 = 1.0$) [5].

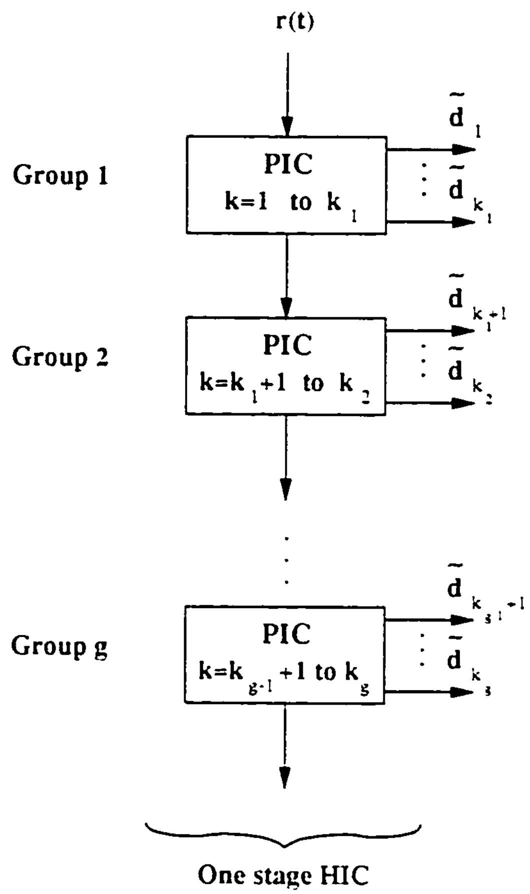


Figure 3.12: **One stage of HIC detector** ($K = k_1 + k_2 + \ldots + k_g$).

First of all, users will be split into different groups of almost equal power. Inside each group, interference cancellation is done in parallel, while between the groups, it is done sequentially. As it will be seen later in Chapter 5, we will apply this approach in our proposed scheme in order to make our proposed scheme more resistant to near-far problem. Furthermore, other combinations of multiuser detectors such as a combination of Decorrelator and PIC (DD/PIC) and MMSE/PIC have been proposed recently and more details can be found in [12].

3.4 Summary

Some well-known MUD techniques were reviewed in this chapter. It is seen that, among these schemes, the PPIC detector is the most promising scheme due to its fastness and of course, its low complexity; to compare to ML and Linear detectors. Therefore, this scheme was chosen for further study. In Chapter 4, a new combination of PPIC detector is presented whose performance surpasses the performance of Decorrelator detector.

Chapter 4

Combined Partial Parallel Interference Cancellation with Amplitude and phase Estimation

A combination of Soft and Hard Partial Parallel Interference Cancellations (SHP-PIC) for iterative multistage detector with amplitude and phase estimation is introduced in this chapter. The outputs of the first stages are more deteriorated by Multiple Access Interference (MAI) than by the thermal noise. This makes amplitude and phase estimation impractical in the first stages. Therefore, soft Interference Cancellation (IC) is used in the earlier stages since soft IC does not require the knowledge of the channel parameters. Once the performance of the soft multistage multiuser detector achieves the same performance as that of the Decorrelator Detector, the amplitude and phase of each user are estimated. Having these parameters estimated, the subsequent stages would be in the form of hard IC. The complexity of such a detector is linearly increased with the number of users.

4.1 Multistage Soft Partial Parallel Interference Cancellation Detector

As mentioned earlier, this type of detector does not need the knowledge of the parameters (e.g. amplitude and phase) of the users. According to Figure 4.1, the output of the mth stage of such a detector for the first user (as the one of interest) is

$$\tilde{d}_1^{(m)}(t) = \frac{1}{T_b}\int_0^{T_b} \lambda_m \left[r(t - mT_b) - \sum_{k=1}^{K} \tilde{S}_k^{(m-1)}(t) \right] c_1(t)dt + \tilde{d}_1^{(m-1)}(t - T_b)$$

where,

$$\tilde{S}_k^{(m-1)} = \tilde{d}_k^{(m-1)} c_k(t)$$

Since the signals of $\tilde{d}_1^{(m)}(t)$, $r(t-mT_b)$, $\tilde{S}_k^{(m-1)}(t)$, and $\tilde{d}_1^{(m-1)}(t-T_b)$ are sampled at $t = mT_b$, the time shifts may be omitted from all signals in order to obtain a simpler notation. Therefore,

$$\begin{aligned} \tilde{d}_1^{(m)} &= \lambda_m \frac{1}{T_b}\int_0^{T_b} \left[r(t) - \sum_{k=1}^{K} \tilde{S}_k^{(m-1)}(t) \right] c_1(t)dt + \tilde{d}_1^{(m-1)} \\ &= \lambda_m \tilde{d}_1^{(0)} + (1 - \lambda_m)\tilde{d}_1^{(m-1)} - \lambda_m \sum_{k=2}^{K} \tilde{d}_k^{(m-1)} \rho_{k1} \end{aligned} \tag{4.1}$$

For a single stage detector (i.e. $m = 1$), we have

$$\tilde{d}_1^{(1)} = \tilde{d}_1^{(0)} - \lambda_1 \sum_{k=2}^{K} \tilde{d}_k^{(0)} \rho_{k1} \tag{4.2}$$

where,

$$\tilde{d}_1^{(0)} = \sqrt{E_{b1}}\, d_1\, e^{j\varphi_1} + \sum_{k=2}^{K} \sqrt{E_{bk}}\, d_k\, \rho_{k1}\, e^{j\varphi_k} + n_1 \tag{4.3}$$

Using (4.3) in (4.2) yields

$$\begin{aligned}
\tilde{d}_1^{(1)} &= \tilde{d}_1^{(0)} - \lambda_1\left(\tilde{d}_2^{(0)}\rho_{21} + \tilde{d}_3^{(0)}\rho_{31} + \ldots + \tilde{d}_K^{(0)}\rho_{K1}\right) \\
&= \left(\sqrt{E_{b1}}d_1 e^{j\varphi_1} + \sqrt{E_{b2}}d_2\rho_{12}e^{j\varphi_2} + \ldots + \sqrt{E_{bK}}d_K\rho_{1K}e^{j\varphi_K} + n_1\right) \\
&\quad -\lambda_1\Big[\left(\sqrt{E_{b1}}d_1\rho_{21}e^{j\varphi_1} + \sqrt{E_{b2}}d_2 e^{j\varphi_2} + \ldots + \sqrt{E_{bK}}d_K\rho_{2K}e^{j\varphi_K} + n_2\right)\rho_{21} \\
&\quad + \left(\sqrt{E_{b1}}d_1\rho_{31}e^{j\varphi_1} + \sqrt{E_{b2}}d_2\rho_{32}e^{j\varphi_2} + \ldots + \sqrt{E_{bK}}d_K\rho_{3K}e^{j\varphi_K} + n_3\right)\rho_{31} \\
&\quad + \ldots \\
&\quad + \left(\sqrt{E_{b1}}d_1\rho_{K1}e^{j\varphi_1} + \sqrt{E_{b2}}d_2\rho_{K2}e^{j\varphi_2} + \ldots + \sqrt{E_{bK}}d_K e^{j\varphi_K} + n_K\right)\rho_{K1}\Big] \\
&= \sqrt{E_{b1}}d_1[\rho_{11} - \lambda_1(\rho_{21}\rho_{21} + \rho_{31}\rho_{31} + \ldots + \rho_{K1}\rho_{K1})]e^{j\varphi_1} \\
&\quad + \sqrt{E_{b2}}d_2[\rho_{21} - \lambda_1(\rho_{22}\rho_{21} + \rho_{32}\rho_{31} + \ldots + \rho_{K2}\rho_{K1})]e^{j\varphi_2} \\
&\quad + \ldots \\
&\quad + \sqrt{E_{bK}}d_K[\rho_{K1} - \lambda_1(\rho_{2K}\rho_{21} + \rho_{3K}\rho_{31} + \ldots + \rho_{KK}\rho_{K1})]e^{j\varphi_K} \\
&\quad + [n_1 - \lambda_1(n_2\rho_{21} + n_3\rho_{31} + \ldots + n_K\rho_{K1})] \\
&= \sqrt{E_{b1}}d_1\left(1 - \lambda_1\sum_{k=2}^{K}\rho_{k1}^2\right)e^{j\varphi_1} \\
&\quad + \sum_{k=2}^{K}\sqrt{E_{bk}}d_k\left(\rho_{k1} - \lambda_1\sum_{k'=2}^{K}\rho_{k'k}\,\rho_{k'1}\right)e^{j\varphi_k} \\
&\quad + \left(n_1 - \lambda_1\sum_{k=2}^{K}n_k\rho_{k1}\right) \qquad (4.4)
\end{aligned}$$

where the first, second, and the third components of (4.4) are useful information, residual interference, and the noise, respectively. For a two-stage detector, we have

$$\tilde{d}_1^{(2)} = \lambda_2\tilde{d}_1^{(0)} + (1-\lambda_2)\tilde{d}_1^{(1)} - \lambda_2\sum_{k=2}^{K}\tilde{d}_k^{(1)}\rho_{k1} \qquad (4.5)$$

Substituting (4.2) into (4.5) yields

$$\tilde{d}_1^{(2)} = \tilde{d}_1^{(0)} + (\lambda_1 + \lambda_2 - \lambda_1\lambda_2)\sum_{k=2}^{K}\tilde{d}_k^{(0)}\rho_{k1} + \lambda_1\lambda_2\sum_{k=2}^{K}\sum_{k'=2}^{K}\tilde{d}_{k'}^{(0)}\rho_{k'k}\rho_{k1} \qquad (4.6)$$

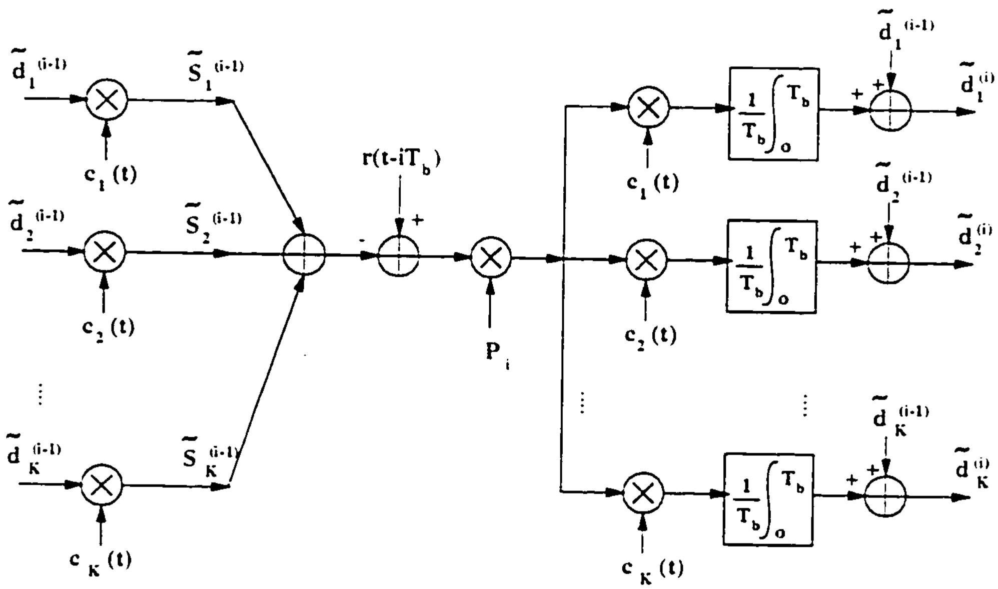


Figure 4.1: **mth stage of a soft interference cancellation**

Again, applying (4.3) in (4.6), we get

$$\tilde{d}_1^{(2)} = \tag{4.7}$$

$$\sqrt{E_{b1}}d_1\left[1-(\lambda_1+\lambda_2-\lambda_1\lambda_2)\sum_{k=2}^{K}\rho_{k1}^2+\lambda_1\lambda_2\sum_{k=2}^{K}\sum_{k'=2}^{K}\rho_{k'k}\,\rho_{k'1}\,\rho_{k1}\right]e^{j\phi_1}$$
$$+\sum_{k=2}^{K}\sqrt{E_{bk}}d_k\left[\rho_{k1}-(\lambda_1+\lambda_2-\lambda_1\lambda_2)\sum_{k'=2}^{K}\rho_{k'k}\rho_{k'1}+\lambda_1\lambda_2\sum_{k'=2}^{K}\sum_{k''=2}^{K}\rho_{k''k'}\rho_{k''k}\rho_{k'k}\right]e^{j\phi_k}$$
$$+\left[n_1-(\lambda_1+\lambda_2-\lambda_1\lambda_2)\sum_{k=2}^{K}\rho_{k1}n_k+\lambda_1\lambda_2\sum_{k=2}^{K}\sum_{k'=2}^{K}\rho_{k'k}\,\rho_{k'1}n_k\right] \tag{4.8}$$

