Multiuser Detection for Synchronous DS-CDMA in AWGN Channel

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***Abstract* - In conventional correlation receiver, the capacity of a single cell using CDMA is limited by Multiple Access Interference (MAI). To overcome this drawback, several advanced receiver structures have been proposed. Unlike the conventional receiver which treats multiple access interference (MAI) as if it were AWGN, multiuser receivers treat MAI as additional information to aid in detection. In this paper I present a comparative study of the most widely discussed receiver structures: the Conventional Matched Filter receiver, the Decorrelator receiver, the Minimum Mean Square Error (MMSE) receiver, and the Successive Interference Cancellation receiver. BER performances of the above mentioned multiuser receivers are studied as a function of SNR, number of users and processing gain.**

***Index Terms* - Direct-sequence code division multiple access (DS-CDMA), Multi-user detection (MUD), Additive White Gaussian Noise (AWGN), Multiple Access Interference (MAI), Minimum Mean Square (MMSE), Signal-to-Noise Ratio(SNR).**

I. INTRODUCTION

In DS-CDMA communication system, users are multiplexed by distinct codes rather than by orthogonal frequency bands or by orthogonal time slots. A conventional DS-CDMA detector follows a single user detection strategy in which each user is treated separately as a signal, while the other users are considered as either interference or noise. A comprehensive look on DS-CDMA system can be found in [1-2].

Multiple access interference (MAI) restricts the capacity and the performance of DS-CDMA systems. As described in [3], MAI is the interference between active users, and causes timing offsets between signals. Conventional detectors detect each user separately, and do not take MAI into consideration.

Due to this, multiuser detection strategies have been proposed in [3-4].

Multiuser detection seeks to enhance the performance of non-orthogonal signaling schemes for multiple-access communications by combating MAI caused by the presence of more than one user in the channel. The conventional CDMA is an interference limited system when MAI is increasing with the number of active users, and when signals are received with different power levels due to near-far problem. Conventional single user detection, when optimized for additive white Gaussian noise (AWGN), orthogonal codes and synchronous symbols, depends on power control, which is susceptible to degradation when the channel condition changes. These factors are taken into account in the simulation with the exception that all active users are assumed to have equal power.

This paper is organized as follows; Conventional receiver is discussed in section 2. Section 3 discusses the multiuser detection techniques. Simulation results are discussed in section 4, and finally conclusion remarks are made in section 5.

II. SYSTEM MODEL

The basic synchronous K-user CDMA model describes the received signal of a CDMA system, in which K synchronous bit streams antipodally modulates the K signature waveforms over an Additive White Gaussian Noise (AWGN) channel. Both the bit streams and signature waveforms are represented by non-return to zero (NRZ) signals. The received signal for one symbol period in such a system can be expressed as

$$r(t)= \sum_{k=1}^{K} A_k bksk(t)+n(t) \qquad (2.1)$$

Where, gk is the deterministic signature waveform assigned to kth user normalized to have unit energy (<gk,gk.> =1), bk Є{-1, 1} is a bit transmitted by kth user, Ak is the received amplitude of the kth user and n(t) is a white-Gaussian noise sequence with zero mean and unit variance.

A one-shot model is used, since only one bit duration is considered. This one-shot model is enough for analysis if synchronous CDMA is considered. We define a cross-correlation matrix as

$$R=\{\rho_{ij}\}$$

$$\text{i.e } R = \begin{pmatrix} \rho_{11} & \rho_{12} \cdots\cdots & \rho_{1k} \\ \rho_{21} & \rho_{22} \cdots\cdots & \rho_{2k} \\ & & \\ \rho_{k1} & \rho_{k2} \cdots\cdots & \rho_{kk} \end{pmatrix}$$

Where ρ_{ij} is the crosscorrelation between users i and j.

Conventional Single User Matched Filter

The current CDMA receivers are based on conventional detector, also known as matched filter [3]. In conventional single user digital communication system as shown in Figure 2.1, the matched filter is used to generate sufficient statistics for signal detection. The detector is implemented as a K separate single-input single-output filters with no joint processing at all. Each user is demodulated separately without taking into account to the existence of other (K-1) active users in the system. In other words, other users are considered as interference or noise. [4]. The exact knowledge of the users' signature sequences and the signal timing is needed in order to implement this detector.

