DS-CDMA System with Linear Multiuser Detection in AWGN Channel

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Abstract
Direct sequence code division multiple access (DS-CDMA) is a popular wireless technology. This paper presents comparative study between linear multiuser detectors, optimal multiuser detector, and conventional single user matched filter in DS-CDMA system. Analysis and simulations are conducted in synchronous AWGN channel, and Gold sequence is used as the spreading codes.
The study shows that optimal multiuser detector performs better than the conventional matched filter and linear multiuser detector in terms of BER performance. However, optimal multiuser detector suffers from complex computation and costly implementation. MMSE detector provides better error performance than the decorrelating detector, but it utilizes the estimation of the received powers.

Keywords: *CDMA, multiuser detection, AWGN*

1. 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 [1-14].

Interference such as multiple access interference (MAI) restricts the capacity and the performance of DS-CDMA systems. As described in [15], 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 [15-29].

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.

The following sections of this paper, overview of conventional detector, and multiuser detectors are presented. The system and the simulation models applied for this work are described. Finally, the channel capacity and BER performance results are presented.

2. Conventional Single User Matched Filter

The current CDMA receivers are based on conventional detector, also known as matched filter [15]. In conventional single user digital communication system as shown in Figure 1, the matched filter is used to generate sufficient statistics for signal detection. The detector is implemented as a K separate single-input (continuous-time) single-output (discrete-time) 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. [16]. The exact knowledge of the users' signature sequences and the signal timing is needed in order to implement this detector.

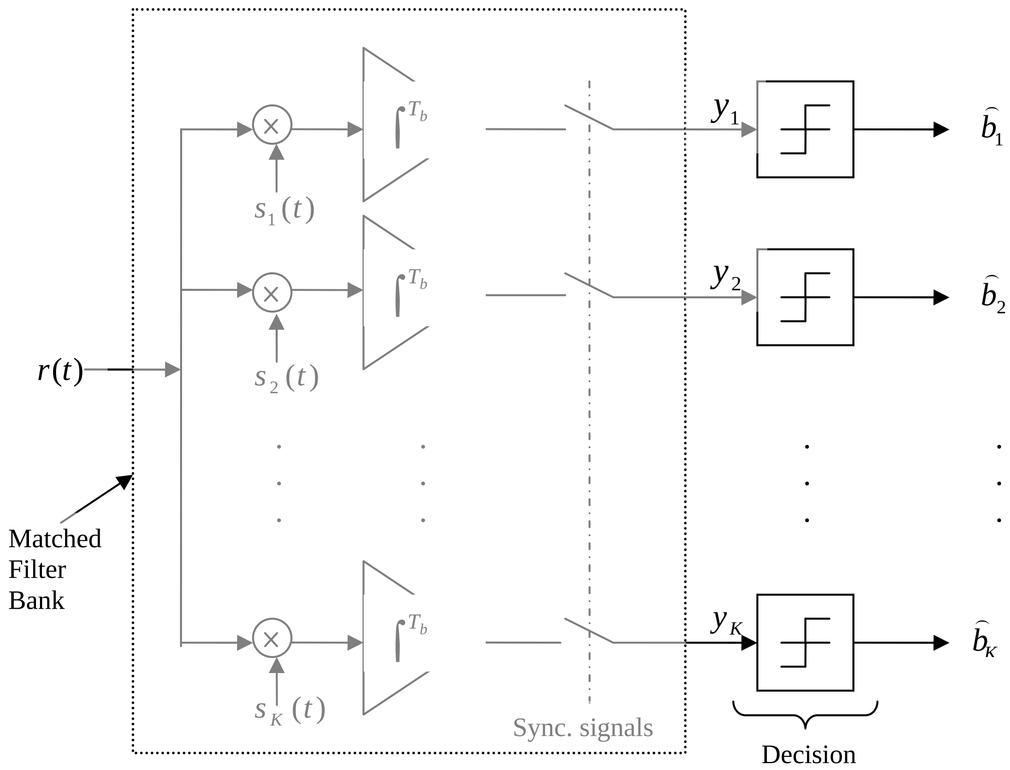

Figure 1: Conventional DS-CDMA detector

For K direct sequence users in the synchronous single-path BPSK real channel, the baseband received signal is expressed as [15]:

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

Each code waveform is regenerated and correlated with the received signal in a separate detector branch. The correlation detector, also known as matched filter detector, is implemented through matched filtering, where the interference is from AWGN in a single user channel. A detailed look at matched filter can be found in [6]. The outputs produced by matched filters are the "soft" estimates of the transmitted data. The final output, which is "hard" data decisions ±1, is based on the signs of the soft estimates.