In general, for an M-stage soft PPIC detector, the output for the first user (assumed to be the desired user) can be expressed as

$$
\begin{aligned}
\tilde{d}_1^{(M)} &= \tilde{d}_1^{(0)} \\
&- \left[A_{11} \sum_{m=1}^{M} \lambda_m - A_{12} \sum^{M} \prod^{2} \lambda_m + \ldots + (-1)^M A_{1,(M-1)} \sum^{M} \prod^{M-1} \lambda_m \right. \\
&\quad \left. + (-1)^{M+1} A_{1,(M)} \prod_{m=1}^{M} \lambda_m \right] \sum_{k=2}^{K} \tilde{d}_k^{(0)} \rho_{k1} \\
&+ \left[A_{21} \sum^{M} \prod^{2} \lambda_m - A_{22} \sum^{M} \prod^{3} \lambda_m + \ldots + (-1)^{M-1} A_{2,(M-2)} \sum^{M} \prod^{M-1} \lambda_m \right. \\
&\quad \left. + (-1)^M A_{2,(M-1)} \prod_{m=1}^{M} \lambda_m \right] \sum_{k=2}^{K} \sum_{k'=2}^{K} \tilde{d}_{k'}^{(0)} \rho_{k'k} \rho_{k1} \\
&+ \ldots \\
&+ (-1)^i \left[A_{i1} \sum^{M} \prod^{i} \lambda_m - A_{i2} \sum^{M} \prod^{i+1} \lambda_m + \ldots + (-1)^{M+1-i} A_{i,(M-i)} \sum^{M} \prod^{M-1} \lambda_m \right. \\
&\quad \left. + (-1)^{M+2-i} A_{i,(M+1-i)} \prod_{m=1}^{M} \lambda_m \right] \sum_{k=2}^{K} \sum_{k'=2}^{K} \cdots \sum_{k^{(i-1)}=2}^{K} \tilde{d}_{k^{(i-1)}}^{(0)} \rho_{k^{(i-1)}k^{(i-2)}} \rho_{k^{(i-2)}k^{(i-3)}} \cdots \rho_{k'k} \rho_{k1} \\
&+ \ldots \\
&+ (-1)^{M-1} \left[A_{(M-1),1} \sum^{M} \prod^{M-1} \lambda_m - A_{(M-1),2} \prod_{m=1}^{M} \lambda_m \right] \\
&\quad \sum_{k=2}^{K} \sum_{k'=2}^{K} \cdots \sum_{k^{(M-2)}=2}^{K} \tilde{d}_{k^{(M-2)}}^{(0)} \rho_{k^{(M-2)}k^{(M-3)}} \rho_{k^{(M-3)}k^{(M-4)}} \cdots \rho_{k'k} \rho_{k1} \\
&+ (-1)^M \prod_{m=1}^{M} \lambda_m \sum_{k=2}^{K} \sum_{k'=2}^{K} \cdots \sum_{k^{(M-1)}=2}^{K} \tilde{d}_{k^{(M-1)}}^{(0)} \rho_{k^{(M-1)}k^{(M-2)}} \rho_{k^{(M-2)}k^{(M-3)}} \cdots \rho_{k'k} \rho_{k1}
\end{aligned}
\tag{4.9}
$$

where, $\sum^M \prod^i \lambda_m$ is defined as the sum of all products of i of λ_ms where $m = 1, 2, \ldots, M$, and

$$
A_{ij} = \begin{cases} 1 & \text{if } (i = 1 \text{ and } 1 \le j \le M) \text{ or } (j = 1 \text{ and } 1 \le i \le M) \\ A_{(i-1),j} + A_{i,(j-1)} & \text{otherwise} \end{cases}
$$

***Proof*:** The proof is by induction. It is seen easily that for $M = 1$, we have

$$\tilde{d}_1^{(1)} = \tilde{d}_1^{(0)} - \lambda_1 \sum_{k=2}^{K} \tilde{d}_k^{(0)} \rho_{k1}$$

Now, if we assume that (4.9) holds for the case of M, we will show that it remains true for the case of $(M+1)$ as well. i.e.,

$$\begin{aligned}
\tilde{d}_1^{(M+1)} &= \tilde{d}_1^{(0)} \\
&- \left[A_{11} \sum_{m=1}^{M+1} \lambda_m - A_{12} \sum^{M+1} \prod^{2} \lambda_m + \ldots + (-1)^{M+1} A_{1,(M)} \sum^{M+1} \prod^{M} \lambda_m \right. \\
&\quad \left. + (-1)^{M+2} A_{1,(M+1)} \prod_{m=1}^{M+1} \lambda_m \right] \sum_{k=2}^{K} \tilde{d}_k^{(0)} \rho_{k1} \\
&+ \left[A_{21} \sum^{M+1} \prod^{2} \lambda_m - A_{22} \sum^{M+1} \prod^{3} \lambda_m + \ldots + (-1)^{M} A_{2,(M-1)} \sum^{M+1} \prod^{M} \lambda_m \right. \\
&\quad \left. + (-1)^{M+1} A_{2,(M)} \prod_{m=1}^{M+1} \lambda_m \right] \sum_{k=2}^{K} \sum_{k'=2}^{K} \tilde{d}_{k'}^{(0)} \rho_{k'k} \rho_{k1} \\
&+ \ldots \\
&+ (-1)^{i} \left[A_{i1} \sum^{M+1} \prod^{i} \lambda_m - A_{i2} \sum^{M+1} \prod^{i+1} \lambda_m + \ldots + (-1)^{M+2-i} A_{i,(M+1-i)} \sum \prod \lambda_m \right. \\
&\quad \left. + (-1)^{M+3-i} A_{i,(M+2-i)} \prod_{m=1}^{M+1} \lambda_m \right] \sum_{k=2}^{K} \sum_{k'=2}^{K} \cdots \sum_{k^{(i-1)}=2}^{K} \tilde{d}_{k^{(i-1)}}^{(0)} \rho_{k^{(i-1)} k^{(i-2)}} \rho_{k^{(i-2)} k^{(i-3)}} \cdots \rho_{k'k} \rho_{k1} \\
&+ \ldots \\
&+ (-1)^{M} \left[A_{(M),1} \sum^{M+1} \prod^{M} \lambda_m - A_{(M),2} \prod_{m=1}^{M+1} \lambda_m \right] \\
&\quad \sum_{k=2}^{K} \sum_{k'=2}^{K} \cdots \sum_{k^{(M-1)}=2}^{K} \tilde{d}_{k^{(M-1)}}^{(0)} \rho_{k^{(M-1)} k^{(M-2)}} \rho_{k^{(M-2)} k^{(M-3)}} \cdots \rho_{k'k} \rho_{k1} \\
&+ (-1)^{(M+1)} \prod_{m=1}^{M+1} \lambda_m \sum_{k=2}^{K} \sum_{k'=2}^{K} \cdots \sum_{k^{(M)}=2}^{K} \tilde{d}_{k^{(M)}}^{(0)} \rho_{k^{(M)} k^{(M-1)}} \rho_{k^{(M-1)} k^{(M-2)}} \cdots \rho_{k'k} \rho_{k1}
\end{aligned}$$

According to (4.1), we have

$$\tilde{d}_1^{(M+1)} = \lambda_{M+1} \tilde{d}_1^{(0)} + (1 - \lambda_{M+1}) \tilde{d}_1^{(M)} - \lambda_{M+1} \sum_{k=2}^{K} \tilde{d}_k^{(M)} \rho_{k1} \tag{4.10}$$

Substitution in (4.10) from (4.9) yields

$$
\begin{aligned}
\tilde{d}_1^{(M+1)} &= \lambda_{M+1}\tilde{d}_1^{(0)} \\
&+ (1-\lambda_{M+1})\Bigg[\tilde{d}_1^{(0)} - B_1\sum_{k=2}^{K}\tilde{d}_k^{(0)}\rho_{k1} + B_2\sum_{k=2}^{K}\sum_{k'=2}^{K}\tilde{d}_{k'}^{(0)}\rho_{k'k}\rho_{k1} + \dots \\
&\quad +(-1)^M B_M \sum_{k=2}^{K}\sum_{k'=2}^{K}\cdots\sum_{k^{(M-1)}=2}^{K}\tilde{d}_{k^{(M-1)}}^{(0)}\rho_{k^{(M-1)}k^{(M-2)}}\rho_{k^{(M-2)}k^{(M-3)}}\cdots\rho_{k'k}\rho_{k1}\Bigg] \\
&- \lambda_{M+1}\sum_{k=2}^{K}\Bigg[\tilde{d}_k^{(0)} - B_1\sum_{k'=2}^{K}\tilde{d}_{k'}^{(0)}\rho_{k'k} + B_2\sum_{k'=2}^{K}\sum_{k''=2}^{K}\tilde{d}_{k''}^{(0)}\rho_{k''k'}\rho_{k'k} + \dots \\
&\quad +(-1)^M B_M \sum_{k'=2}^{K}\sum_{k''=2}^{K}\cdots\sum_{k^{(M)}=2}^{K}\tilde{d}_{k^{(M)}}^{(0)}\rho_{k^{(M)}k^{(M-1)}}\rho_{k^{(M-1)}k^{(M-2)}}\cdots\rho_{k''k'}\rho_{k'k}\Bigg]\rho_{k1}
\end{aligned}
$$

where

$$
B_1 = \left[A_{11}\sum_{m=1}^{M}\lambda_m - A_{12}\sum^{M}\prod^{2}\lambda_m + \dots + (-1)^M A_{1,(M-1)}\sum^{M}\prod^{M-1}\lambda_m + (-1)^{M+1}A_{1,(M)}\prod_{m=1}^{M}\lambda_m\right]
$$

$$
B_2 = \left[A_{21}\sum^{M}\prod^{2}\lambda_m - A_{22}\sum^{M}\prod^{3}\lambda_m + \dots + (-1)^{M-1}A_{2,(M-2)}\sum^{M}\prod^{M-1}\lambda_m + (-1)^M A_{2,(M-1)}\prod_{m=1}^{M}\lambda_m\right]
$$