Currently deployed DS-CDMA receivers use SUMF detection. The detection is performed by correlating a locally generated replica of the spreading sequence of the user of interest with the incoming signal.

The sampled output of the kth matched filter is :

$$y_k = \int_0^{T_b} r(t) g_k(t)dt$$

$$= A_k b_k + \sum_{i=1, i\neq k}^{K} A_i b_i \rho_{i,k} + \int_0^{T_b} n(t)\, g_k(t)dt \qquad (2.3)$$

$$= A_k b_k + MAI_k + n_k$$

Where,

$$\rho_{i,k} = \int_0^{T_b} g_i(t) g_k(t)dt \qquad (2.4)$$

$\boldsymbol{\rho_{i,k}}$ is the crosscorrelation of the spreading sequences between the k^{th} and the j^{th} user.
The decision is made by:

$$\hat{b}_k = \text{sgn}(y_k) \qquad (2.5)$$

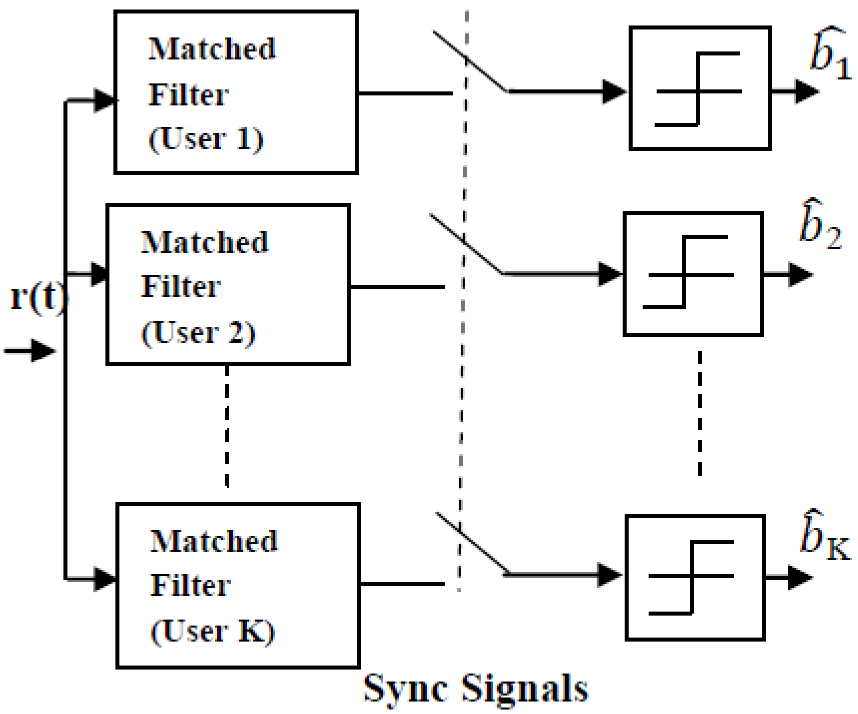


Fig 1 Conventional Single-User matched filter receiver for multiple user detection.

y_k consists of three terms. The first is the desired information which gives the sign of the information bit b_k. The second term is the result of the multiple access interference (MAI), and the last is due to noise. The single-user matched filter receiver takes the MAI as noise and cannot suppress MAI.
In matrix form, we present the outputs of the match filters as

$$y=RAb+n \qquad (2.6)$$

where **R** is the normalized crosscorrelation matrix whose diagonal elements are equal to 1 and whose (i,j) elements is equal to the cross-correlation ρ_{ij}, $\mathbf{A}=\text{diag}\{A_1, \dots, A_k\}$, and $\mathbf{y}=[y_1, \dots, y_k]^T$. $\mathbf{b}=[b_1, \dots, b_k]^T$ and **n** is a Gaussian random vector with zero mean and covariance matrix $\sigma^2\mathbf{R}$.
Another serious limitation of the conventional detector is that it is seriously affected by the near far problem. This causes a significant degradation in the system performance even when the numbers of users are small.

III. MULTIUSER DETECTION

There has been great interest in improving DS-CDMA detection through the use of multiuser detectors as proposed in [4-5]. Multiuser detection refers to the problem of detecting transmitted signals by considering all users. In multiuser DS-CDMA systems, detection involves exploitation of the base station's knowledge of signature sequence and the correlation properties contained in MAI to extenuate interference among users and subsequently, suppress noise to better detect each user [15].