The correlation between the same code waveforms (autocorrelations) is required to be larger than the correlations between different codes (cross-correlation) for successful detection. The correlation value algorithm defined in [15] can be simplified as in Figure 2.

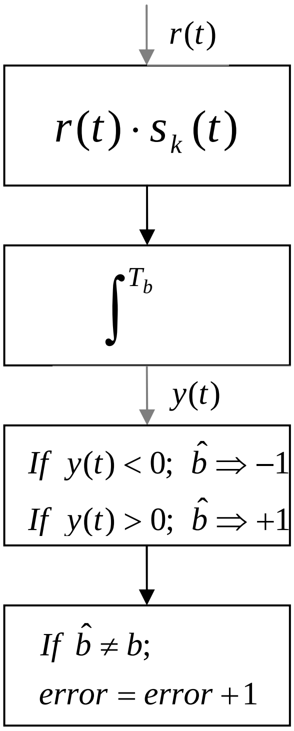

Figure 2: Algorithm for the conventional matched filter detector

3. Multiuser Detection

There has been great interest in improving DS-CDMA detection through the use of multiuser detectors as proposed in [16-29]. 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 [26], this detector is much too 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 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 [23]. The soft outputs are passed to the single user decoders. With the statistic $\{y_1, y_2, ..., y_K\}$ at the output of the matched filter, an estimate for the transmitted bits $\{b_1, b_2, ..., b_K\}$ that minimizes the probability of error can be found.

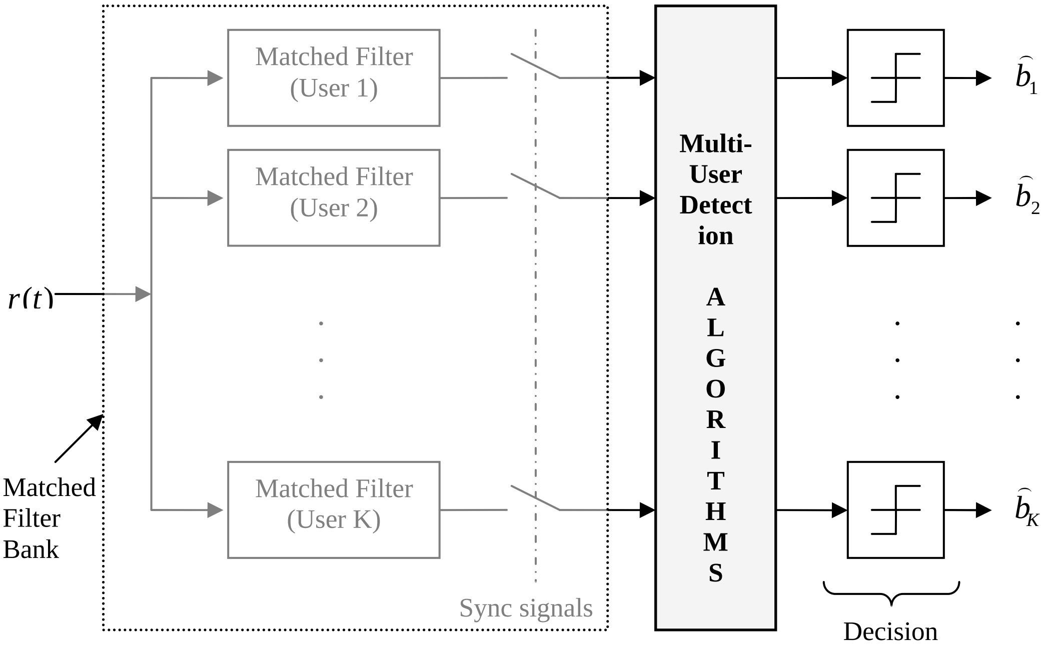

Figure 3: A typical multiuser detector for DS-CDMA system

4. Linear Multiuser Detectors

a) Decorrelating Detector

The decorrelating detector algorithm presented in [23] can be summarized in Figure 4 and Figure 5. Decorrelating detector can achieve any given performance level in the multiuser environment regardless of the multiuser interference, provided that the desired user is supplied enough power. Thus, it provides a substantial performance or capacity gains over the conventional detector under most conditions. The decorrelating detector corresponds to the maximum likelihood sequence detector when the energies of all users are not known at the receiver. In other words, it yields the joint maximum likelihood sequence estimation of the transmitted bits and their received amplitudes [23].