$\vdots$

$$
B_M = \prod_{m=1}^{M}\lambda_m
$$

After rearrangement, we will get

$$
\begin{aligned}
\tilde{d}_1^{(M+1)} &= \tilde{d}_1^{(0)} \\
&\quad - D_1\sum_{k=2}^{K}\tilde{d}_k^{(0)}\rho_{k1} + D_2\sum_{k=2}^{K}\sum_{k'=2}^{K}\tilde{d}_{k'}^{(0)}\rho_{k'k}\rho_{k1} + \dots \\
&\quad +(-1)^M D_M\sum_{k=2}^{K}\sum_{k'=2}^{K}\cdots\sum_{k^{(M-1)}=2}^{K}\tilde{d}_{k^{(M-1)}}^{(0)}\rho_{k^{(M-1)}k^{(M-2)}}\rho_{k^{(M-2)}k^{(M-3)}}\cdots\rho_{k'k}\rho_{k1} \\
&\quad +(-1)^{M+1}D_{M+1}\sum_{k=2}^{K}\sum_{k'=2}^{K}\cdots\sum_{k^{(M)}=2}^{K}\tilde{d}_{k^{(M)}}^{(0)}\rho_{k^{(M)}k^{(M-1)}}\rho_{k^{(M-1)}k^{(M-2)}}\cdots\rho_{k''k'}\rho_{k'k}]\rho_{k1}
\end{aligned}
$$

where

$$
\begin{aligned}
D_1 &= (1-\lambda_{M+1})B_1 + \lambda_{M+1} \\
&= (1-\lambda_{M+1})\left[A_{11}\sum_{m=1}^{M}\lambda_m - A_{12}\sum^{M}\prod^{2}\lambda_m + \ldots + (-1)^{M}A_{1.(M-1)}\sum^{M}\prod^{M-1}\lambda_m \right. \\
&\quad \left. +(-1)^{M+1}A_{1.(M)}\prod_{m=1}^{M}\lambda_m\right] + \lambda_{M+1} \\
&= A_{11}\sum_{m=1}^{M+1}\lambda_m - A_{12}\sum^{M+1}\prod^{2}\lambda_m + \ldots + (-1)^{M+1}A_{1.(M)}\sum^{M+1}\prod^{M}\lambda_m + (-1)^{M+2}A_{1.(M+1)}\prod_{m=1}^{M+1}\lambda_m
\end{aligned}
$$

and

$$
\begin{aligned}
D_2 = &\quad (1-\lambda_{M+1})B_2 + \lambda_{M+1}B_1 \\
= &\quad (1-\lambda_{M+1})\left[A_{21}\sum^{M}\prod^{2}\lambda_m - A_{22}\sum^{M}\prod^{3}\lambda_m + \ldots + (-1)^{M-1}A_{2.(M-2)}\sum^{M}\prod^{M-1}\lambda_m \right. \\
&\quad \left. +(-1)^{M}A_{2.(M-1)}\prod_{m=1}^{M}\lambda_m\right] \\
+ &\quad \lambda_{M+1}\left[A_{11}\sum_{m=1}^{M}\lambda_m - A_{12}\sum^{M}\prod^{2}\lambda_m + \ldots + (-1)^{M}A_{1.(M-1)}\sum^{M}\prod^{M-1}\lambda_m \right. \\
&\quad \left. +(-1)^{M+1}A_{1.(M)}\prod_{m=1}^{M}\lambda_m\right] \\
= &\quad \left(A_{21}\sum^{M}\prod^{2}\lambda_m + A_{11}\lambda_{M+1}\sum_{m=1}^{M}\lambda_m\right) - \left(A_{22}\sum^{M}\prod^{3}\lambda_m + A_{21}\lambda_{M+1}\sum^{M}\prod^{2}\lambda_m \right. \\
&\quad \left. +A_{12}\lambda_{M+1}\sum^{M}\prod^{2}\lambda_m\right) \\
+ &\quad \ldots + (-1)^{M+1}\left[A_{2.(M-1)} + A_{1.(M)}\right]\prod_{m=1}^{M+1}\lambda_m
\end{aligned}
$$

Applying the relationship between the coefficients, we get

$$
D_2 = A_{21}\sum^{M+1}\prod^{2}\lambda_m - A_{22}\sum^{M+1}\prod^{3}\lambda_m + \ldots + (-1)^{M+1}A_{2.(M)}\prod_{m=1}^{M+1}\lambda_m
$$

Similarly, D_M and D_{M+1} are obtained as follows

$$
\begin{aligned}
D_M &= (1-\lambda_{M+1})B_M + \lambda_{M+1}B_{M-1} \\
&= A_{(M),1}\sum^{M+1}\prod^{M}\lambda_m - A_{(M),2}\prod_{m=1}^{M+1}\lambda_m
\end{aligned}
$$

$$
\begin{aligned}
D_{M+1} &= \lambda_{M+1}B_M \\
&= \prod_{m=1}^{M+1}\lambda_m
\end{aligned}
$$

Therefore, (4.9) is proven.

As an example, for a three-stage detector, the output will be as follows

$$
\begin{aligned}
\tilde{d}_1^{(3)} &= \lambda_3\tilde{d}_1^{(0)} + (1-\lambda_3)\tilde{d}_1^{(2)} - \lambda_3\sum_{k=2}^{K}\tilde{d}_k^{(2)}\rho_{k1} \\
&= \tilde{d}_1^{(0)} \\
&\quad -(\lambda_1+\lambda_2+\lambda_3-\lambda_1\lambda_2-\lambda_1\lambda_3-\lambda_2\lambda_3+\lambda_1\lambda_2\lambda_3)\sum_{k=2}^{K}\tilde{d}_k^{(0)}\rho_{k1} \\
&\quad +(\lambda_1\lambda_2+\lambda_1\lambda_3+\lambda_2\lambda_3-2\lambda_1\lambda_2\lambda_3)\sum_{k=2}^{K}\sum_{k'=2}^{K}\tilde{d}_{k'}^{(0)}\rho_{k'k}\rho_{k1} \\
&\quad -\lambda_1\lambda_2\lambda_3\sum_{k=2}^{K}\sum_{k'=2}^{K}\sum_{k''=2}^{K}\tilde{d}_{k''}^{(0)}\rho_{k''k'}\rho_{k'k}\rho_{k1}
\end{aligned}
$$

It is seen that for a large number of interference cancellation stages, the expression for the corresponding output in terms of the output of the matched filter ($\tilde{d}_k^{(0)}$) becomes very complicated. Therefore, instead of analytical study of multistage detector we will take advantage of computer simulations. Figure 4.2 shows the output of the soft PPIC detector for up to ten soft interference cancellation stages. In this figure, $N = 63$, $E_b/N_o = 10dB$, and $0 \leq \varphi_k \leq 2\pi$, and the number of active users (K) is assumed to be 40. In order to achieve a good confidence level which will be calculated later in this chapter, 100 packets of 10000 bits will be run for each simulation. Otherwise, it will be explicitly specified for different packets. It is seen

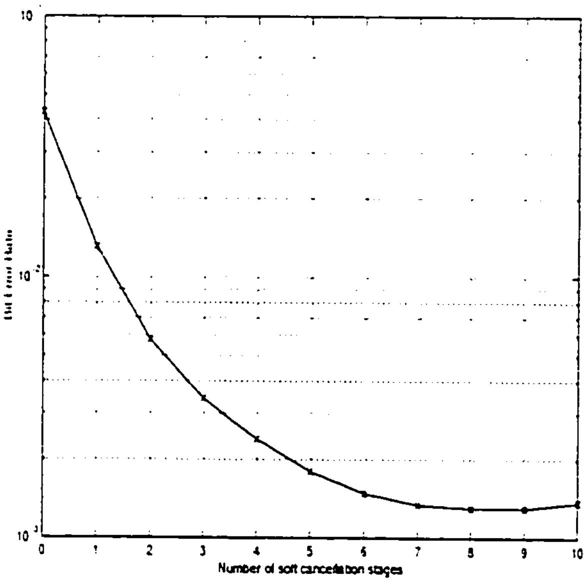


Figure 4.2: **Output of the multistage soft PPIC detector.** $N = 63$, $E_b/N_o = 10dB$, $K = 40$, **and** $0 \leq \varphi_k \leq 2\pi$. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = \lambda_8 = \lambda_9 = \lambda_{10} = 0.9$.

that after some stages. improving the performance is not possible. In fact. the performance saturates in the vicinity of Decorrelator Detector output. Note that when φ_k is in $[0, 2\pi]$. the interference affecting each user is less than the case where we assign the same phase shift to all users (i.e. $\varphi_k = 0$). Figure 4.3 depicts the number of active users versus BER. It is easily discernible that these two figures support each other: as the steps taken to further stages. the performance improvement is less beyond certain number of stages.

Figure 4.4 compares a seven-stage PPIC detector with the case of BPSK single user. Note that the knowledge of users' amplitudes and phases have not been taken into consideration yet.

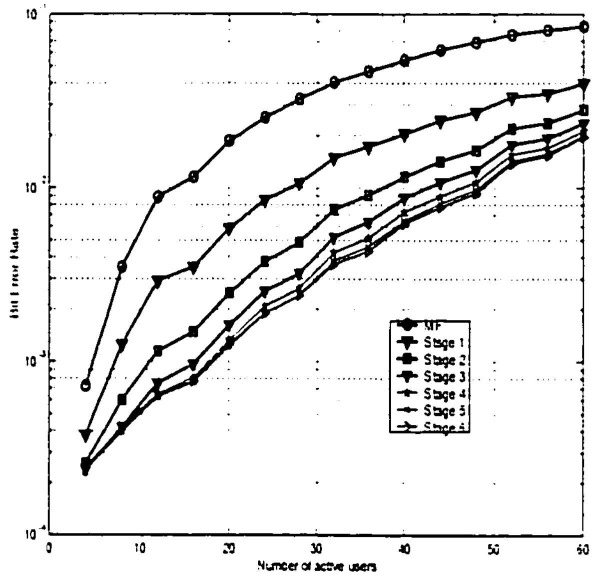


Figure 4.3: Output of the multistage soft PPIC detector for different stages and system loads. $N = 63$, $E_b/N_o = 8dB$, and $0 \leq \varphi_k \leq 2\pi$. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$.

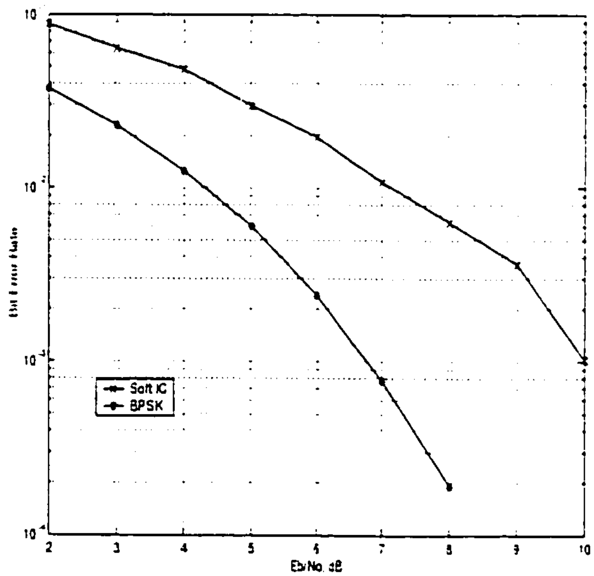


Figure 4.4: Comparison of the performance of the multistage soft PPIC detector with BPSK single user. $N = 63$, $K = 40$, $0 \leq \varphi_k \leq 2\pi$, and equal power. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$.

4.2 Multistage Hard Partial Parallel Interference Cancellation Detector

As it is known from Chapter 3, when a hard cancellation detector is used, the knowledge of the amplitude and phase of each user has a key role in obtaining a good performance. The less accurate the knowledge of parameters is, the more is the resulting interference, and it turns out that having no cancellation is better than the wrong cancellation. According to Figure 4.5, the output of the mth stage for the first user is

$$\begin{aligned} \widetilde{d}_1^{(m)}(t) &= \frac{1}{T_b}\int_0^{T_b} \lambda_m \left[r(t-mT_b) - \sum_{k=1}^{K} \widehat{S}_k^{(m-1)}(t) \right] c_1(t)dt \\ &+ (1-\lambda_m)\,\widetilde{d}_1^{(m-1)}(t-T_b) + \lambda_m \sqrt{E_{b1}}\widehat{d}_1^{(m-1)}(t-T_b)e^{j\varphi_1} \end{aligned}$$

where

$$\widehat{S}_k^{(m-1)}(t) = \sqrt{E_{bk}}\widehat{d}_k^{(m-1)}c_k(t)e^{j\varphi_k}$$

and $\widetilde{d}_1^{(m-1)}$ and $\widehat{d}_1^{(m-1)}$ are the soft and hard estimates of the (m-1)-stage detector output for the first user, respectively.