Initially, optimal multiuser detector, or the maximum likelihood sequence estimation detector was proposed by Verdú. As presented in [6], this detector is too much complex for practical DS-CDMA systems.

There are two categories of the most proposed detectors: linear multiuser detectors and non-linear detectors. In linear multiuser detection, a linear mapping (transformation) is applied to the soft outputs of the conventional detector to produce a new set of outputs, which hopefully provide better performance. In non-linear detection, estimates of the interference are generated and subtracted out. Figure 3.1 shows the general structure of multiuser detection systems for detecting each K user's transmitted symbols from the received signal, which consists of a matched filter bank that converts the received continuous-time signal to the discrete-time statistics sampled at chip rate without masking any transmitted information relevant to demodulation. This is followed by applying multiuser detection algorithm for optimality conditions to produce the soft output statistics. The soft outputs are passed to the single user decoders. With the statistic at the output of the matched filter, an estimate for the transmitted bits {b1,b2,…..,bk} that minimizes the probability of error can be found.

Decorrelating Detector

The Decorrelating Detector attempts to completely eliminate the MAI in a DS-CDMA system without regard to AWGN. Using Eq. (2.6) for all the users, we write the received signal after despreading in matrix form :

$$y= RAb + n \qquad (3.1)$$

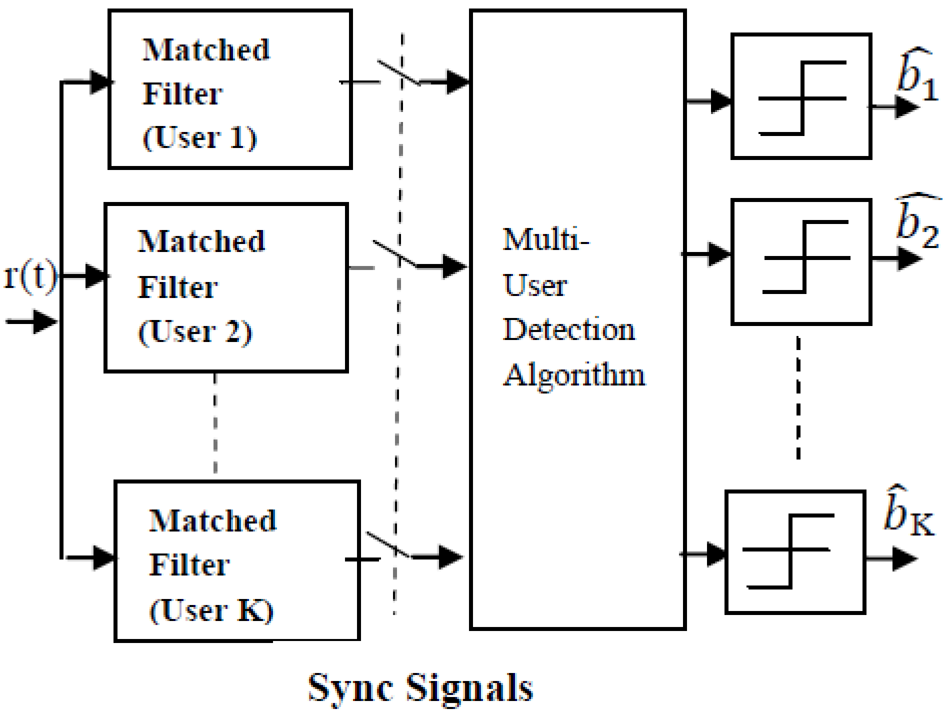


Fig 2 A Typical Multiuser Detector for DS-CDMA System.

Since **R** is not a diagonal matrix in general, it reflects the MAI introduced due to non-zero cross-correlations. The decorrelating detector is derived with the following idea: In the absence of noise, equation (3.1) turns

$$y = RAb \quad (3.2)$$

Multiplying both sides of above equation by the inverse of R we get

$$R^{-1} y = R^{-1} R A b = A b \quad (3.3)$$

where **R** is supposed to be invertible. Then the transmitted data is recovered by

$$\hat{b}_k = \text{sgn}((R^{-1}y)_k) = \text{sgn}((Ab)_k) = b_k \quad (3.4)$$

If we bring in the noise then (3.2) turns into

$$R^{-1} y = A b + R^{-1} n \quad (3.5)$$

This is just the decoupled data plus a noise term. Thus it can be seen that the decorrelating detector completely eliminates the MAI. The decorrelating detector is discussed extensively by Verdu, and has several desirable properties, foremost amongst which are:

- Provides substantial capacity gains over the conventional detector.
- Does not need to estimate the received amplitudes.
- Has a probability of error independent of the signal energies.