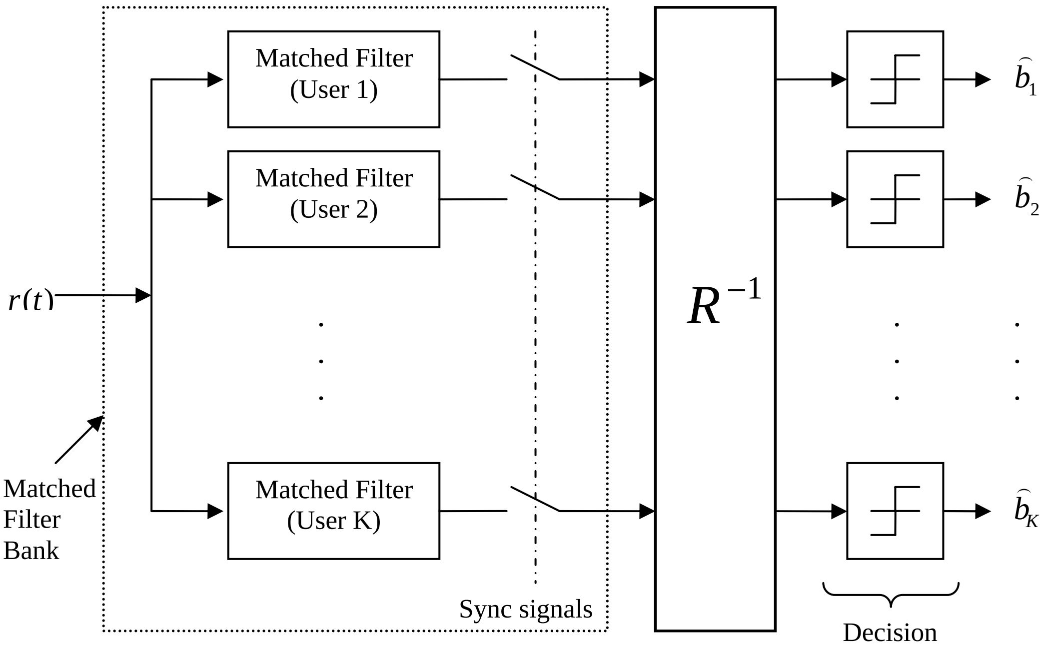

Figure 4: The decorrelating detector

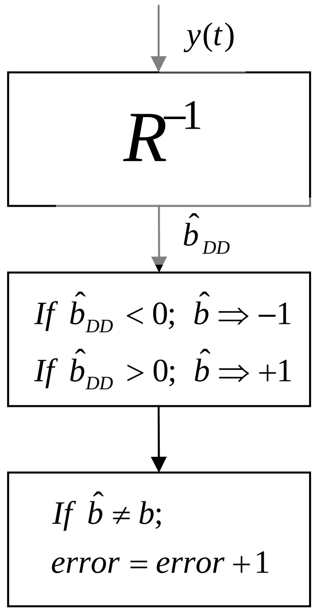

Figure 5: Algorithm for the decorrelating detector

b) Minimum Mean-Squared Error (MMSE) Detector

The description of MMSE detector in [29] can be graphically represented in Figure 6. The MMSE implements the linear mapping which minimizes the mean-squared error between the actual data and the soft output of the conventional detector. At this stage, the MMSE detector applies a modified inverse of the correlation matrix to the matched filter bank outputs, and takes into account the background noise and utilizes knowledge of the received signal powers.

The amount of modification is directly proportional to the background noise; the higher the noise level, the less complete an inversion of **R** can be done without noise enhancement causing performance degradation. Thus, the MMSE detector balances the desire to decouple the users (and completely eliminate MAI) with the desire to not enhance the background noise [29][15]. The algorithm presented in [21] is summarized in Figure 7.