Similar to soft cancellation case, time shifts of delayed signals can be dropped. Therefore,

$$\begin{aligned} \widetilde{d}_1^{(m)} &= \frac{1}{T_b}\int_0^{T_b}\lambda_m \left[r(t) - \sum_{k=1}^{K} \widehat{S}_k^{(m-1)}(t) \right] c_1(t)dt + (1-\lambda_m)\,\widetilde{d}_1^{(m-1)} + \lambda_m \sqrt{E_{b1}}\widehat{d}_1^{(m-1)}e^{j\varphi_1} \\ &= \lambda_m \widetilde{d}_1^{(0)} + (1-\lambda_m)\widetilde{d}_1^{(m-1)} - \lambda_m \sum_{k=2}^{K} \sqrt{E_{bk}}\widehat{d}_k^{(m-1)}\rho_{k1}e^{j\varphi_k} \end{aligned}$$

where

$$\widehat{d}_k^{(m-1)} = sgn\left\{ Re\left[\widetilde{d}_k^{(m-1)} e^{-j\varphi_k} \right] \right\}$$

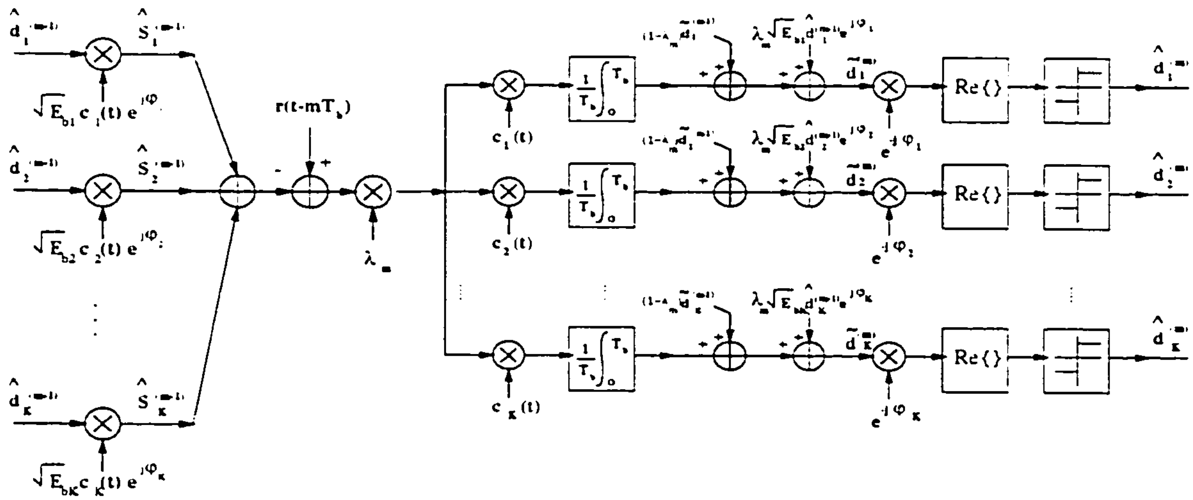


Figure 4.5: **The mth stage of a hard PPIC detector.**

One thing that ought to be noted here is that, since in the hard cancellation case, the knowledge of parameters is used. the performance of such a detector is better than its soft cancellation counterpart assuming that the reliability of the used parameters is high enough. Numerical simulation validates our claim and in less stages, the output of detector gets its highest possible performance. Figure 4.6 shows the output of the hard PPIC detector when $N = 63$, $E_b/N_0 = 7db$, $0 \leq \varphi_k \leq 2\pi$, and $K = 40$. Figure 4.7 shows the performance of different stages of hard IC detector for different amounts of system load. Eventually, the probability of error for different levels of SNR has been depicted through Figure 4.8. It is noted that a perfect estimation is assumed for these figures.

As pointed out at the beginning of this section, having a good knowledge of the amplitude and phase of each user has a profound impact on the performance of the hard PPIC detector. Hence, when the estimation of such parameters with good accuracy is practical, the performance could be superior to that of the soft PPIC detector where no knowledge of parameters is assumed. Consequently. seeking an approach to estimate the parameters with good accuracy and, of course. offering an easy to use method, merit special attention.

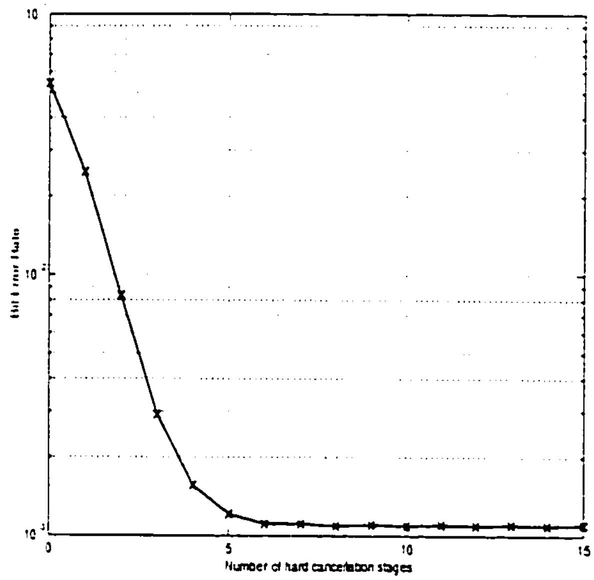


Figure 4.6: **Output of the multistage hard PPIC detector.** $N=63$, $E_b/N_o=7dB$, $0 \leq \varphi_k \leq 2\pi$, **and** $K=40$. $\lambda_1=0.3$, $\lambda_2=0.4$, $\lambda_3=0.5$, $\lambda_4=0.6$, $\lambda_5=0.7$, $\lambda_6=0.8$, $\lambda_7=\lambda_8=\ldots=\lambda_{15}=0.9$.

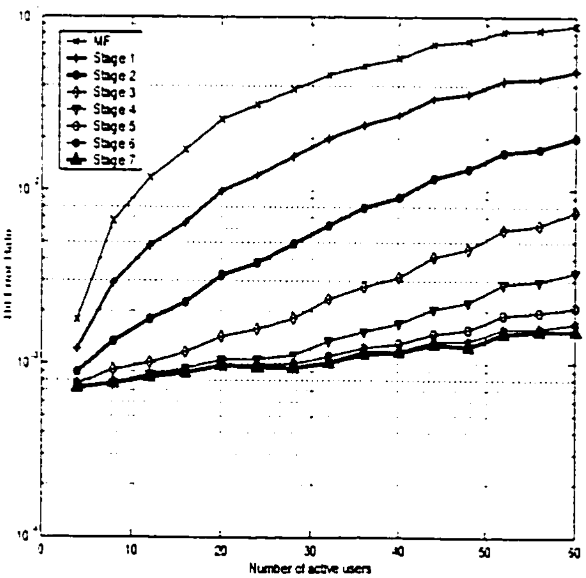


Figure 4.7: **Output of the multistage hard PPIC detector for different stages and system loads.** $N=63$, $E_b/N_o=7dB$, **and** $0 \leq \varphi_k \leq 2\pi$. $\lambda_1=0.3$, $\lambda_2=0.4$, $\lambda_3=0.5$, $\lambda_4=0.6$, $\lambda_5=0.7$, $\lambda_6=0.8$, $\lambda_7=0.9$.

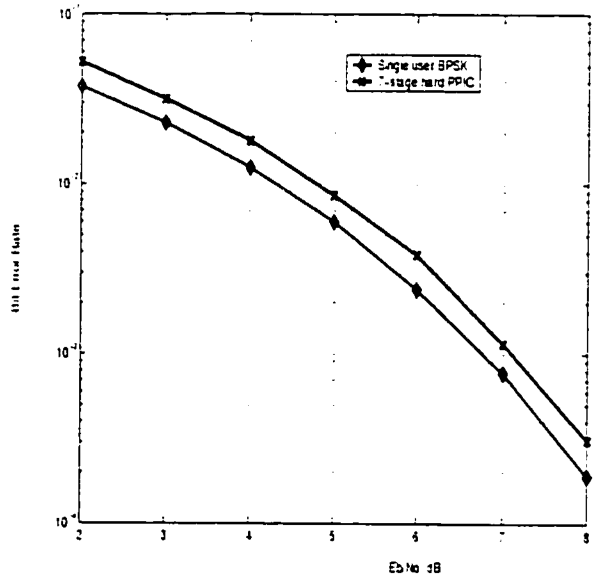


Figure 4.8: **Comparison of the performance of multistage hard PPIC detector with BPSK single user.** $N = 63$, $K = 40$, and $0 \leq \varphi_k \leq 2\pi$. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$.

4.3 Amplitude and Phase Estimation

As we know, the outputs of matched filters are more contaminated by MAI than by the thermal noise. Therefore, as far as there exists a large amount of such an interference affecting each user, the estimation of amplitude and phase pertaining to each user is not feasible. Hence, we primarily try to lower the interference through multistage ***soft*** PPIC detector since this type of detector does not require any information about the parameters. This approach is continued until obtaining better performance is not achievable. At this point, the estimation of users' parameters with good accuracy is feasible provided that the SNR is high enough, and it is assumed that users are mostly corrupted by the enhanced thermal noise rather than the MAI. Therefore, the lth bit of the kth user's signal can be shown as

$$\tilde{d}_k(l) \simeq \sqrt{E_{bk}(l)}\, d_k(l) e^{j\varphi_k(l)} + n_k(l) \tag{4.11}$$

where [6] $var\left[n_k(l)\right] \leq N_o$. If both sides of (4.11) are multiplied by $d_k(l)$, we get

$$\tilde{d}_k(l)d_k(l) \simeq \sqrt{E_{bk}(l)}d_k(l)d_k(l)e^{j\varphi_k(l)} + n_k(l)d_k(l) \tag{4.12}$$

Now, if (4.12) is averaged over a block of data which need not to be very long, the effect of noise will be eliminated effectively.

$$\begin{aligned} E\left[\tilde{d}_k(l)d_k(l)\right] &= E\left[\sqrt{E_{bk}(l)}e^{j\varphi_k(l)}\right] + E\left[n_k(l)d_k(l)\right] \\ &\simeq \sqrt{E_{bk}}e^{j\varphi_k} \end{aligned} \tag{4.13}$$

where the exact equality holds in the absence of noise. In order to do (4.13), $d_k(l)$ is unknown and is needed to be estimated in somehow. The approach which is followed for the estimation purpose is same as what is proposed in [6]. It is assumed that the phase shifts of users (φ_k) lie in $[-\pi/2,\ \pi/2]$. Whenever the risk of phase ambiguity exists (i.e.$-\pi \leq \varphi_k \leq \pi$), differential coding can be used in order to avoid this matter. It is useful to split the interval of $[-\pi/2,\ \pi/2]$ into two intervals of $\{[-\pi/4,\ \pi/4]\}$ and $\{[-\pi/2, -\pi/4]$ or $[\pi/4,\ \pi/2]\}$ such that in the first interval, $Re[\tilde{d}_k(l)]$ is greater than $Im[\tilde{d}_k(l)]$, while in the second interval, we experience greater $Im[\tilde{d}_k(l)]$ than $Re[\tilde{d}_k(l)]$.