The decorrelating detector has received the most attention of any multi-user detector due to its many advantages. However, it leads to noise enhancement. The power associated with the noise term $R^{-1}n$ at the output of the decorrelating detector is always greater than the power associated with the noise term at the output of the conventional detector.

MMSE Linear Multiuser Detector

Minimizing the mean squared error is an approach to linear multiuser detection that performs as well as or better than the Decorrelating detector for all SNRs. The zero forcing solution works on the principle of channel inversion and, therefore, leads to poor BER performance at very low signal-to-noise ratios. Decorrelating detector is the most near-far resistant detector, since it completely eliminates MAI. However, the BER performance of decorrelating detector is not optimal because the R-1 decorrelating filter merely aims to eliminate MAI without regard to AWGN, which results in additive colored Gaussian noise in the detector output $\hat{y}$.

MMSE linear MUD performs better than the Decorrelating linear MUD at low and moderate SNRs since it accounts for AWGN. This detector implements the linear mapping which minimizes the mean-square error between actual data and soft output of matched filter detector.

The transformation that achieves MMSE is given by $T = (R + \sigma^2 A^{-2})^{-1}$

So the decision for the k^{th} user is made based on

$$\hat{b}_k = \text{sgn}(((R+\sigma^2 A^{-2})^{-1} y)_k)$$
$$= \text{sgn}((R+\sigma^2 A^{-2})^{-1}(RAb+n)_k) \quad (3.6)$$

If noise is very low $\sigma^2 \approx 0$, then $T = R^{-1}$ and the MMSE detector is equivalent to decorrelator. If noise level is relatively high, then in this case MMSE detector approximates the matched filter detector with amplitude scaling. Thus It is a compromise solution of the conventional receiver and the decorrelating detector, since they are the limiting cases of the MMSE detector.

Successive Interference Cancellation Scheme

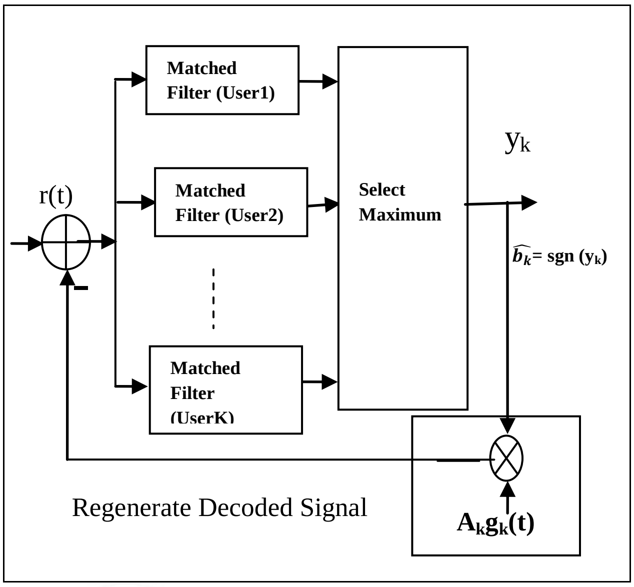
The successive interference canceller is a kind of nonlinear multiuser receiver which estimates and cancels multiple access interference successively using feedback. In the scheme, the received signal $y(t) = \sum_{k=1}^{K} A_k b_k g_k(t) + n(t)$, $t \in [0,T]$ is first passed through a bank of matched filters. Then the user with the strongest correlation value (the correlations of each of the users' spreading sequence $g_k(t)$ with the received signal y(t)) is selected for decoding. The signal of the user can be regenerated and subtracted from the received waveform.

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

$$\hat{y}(t) = y(t) - A_k b_k g_k(t)$$

$$= \sum_{j=1, j\neq k}^{K} A_j b_j g_j(t) + A_k(b_k - \hat{b}_k) g_k(t) + n(t) \quad (3.7)$$

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



IV. SIMULATION RESULTS

Detectors under investigation includes conventional single user matched filter (MF), Decorrelating Detector, Minimum Mean-Squared Error (MMSE) and SIC Detector. First of all, the BER performance comparison between the conventional detector, the Decorrelating detector, the MMSE detector and the SIC detector is conducted. The study is followed by the performance with increasing number of active users is investigated. These simulations are done with the assumption that all active users have equal power, in synchronous AWGN channel with varying number of Users (K), SNR and processing gain.