Case I : $-\pi/4 \leq \varphi_k \leq \pi/4$

In order to do (4.13), first of all, we need to suppress the effect of $d_k(l)$. Hence, if we could estimate $d_k(l)$, multiply it by $\tilde{d}_k(l)$, and then taking the average yields

$$\Psi'_k = \frac{1}{L}\sum_{l=1}^{L} d_k(l)\tilde{d}_k(l)$$

since in this interval $Re[\tilde{d}_k(l)] \geq Im[\tilde{d}_k(l)]$, we have

$$sgn\left\{Re\left[\tilde{d}_k(l)\right]\right\} \simeq d_k(l)$$

then

$$
\begin{aligned}
\Psi'_k &\simeq \frac{1}{L}\sum_{l=1}^{L} sgn\left\{Re\left[\tilde{d}_k(l)\right]\right\}\tilde{d}_k(l) \\
&\simeq \frac{1}{L}\sum_{l=1}^{L} d_k(l)\tilde{d}_k(l) \\
&= \frac{1}{L}\sum_{l=1}^{L} d_k(l)\left[\sqrt{E_{bk}(l)}d_k(l)e^{j\varphi_k(l)} + n_k(l)\right] \qquad (4.14)
\end{aligned}
$$

where $d_k(l).d_k(l) = 1$, $d_k(l).n_k(l) = \pm n_k(l)$.

Simplification of 4.14, yields

$$
\begin{aligned}
\Psi'_k &\simeq \frac{1}{L}\sum_{l=1}^{L}\sqrt{E_{bk}(l)}e^{j\varphi_k(l)} \pm \frac{1}{L}\sum_{l=1}^{L} n_k(l) \\
&= \sqrt{E_{bk}}e^{j\varphi_k} + \overline{n}_k
\end{aligned}
$$

Finally, the estimation of amplitude and phase will be as

$$\widehat{\sqrt{E_{bk}}} = \left|\Psi'_k\right|$$

$$\widehat{\varphi_k} = arctan\left[Im\left(\Psi'_k\right)/Re\left(\Psi'_k\right)\right]$$

Case II : $-\pi/2 \leq \varphi_k \leq -\pi/4$ or, $\pi/4 \leq \varphi_k \leq \pi/2$

Since in this interval $Im[\tilde{d}_k(l)] \geq Re[\tilde{d}_k(l)]$, then we define

$$\Psi''_k = \frac{1}{L}\sum_{l=1}^{L} sgn\left\{Im\left[\tilde{d}_k(l)\right]\right\}\tilde{d}_k(l)$$

and

$$
\begin{aligned}
sgn\left\{Im\left[\tilde{d}_k(l)\right]\right\} &\simeq sgn\left\{\sqrt{E_{bk}}d_k(l)sin\left[\varphi_k(l)\right]\right\} \\
&= sgn\left\{d_k(l)sin\left[\varphi_k(l)\right]\right\} \\
&= \pm d_k(l)
\end{aligned}
$$

then

$$\begin{aligned} \Psi_k^{''} &\simeq \frac{1}{L}\sum_{l=1}^{L}\left[\pm d_k(l)\right]\left[\sqrt{E_{bk}(l)}d_k(l)e^{j\varphi_k(l)} + n_k(l)\right] \\ &= \pm\sqrt{E_{bk}}e^{j\varphi_k} \pm \overline{n}_k \end{aligned}$$

Now, in order to derive a closed form same as case I, we define

$$\begin{aligned} \Psi_k^{'''} &= sgn\left\{Re\left[\Psi_k^{''}\right]\right\}\Psi_k^{''} \\ &\simeq \left\{sgn\left[\pm\sqrt{E_{bk}}cos(\varphi_k)\right]\right\}\left\{\pm\sqrt{E_{bk}}e^{j\varphi_k} \pm \overline{n}_k\right\} \\ &= \{\pm 1\}\left\{\pm\sqrt{E_{bk}}e^{j\varphi_k} \pm \overline{n}_k\right\} \\ &= \sqrt{E_{bk}}e^{j\varphi_k} + \overline{n}_k \end{aligned}$$

Again, similar to case I, we get

$$\widehat{\sqrt{E_{bk}}} = \left|\Psi_k^{'''}\right|$$

$$\widehat{\varphi_k} = arctan\left[Im\left(\Psi_k^{'''}\right)/Re\left(\Psi_k^{'''}\right)\right]$$

If there is not enough information to guess the range of φ_k primarily, then $\Psi_k^{'}$ and $\Psi_k^{'''}$ need to be calculated, and the one with larger norm is selected, i.e.,

$$\Psi_k = \begin{cases} \Psi_k^{'} & \text{if } \left|\Psi_k^{'}\right| \geq \left|\Psi_k^{'''}\right| \\ \Psi_k^{'''} & \text{otherwise} \end{cases}$$

4.4 Combined Soft and Hard Multistage Detector

So far, we have introduced soft PPIC detector, parameter estimation, and hard PPIC detector. As a novel approach, one may employ a combination of aforementioned methods. We will call this new scheme as ***Soft and Hard Partial Parallel Interference Cancellation*** (***SHPPIC***) detector. Such a scheme, takes three steps in order to generate a final output. Figure 4.9 shows the block diagram of the proposed

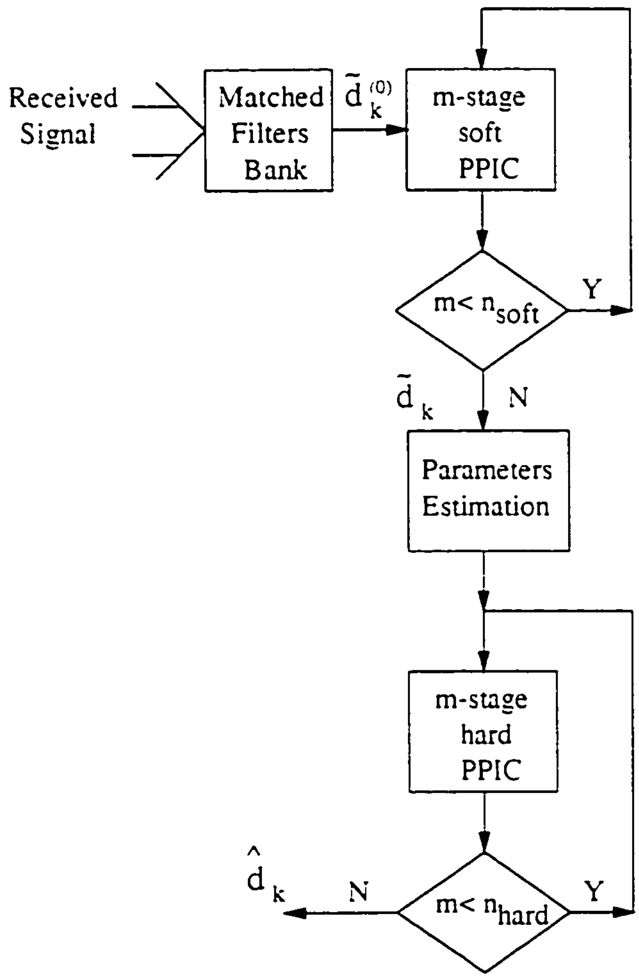


Figure 4.9: **Combined Soft and Hard Partial Parallel Interference Cancellation (SHPPIC) detector.**

method where. n_{soft} and n_{hard} denote the number of required soft and hard stages, respectively.

As a first step, some stages of soft cancellation are in place until obtaining better performance is not possible. Through numerical simulations (Figure 4.10), it is shown that the performance of this first step is same as that of the Decorrelator Detector which is usually considered as a good reference to compare. At this point, parameter estimation will be done, and eventually a few stages of hard cancellation will complete the procedure. It is claimed that the performance of the detector obtained in this manner, surpasses the performance of the Decorrealtor Detector as the numerical simulations justify this.

Figure 4.10 compares the performance of our proposed method with SIC and Decorrelator detectors. It is notable that in both cases of either perfect or proposed estimation method, the efficiency is better than or equal to the SIC method which has been proposed in [6].

In Figure 4.11 a performance comparison is demonstrated for different system loads. One may raise this question that when the system load is not high. the performance of SHPPIC detector seems inferior to SIC method. Indeed. when the number of simultaneous users is low, we do not have to proceed through as many stages as in the case of high system load. This is because there is less interference affecting each user, and taking further steps through stages results in more useful data cancellation rather than interference cancellation. As a result, if we adjust our detector to make the number of stages proportional to system load (less stages for low system load and vice versa), the performance of our proposed method will always be better than that of the other detectors.

In Figure 4.12 a performance comparison between a ten-stage (seven soft and three hard stages) SHPPIC and BPSK single user detectors is shown.

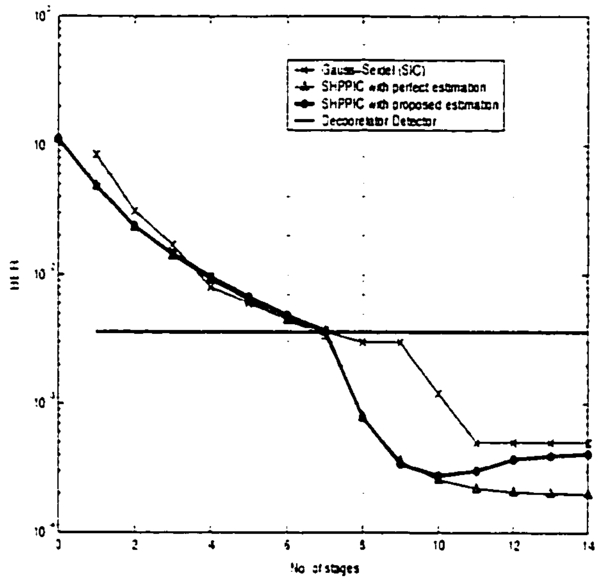


Figure 4.10: Performance comparison of SHPPIC with SIC [6] and Decorrelator Detector [6]. $N = 31$, $E_b/N_o = 11dB$, $K = 20$, $\varphi_k = 0$, and equal power. $\lambda_1 = \lambda_8 = 0.3$, $\lambda_2 = \lambda_9 = 0.4$, $\lambda_3 = \lambda_{10} = 0.5$, $\lambda_4 = \lambda_{11} = 0.6$, $\lambda_5 = \lambda_{12} = 0.7$, $\lambda_6 = \lambda_{13} = 0.8$, $\lambda_7 = \lambda_{14} = 0.9$.

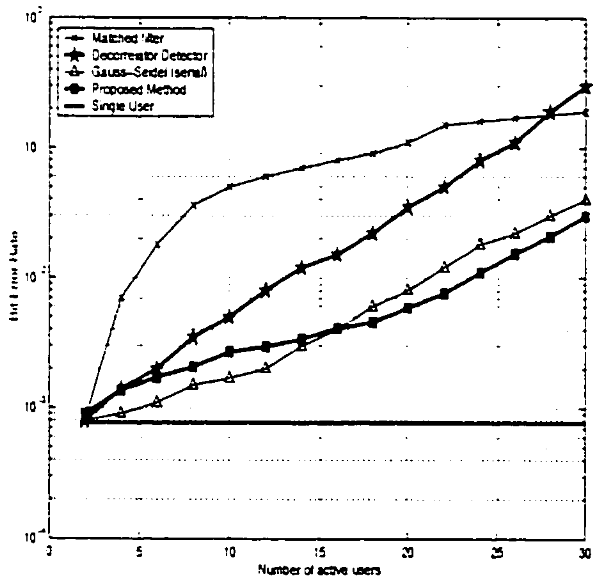


Figure 4.11: Performance comparison of SHPPIC with Matched Filter [6], Decorrelator Detector [6], SIC [6] and single user case. $N = 31$, $E_b/N_o = 7dB$, $\varphi_k = 0$, and equal power. $\lambda_1 = \lambda_8 = 0.3$, $\lambda_2 = \lambda_9 = 0.4$, $\lambda_3 = \lambda_{10} = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$.

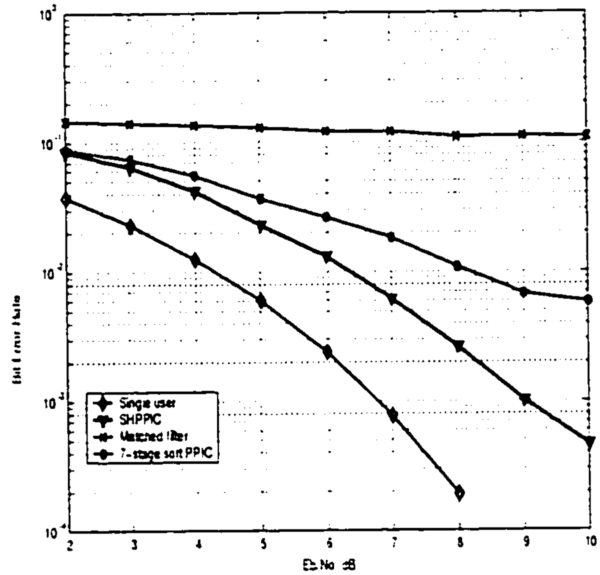


Figure 4.12: **Comparison of the performance of the multistage SHPPIC detector with BPSK single user.** $N = 31$, $K = 20$, $\varphi_k = 0$, **and equal power.** $\lambda_1 = \lambda_8 = 0.3$, $\lambda_2 = \lambda_9 = 0.4$, $\lambda_3 = \lambda_{10} = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, **and** $\lambda_7 = 0.9$.

At this point, we have a brief discussion about the confidence interval of the simulation results. As an example, let us choose the point of $E_b/N_o = 9dB$ in Figure 4.12 for SHPPIC detector. The cost function $D(i)$ is defined as

$$D(i) = \begin{cases} 1 & \text{if error} \\ 0 & \text{if no-error} \end{cases}$$

The confidence interval for the probability of 0.9 is defined as [35]

$$P\left(\widehat{p_e} - Z_{\alpha/2}\frac{\sigma_D}{\sqrt{n}} \leq p_e \leq \widehat{p_e} + Z_{\alpha/2}\frac{\sigma_D}{\sqrt{n}}\right) = 1 - \alpha \tag{4.15}$$

where

$$1 - \alpha = 0.9 \quad \Rightarrow \quad Z_{\alpha/2} = 1.645$$

$$\widehat{p_e} = \frac{1}{n}\sum_{i=1}^{n} D(i)$$

$$\sigma_D^2 = E\left[D^2\right] - E^2\left[D\right] \tag{4.16}$$

As it was mentioned earlier, simulation is run for 100 packets of 10000 bit sequences. Therefore

$$n = 100 \times 10000 = 10^6$$

From Figure 4.12

$$\widehat{p}_e = \frac{1}{10^6} \sum_{i=1}^{10^6} D(i) = 0.00112$$

In order to calculate σ_D from (4.16), we need to find $E[D^2]$ and $E[D]$.

$$E\left[D^2\right] = 0^2 \times (1 - \widehat{p}_e) + 1^2 \times (\widehat{p}_e) = \widehat{p}_e$$

$$E\left[D\right] = 0^{\times} (1 - \widehat{p}_e) + 1 \times (\widehat{p}_e) = \widehat{p}_e$$

substituting in (4.16), yields

$$\begin{aligned} \sigma_D^2 &= \widehat{p}_e - \widehat{p}_e^2 \\ &= \widehat{p}_e (1 - \widehat{p}_e) \\ &= 0.00112(1 - 0.00112) \\ &= 1.1187 \times 10^{-3} \end{aligned}$$

Finally, using (4.15), we get

$$P\left(0.00112 - 1.645\frac{\sigma_D}{\sqrt{n}} \leq p_e \leq 0.00112 + 1.645\frac{\sigma_D}{\sqrt{n}}\right) = 0.9$$

$$P\left(1.06 \times 10^{-3} \leq p_e \leq 1.17 \times 10^{-3}\right) = 0.9$$

Similarly, for the confidence level of %99, we have

$$1 - \alpha = 0.99 \quad \Rightarrow \quad Z_{\alpha/2} = 2.567$$

$$P\left(1.03 \times 10^{-3} \leq p_e \leq 1.20 \times 10^{-3}\right) = 0.99$$

Finally, in order to get some points with higher SNRs, the simulation of our proposed method is run for 100 packets of 100000 bits. Other conditions remain the same as in Figure 4.12. The resulting outputs are $2.16000e - 04$ and $8.46000e - 05$ for $E_b/N_0 = 11dB$ and $12dB$, respectively.

4.5 Complexity Issue

For the sake of comparison, in what follows, the computational complexity of some well-known schemes is studied. First of all, the complexity of the optimal (ML) multiuser detector is subject to exponential growth as the number of users increases ($O(2^K)/bit$). Such a receiver, as mentioned before, suits the situations where the number of users is small. Otherwise, it turns out to be too complicated to implement. Another receiver is Decorrlator Detector which is classified under the linear group. It has a complexity proportional to the square of the number of interfering users ($O(K^2)/bit$). Hence, this approach is attractive for the case where the system load is low to moderate. Gauss-Seidel (SIC) Soft/Hard detector proposed in [6] belongs to the class of Interference Cancellation detectors and takes advantage of a simple structure whose complexity grows linearly with the number of users ($O(K)/bit/stage$). Therefore, this sort of structure seems more promising when the system load is moderate to high. However. since this method employs the Successive Interference Cancellation (SIC), it is compulsory to detect users one by one. The drawback in this situation is the latency, which makes such a scheme too slow for a large number of users. Finally, in what was proposed in this chapter. although the complexity of each stage is higher than SIC approach, it still grows linearly ($O(K)/bit/stage$), and since there is no need to wait for updated data as in SIC scheme, our proposed method is much faster. In addition, when the partial cancellation coefficients (λ_m) are chosen properly, the number of stages will be less. Obviously, this results in more saving in terms of latency as well as the complexity.

4.6 Summary

A multiuser detection scheme consisting of a combination of iterative soft and hard Partial Parallel Interference Cancellation (SHPPIC) detectors with parameter estimation was addressed in this chapter. The efficiency of our method was gauged through comparison with other known schemes such as Decorrelator Detector and Successive Interference Cancellation detector. Our proposed approach can be considered as a satisfactory alternative considering complexity and latency aspects, since it is less complex than the Decorrelator Detector and faster than the SIC receiver.

Chapter 5

Trends in Multi User Detection

Parallel Interference Cancellation (PIC) detectors are usually discussed under the conditions where the users' data arrive at the receiver with almost the same power level (or power control is in place). In this chapter, a modified version of PPIC detector is introduced that is more resilient to the near-far problem. Also some applications of SHPPIC method (which was proposed in Chapter 4) to some newly-proposed standards will be studied

5.1 Near-Far Problem

As pointed out in Chapter 1, one of the main issues contributed to CDMA in general, and to PIC or PPIC detectors, in particular, is the near-far issue where the interference originating from the strong users worsen the situation of information transmitted by the weak users. Among multiuser detection techniques, PIC and PPIC detectors are vulnerable to this matter. Since these detectors are attractive due to their simple structure, any effort to make them more resistant against the near-far problem, is of great interest. One method that has been proposed recently is to split the users into groups with (ideally) the same power [12]. Figure 5.1 shows the block diagram of such an approach. As it is seen, interference cancellation is done in PIC form inside the groups, while between the groups cancellation will be in the form of SIC. This scheme is called Hybrid Interference Cancellation (HIC) detector. In this approach, the positive aspects of SIC and PIC are combined such that the resulting scheme is less complex and more tolerant to the situations where the user signals arrive with different power at the receiver.

It is noted that in the HIC scheme, before any cancellation, groups of equal power users are sorted according to their received power. The first group to detect is the one with the strongest power. As soon as the outputs pertaining to this group are available, they will be exploited to detect the second strongest group of users. This procedure is continued until the last group of users with the weakest received power level is detected, and same as in PPIC case, in order to obtain a better performance, this procedure can be done through a multitude of stages. This will be called multistage HIC detector.

Figure 5.2 shows the performance of an HIC detector. In this figure, it is assumed that there are two groups each of which includes five users with the SNRs of 5.5 and 10 dB. This situation is compared with the equal power cases where in the first case there are 10 users with the SNRs of 5.5 dB, and in the second case, there are 10 users with the SNRs of 11 dB. As it is expected, the performance for the strong users in near-far case is better than the the performance of equal-power case since in the former, there are less numbers of strong active users. On the other hand, the performance of the weak users approaches the performance of equal power case, although these weak users experience a large amount of interferences coming from the strong users.

We will end this section with a brief discussion about the complexity issue. The method used for HIC is less complex than PIC, since it splits the total number of users into several groups whose outputs get ready one after the other. However, since SIC method is applied between groups of users, such a system has more latency than PIC or PPIC scheme.

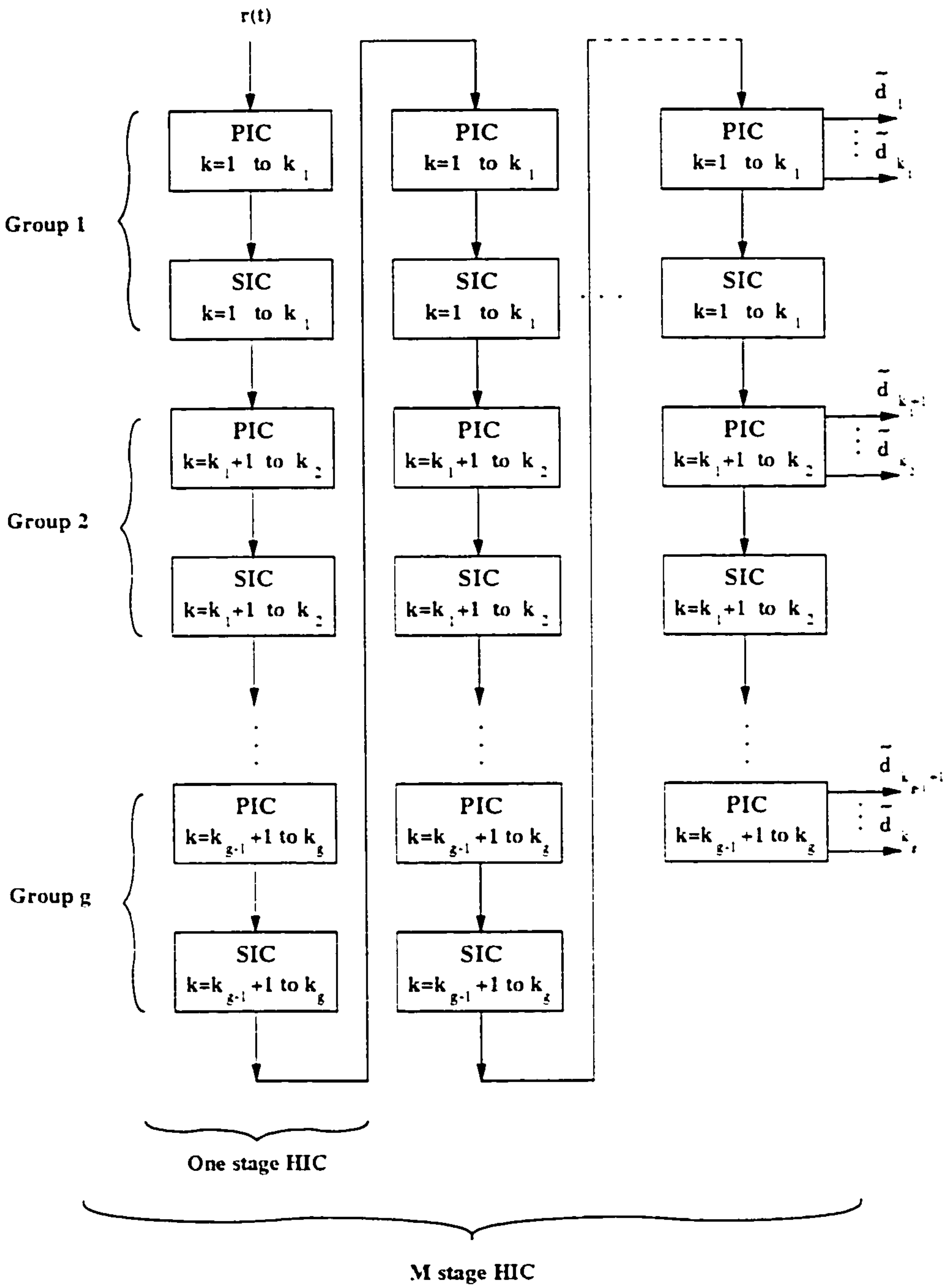


Figure 5.1: Block diagram of the multistage HIC detector.