Figure 3 shows the BER performances as a function of SNR for K=10 and processing gain=31. Figure 4.1 & 4.2 together gives the Comparison between the Performances of the Detectors with increase in the number of users in the system. It is observed that the MMSE detector provides better BER performance compared to other three mentioned multiuser detectors. At the same time, the Decorrelating Detector showed better performance than the conventional and SIC detectors. While the successive interference canceller provides a small improvement over the conventional detector. It is also observed that the performances of all the mentioned detectors degrades with increase in the number of Users.

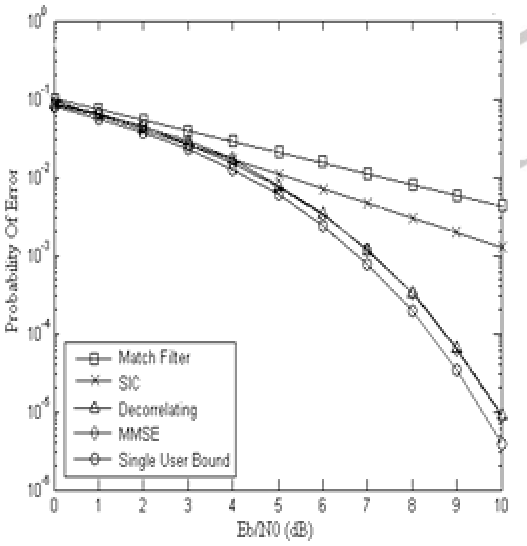


Figure 3 BER vs. E_b/N_o for 10 users and processing gain = 31

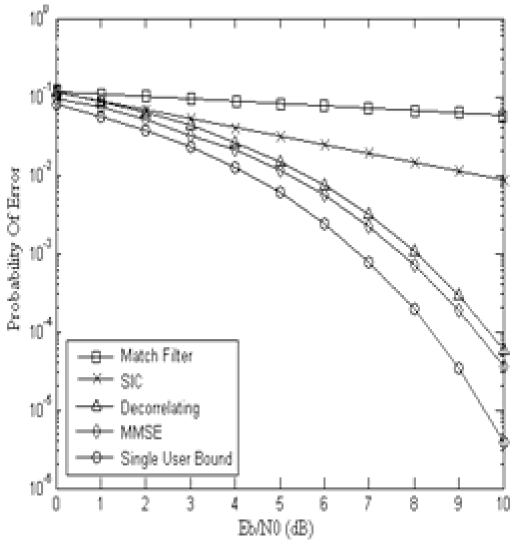


Fig 4 BER vs. E_b/N_o for20 users and processing gain = 31

Figure 4 shows the BER performances of the detectors for increasing number of active users (Capacity Curves) in the same channel. All interfering users, from K=1 through K=30 are signaling at SNR=8dB. The performance of the conventional detector degrades sharply than the linear detectors as the number of active users' increases. For example for a system of K=10 users in Gaussian noise, the conventional detector error is more than 10^{-3} while the linear detectors errors are still less than 10^{-3}. The linear detectors degrade slightly with increasing number of equal-power active users, although for very large loads, the performance of decorrelating and MMSE detectors are slightly similar. This is due to the fact that as the number of interfering users increases so does the MAI term becomes more significant than the channel noise interference which only forms a small part of the total interference.

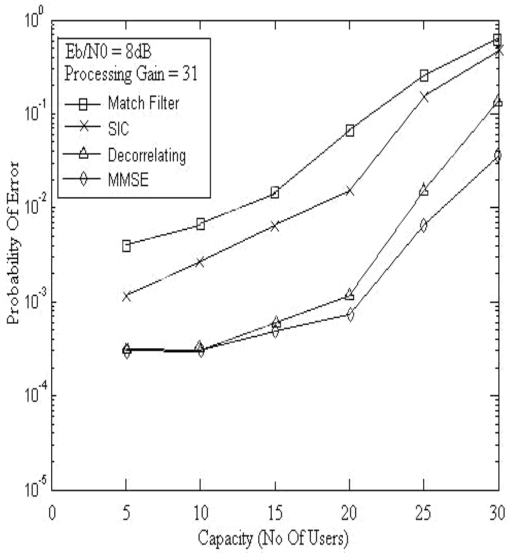


Fig 5 Capacity curves for E_b/N_o=8dB and processing gain = 31

Figure 6 & 7 shows the BER performances of the detectors for increasing SNR and increasing number of active users in the same channel with Processing Gain of 63 respectively. In figure 8 all interfering users, from K=1 through K=30 are signaling at SNR=8dB and the processing gains of 31 & 63 are considered. The performance of all the aforementioned detectors increases with increase in the processing gain.