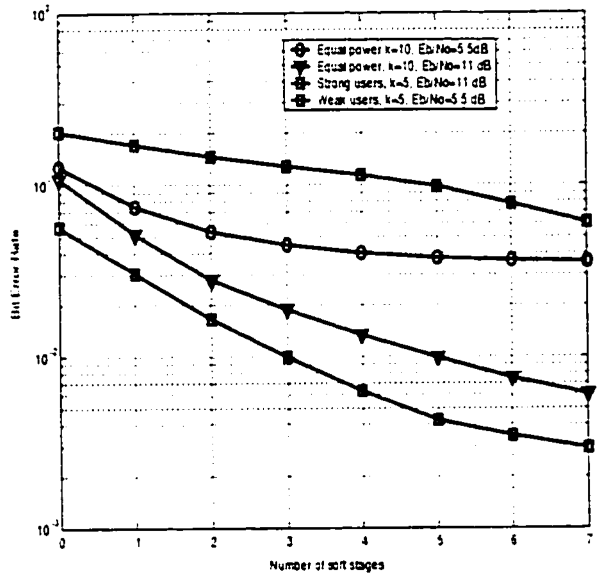


Figure 5.2: **A comparison of soft HIC and soft PPIC detectors.** $N = 15$, **and** $\varphi_k = 0$. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$.

5.2 Application to UMTS Satellite

As stated in Chapter 1, the third generation of communication systems are supposed to provide a higher rate and more flexible services in order to serve more simultaneous users while keeping link performance at a high level. In order to achieve this goal, satellite communication systems play an important role. The SHPPIC detector which was proposed in Chapter 4 is suitable for Digital Video Broadcasting- Return Channel via Satellite (DVB-RCS). Our proposed scheme can be applied to the evolutionary satellite communication system where a combination of TDMA and CDMA (CTDMA) is used. As an example [17], a 2048 kbit/s data stream can be divided into 128 slots of 16 kbit/s data rate. Now, in each of these TDMA slots, CDMA and Multi User Detection (MUD) techniques can be exploited. In satellite communications, the spreading codes are usually constructed with a Walsh-Hadamard (WH) code as an inner spreading sequence which is concatenated with an outer PN codes. This configuration will be repeated with different PN codes for different spotbeams.

Therefore, in the case of long PN codes, the inter-beam interference will be random-like. At the receiver section of the satellite, despreading and MUD operations will be occured before any decoding part of the on-board processing satellite.

WCDMA with new parameters has been introduced as a promising air interface [2], [9], [31]. Some of the main parameters attributed to WCDMA are

- In order to establish a flexible user-to-user connection (up to 2Mbps), a variable processing gain with different types of codes (pure random, PN, and Gold codes) and modulation schemes (BPSK, QPSK, 8PSK, and 16 QAM) have been proposed.

- Higher chip rate of 3.84Mcps, carrier spacing of 5MHz, and frame duration of 10ms have been proposed. Therefore, a combination of Time-Frequency-Code Division Multiple Access (TFCDMA) is feasible. This means that in each time frame, the available spectrum is divided among some carriers each of which carry simultaneous spread spectrum signals [17], [31].

In order to ensure the applicability of our proposed method to the third generation communication standards (e.g. UMTS and IMT-2000), some recently-defined parameters for WCDMA need to be employed by our proposed scheme. So far, what we have used as the parameters were pure random codes with BPSK modulation in order to make a more fair comparison with other known multiuser detectors. Now that we have justified the advantages of our proposed method, steps will be taken further to change the modulation scheme from BPSK to QPSK and instead of using pure random codes, PN codes will be employed with processing gains of 31 and 63.

Figure 5.3 and 5.4 show the feedback shift registers to generate PN codes of 31 and 63, respectively [32].

Figures 5.5 and 5.6 compare the performance of our proposed method (SHP-PIC) when two types of pure random and Pseudo-noise (PN) codes are employed.

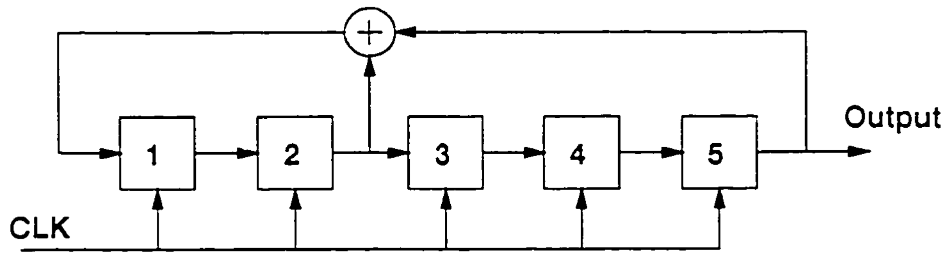


Figure 5.3: **PN code generator with N=31.**

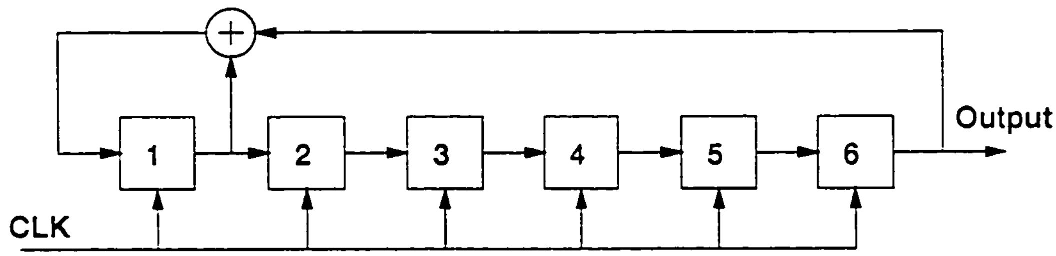


Figure 5.4: **PN code generator with N=63.**

Figures 5.7 and 5.8 show the same comparison when the modulation scheme is QPSK.

These figures may raise this question that by applying PN codes, the interference corrupting each user is eliminated completely. In fact, this is true as far as the system is ideally synchronous and there is no multiple path for signal to travel; and even sometimes without any interference cancellation, the performance is still better than that of the case where random codes are used. However, if the asynchronous and multipath issues are taken into consideration, this great performance will be diminished. In these situations, even better signature waveforms such as Gold codes are needed. In addition, since the same codes are used in neighboring beams (cells in cellular communications), the inter-beam (inter-cell) interferences should be added to the basic intra-beam (intra-cell) interference.

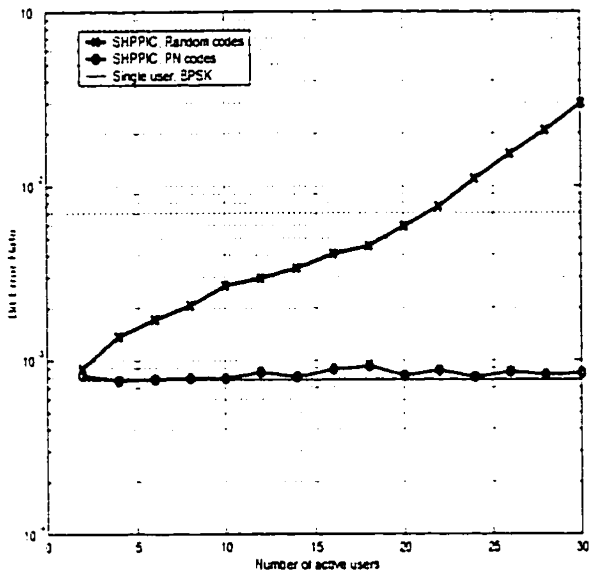


Figure 5.5: Performance of a ten-stage SHPPIC detector using different types of codes for different system loads. $N = 31$, $E_b/N_o = 7dB$, $\varphi_k = 0$, and equal power. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$, $\lambda_8 = 0.3$, $\lambda_9 = 0.4$, and $\lambda_{10} = 0.5$.

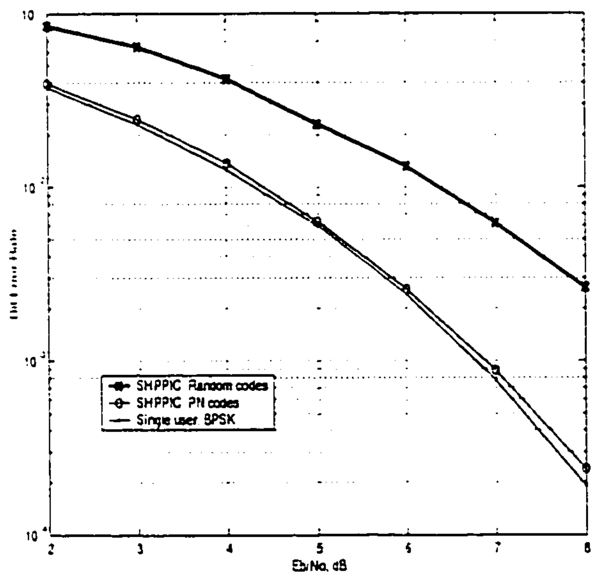


Figure 5.6: Performance of a ten-stage SHPPIC detector using different types of codes for different SNR levels. $N = 31$, $K = 20$, $\varphi_k = 0$, and equal power. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$, $\lambda_8 = 0.3$, $\lambda_9 = 0.4$, and $\lambda_{10} = 0.5$.

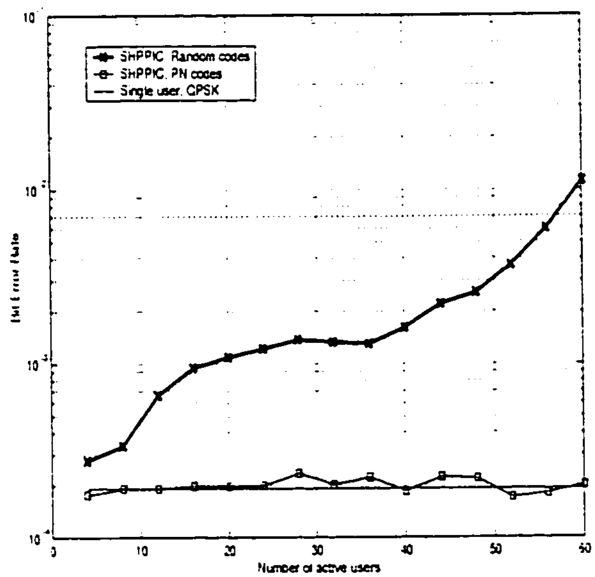


Figure 5.7: Performance of a ten-stage SHPPIC detector using different types of codes for different system loads. $N = 63$, $E_b/N_o = 8dB$, $\varphi_k = 0$, and equal power. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$, $\lambda_8 = 0.3$, $\lambda_9 = 0.4$, and $\lambda_{10} = 0.5$.

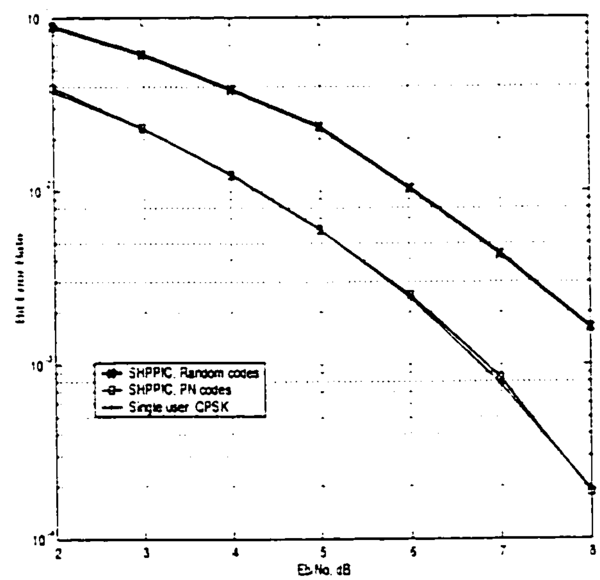


Figure 5.8: Performance of a ten-stage SHPPIC detector using different types of codes for different SNR levels. $N = 63$, $K = 40$, $\varphi_k = 0$, and equal power. $\lambda_1 = 0.3$, $\lambda_2 = 0.4$, $\lambda_3 = 0.5$, $\lambda_4 = 0.6$, $\lambda_5 = 0.7$, $\lambda_6 = 0.8$, $\lambda_7 = 0.9$, $\lambda_8 = 0.3$, $\lambda_9 = 0.4$, and $\lambda_{10} = 0.5$.

5.3 Summary

The Hybrid Interference Cancellation (HIC) detector was discussed for near-far conditions. Through numerical simulations, it was shown that the overall performance would be better when users arrive at the receiver with different levels of power, since the strong users are detected more reliably and weak users will obtain almost the same performance as that in the case of equal power. In addition, we studied our proposed method by applying some parameters of recent standards of communication systems.

Chapter 6

Conclusions and Suggestions for further research

6.1 Conclusions

A new scheme for Multi User Detection (MUD) using a combination of Soft and Hard Partial Parallel Interference Cancellation (SHPPIC) with parameter estimation was presented in this thesis. This scheme is appropriate for Digital Video Broadcasting-Return Channel via Satellite (DVB-RCS) communication systems. Our proposed method can also be applied to the evolutionary satellite communication systems that use a combination of TDMA and CDMA (Slotted CDMA in [17]). The placement of our detector at payload's receiver section would be after bandpass filtering of the received signal and before channel decoding. It is noted that in satellite communications, intra-beam users are encoded by Walsh-Hadamard codes, whereas, the inter-beam users are encoded by PN codes. Some advantages of this novel method are

- The computational complexity of our proposed method is much less than that of the ML and linear multiuser detectors.

- The first part of our proposed method applies multistage soft PPIC detector. This type of detector does not require any knowledge of users' parameters. The resulting performance is almost equal to that of the Decorrelator Detector (DD).

- Parallel Interference Cancellation (PIC) detectors are usually studied under circumstances that perfect knowledge of users' parameters (e.g. amplitude and phase) is available. We applied a simple method to estimate the parameters whose accuracy is good if the SNR is high enough.

- Using multistage hard PPIC detector, the overall performance of our proposed method is much better than that of DD which is usually used to gauge the performance of sub-optimum detectors.

Simulation results demonstrated the excellence of our proposed method and that it can be considered as a suitable alternative considering the complexity and latency aspects.

We introduced a multistage Hybrid Interference Cancellation (HIC) method which has better performance than that of pure PIC and PPIC under near-far conditions when the signals arrive at the receiver with different levels of power. In addition, this new scheme is less complex than PIC and PPIC detectors.

From simulations, it was perceived that the strong users are detected with better quality than that of equal-power case, and weak users are detected with almost the same quality as that of the equal-power condition.

Finally, we considered the application of our proposed system for some new standards of the third generation systems (e.g. UMTS and IMT-2000) as an alternative to other schemes.

6.2 Direction for Further Research

In what was proposed in this thesis, efforts have been made to define a scheme that gives better performance than that of the schemes already proposed in synchronous and single-path environments. Some topics for further study are

- to analyze and simulate SHPPIC detector in asynchronous and multi-path fading channels,
- to analyze and simulate SHPPIC for coded DS-CDMA signals by applying different coding methods, and
- applying other modulation schemes (16QAM) on DS-CDMA signals.

Bibliography

[1] S. Moshavi, "Multi-user detection for DS-CDMA communications," *IEEE Commun. Mag.*, vol. 34, pp. 124-136, October 1996.

[2] R. Prasad, T. Ojanpera, "An overview of CDMA evolution toward wideband CDMA," *IEEE Commun. Surveys*, vol. 1, pp. 2-29, Fourth Quarter 1998.

[3] D. Divsalar, M. K. Simon, and D. Raphaeli, "Improved parallel interference cancellation for CDMA," *IEEE Trans. Commun.*, vol. 46, pp. 258-268, February 1998.

[4] D. Divsalar and M. Simon, "Improved CDMA performance using parallel interference cancellation," Technical report, JPL, California Institute of Technology, October 1995.

[5] R. M. Buehrer and S. P. Nicoloso, "Comments on partial parallel interference cancellation for CDMA," *IEEE Trans. Commun.*, vol. 47, pp. 658-661, May 1999.

[6] Z. Feng and C. Schlegel, "An iterative CDMA multiuser detector with embedded phase amplitude estimation," submitted to *IEEE Trans. Commun.*, Sept. 1999.

[7] P. Shan and T. S. Rappaport, "Parallel interference cancellation (PIC) improvements for CDMA multiuser receivers using partial cancellation of MAI estimates," *Proc. IEEE Globecom 98*, vol. 6, pp. 3282-3287.

[8] T. Suzuki and Y. Takeuchi. "Near-decorrelating multistage detector for asynchronous DS-CDMA," *IEICE Trans. Commun.*, vol. E81-B, pp. 553-564, March 1998.

[9] A. L. Johansson and A. Svenson, "A hybrid interference cancellation scheme for multiuser systems in multipath fading channels," *Elsevier Signal Processing*, vol. 11. pp. 207-217, March-April 2000.

[10] R. D. Giloramo, P. Takats, R. Soleymani, "Advanced CDMA study," Technical report EMS Technologies Canada Ltd., May 2000.

[11] R. L. Pickoltz. L. B. Milstein, and D. L. Schilling, "Spread spectrum for mobile communications." *IEEE Trans. Veh. Tech.*, vol. 40, pp. 313-321, May 1991.

[12] D. Koulakiotis and A. H. Aghvami, "Data detection techniques for DS CDMA mobile systems: A review," *IEEE Personal Commun.*. vol. 7. pp. 24-34. June 2000.

[13] P. G. Renucci, "optimization of soft interference cancellation in DS-CDMA receivers," Master's thesis, Virginia Polytechnic Institute and State University. Blacksburg, Virginia, May 1998.

[14] S. Nagaraj and Y. F. Huang, "A linear estimation technique for improved BER performance in interference cancellers for random-code CDMA communications," *Proc. Conf. Inform. Science Sys.*, March 2000.

[15] A. N. Fawzy, A. W. Fayez, and M. M. Riad, "Optimization of partial parallel interference cancellation (PPIC) factor in CDMA systems," *Proc. IEEE sys.. man. cyber. 2000*, vol. 4. pp. 2375-2380.

[16] M. J. Borran and M. N. Kenari. "An efficient detection technique for synchronous CDMA communication systems based on the expectation maximization algorithm," *IEEE Trans. veh. Tech.*, vol. 49, pp. 1663-1668, September 2000.

[17] C. G. F. Valadon, G. A. Verelst, p. Taaghol, R. Tafazolli, and B. G. Evans, "Code-division multiple access for provision of mobile multimedia services with a geostationary regenerative payload," *IEEE JSAC*, vol. 17, pp. 223-237, February 1999.

[18] A. Duel-Hallen. J. Holtzman. and Z. Zvonar, "Multiuser detection for CDMA systems," *IEEE Personal Commun.*, vol. 2, pp. 46-58, April 1995.

[19] W. C. Lee, "Overview of cellular CDMA," *IEEE Trans. veh. Tech.*, vol. 40. pp. 291-302, May 1991.

[20] Z. Guo and K. B. Letaief, "An efficient multiuser receiver for DS CDMA systems," *IEEE JSAC*, vol. 19. pp. 1019-1028. June 2001.

[21] P. Spasojevic and A. Yener, "Improving soft interference cancellation for CDMA systems," *Proc. IEEE ICC 2001.*

[22] G. Xue and L. Chengshu. "An analysis of HD-parallel interference cancellation in asynchronous DS-CDMA systems," *Proc. IEEE WCC-ICCT 2000*, vol. 2, pp. 1522-1525.

[23] P. D. Alexander, M. C. Reed, J. A. Asenstorfer, and C. B. Schlegel, "Iterative multiuser interference reduction: Turbo CDMA," *IEEE Trans. Commun.*, vol. 47. pp. 1008-1014. July 1999.

[24] M. Moher and P. Guinand. "An iterative algorithm for asynchronous coded multiuser detection," *IEEE Commun. Letters*, vol. 2, pp. 229-231, August 1998.

[25] M. Moher, "An iterative multiuser decoder for near-capacity communications," *IEEE Trans. Commun.*, vol. 46, pp. 870-880, July 1998.

[26] X. H. Chen, H. K. Sim, and P. S. Kooi, "An effective CDMA multiuser detection scheme orthogonal decision-feedback detection and its performance analysis," *IEICE Trans. Commun.*, vol. E80-B, pp. 145-155, January 1997.

[27] S. Yishen, Z. Xiaobo, Z. Lei, and Z. Xianda, "Adaptive parallel interference cancellation performance in Rayleigh fading time-multiplexed pilot channel," *Proc. IEEE WCC-ICCT 2000*, vol. 1, pp. 196-199.

[28] D. Gerakoulis and E. Geraniotis, "A code-division switch architecture for satellite applications," *IEEE JSAC*, vol. 18, pp. 481-495, March 2000.

[29] S. R. Kim, Y. G. Jeong, J. G. Lee, and I. K. Choi, "Incorporation of adaptive interference cancellation into parallel interference cancellation," *Proc. IEEE Veh. Tech.*, vol. 2, pp. 1242-1245, 1999.

[30] R. M. Buehrer, "On the convergence of multistage interference cancellation," *Proc. IEEE Asilomar Sig. Sys. Comp.*, vol. 1, pp. 634-638, 1999.

[31] H. Holma and A. Toskala, *WCDMA for UMTS*, 1st edition, John Wiley, 2000.

[32] S. Haykin, *communication Systems*, 3rd edition, John Wiley, 1994.

[33] S. Verdu, *Multiuser Detection*, 1st edition, Cambridge, 1998.

[34] J. G. Proakis, *Digital Communications*, Fourth edition, Mc-Graw Hill, New York, 2001.

[35] M. D. Srinath, P. K. Rajasekaran, and R. Viswanathan *Introduction to Statistical Signal Processing with Applications*, Prentice-Hall, New Jersy, 1996.

[36] M. Ghotbi and M. R. Soleymani, "Multiuser detection of DS-CDMA signals using partial parallel interference cancellation with amplitude and phase estimation," submitted to *IEEE Trans. Commun.*, July 2001.