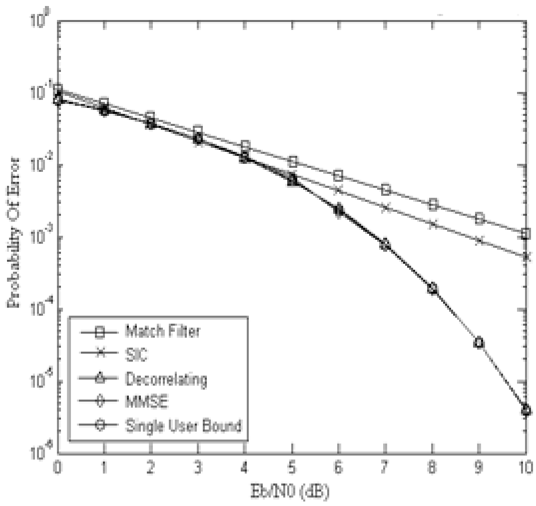


Fig 6 BER vs. E_b/N_o 10 users and Processing gain =63

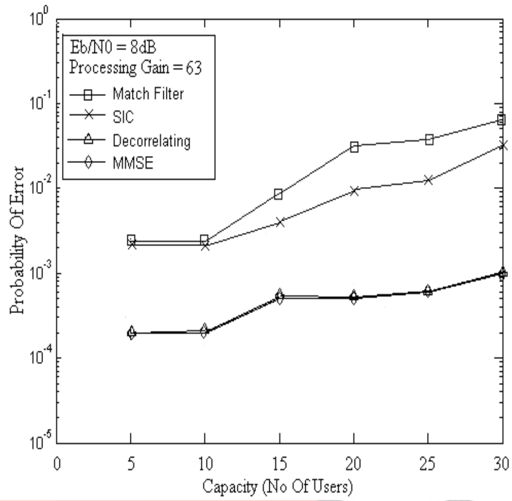


Fig 7 Capacity Curves for E_b/N_o=8dB and processing gain = 63

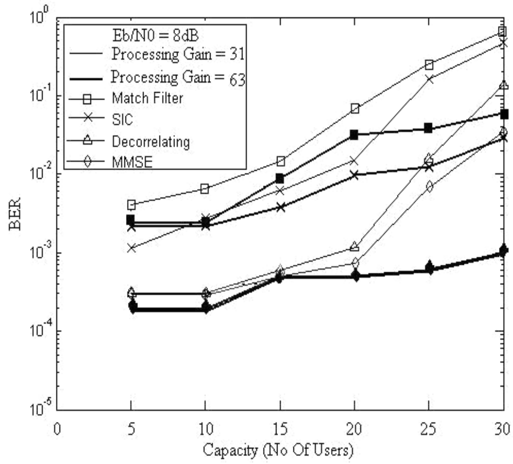


Fig 8 Capacity Curves for E_b/N_o=8dB and processing gain = 31 & 63**.**

V. CONCLUSION

In this paper, I simulated and analysed the performance of the conventional matched filter receiver and three kinds of multiuser receivers (the Decorrelator, the MMSE receiver, the Successive Interference Canceller) in a synchronous CDMA system. In AWGN channel, the decorrelator and the MMSE receiver provide a significant performance improvement relative to the conventional matched filter receiver when all the users in the system have the same received powers (perfect power control). However, the performance of the successive interference canceller is poorer because this multiuser detection scheme needs to take advantage of the variance of the received powers of all users to suppress multiple access interference.

The BER performances for the aforementioned receivers is also analyzed and simulated with increasing the number of users in the system. With increasing in the number of users, the performance of all receivers degrades. This is because as the number of interfering users increases, the amount of MAI becomes greater as well.

Finally it is found that the BER performances of the studied receivers increases with increase in the processing Gain.

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