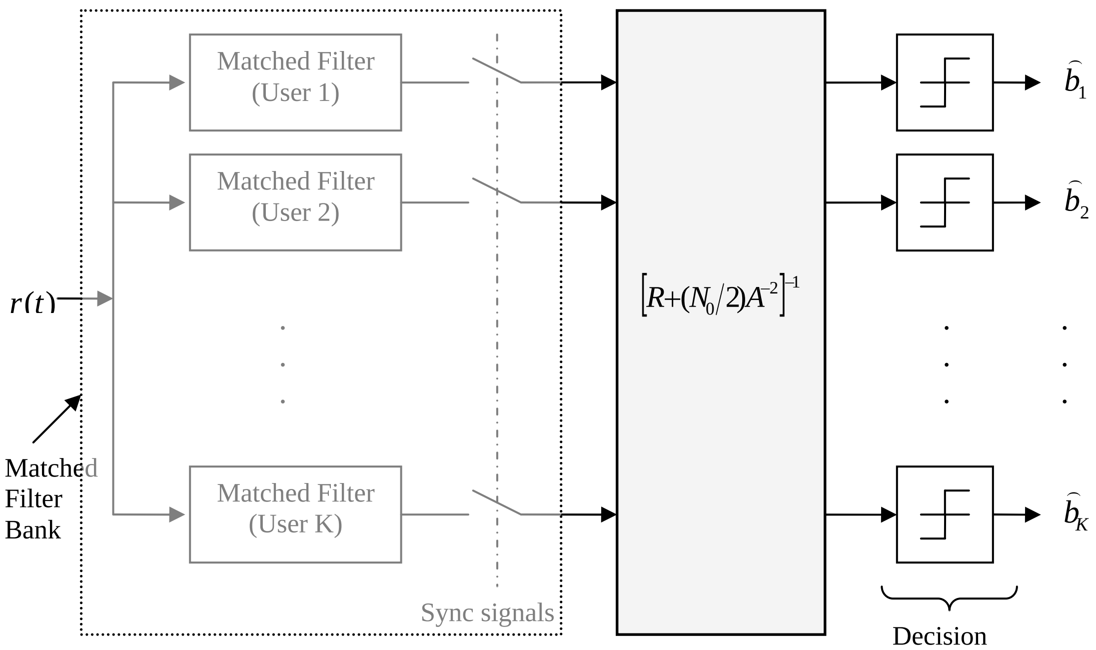

Figure 6: The Minimum Mean-Squared Error (MMSE) detector

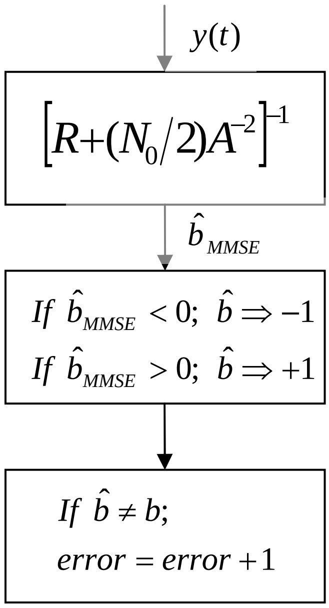

Figure 7: Algorithm for the Minimum Mean-Squared Error (MMSE) detector

Results

Detectors under investigation include conventional single user matched filter (MF), decorrelating and minimum mean-squared error (MMSE). First of all, the BER performance comparison between the conventional detector, the optimal multiuser detector and two suboptimal linear multiuser detectors is conducted. The study is followed by the performance with increasing number of active users is investigated. These simulations are done with the assumption all active users have equal power.

Figure 8 and 9 show the BER performances of the detectors are investigated for increasing SNR. The simulation result shows the optimal multiuser detector provides better performance compared to conventional detector and also linear multiuser detectors. At the same time, both linear multiuser detectors showed better performance than the conventional detection. The MMSE detector has slightly better performance than the decorrelating detector because it takes into account the background noise and provides better probability of error performance than the decorrelating detector.

Figure 10 shows the performance for a given number of active users in the same channel and using the same spreading sequences (gold sequences). Although the optimal detector performs significantly better than the rest, it comes at the cost of increased complexity and computation time. As consequences, the graph BER versus number of user was simulated up to a maximum of 10 users only in this project. A realistic DS-CDMA system has a relatively large number of active users; thus, the exponential complexity in the number of users makes the cost of this detector too high and it is not practical. Therefore, in the later simulations, the optimal detector was removed altogether since the time it took increased exponentially with the increased number of users.

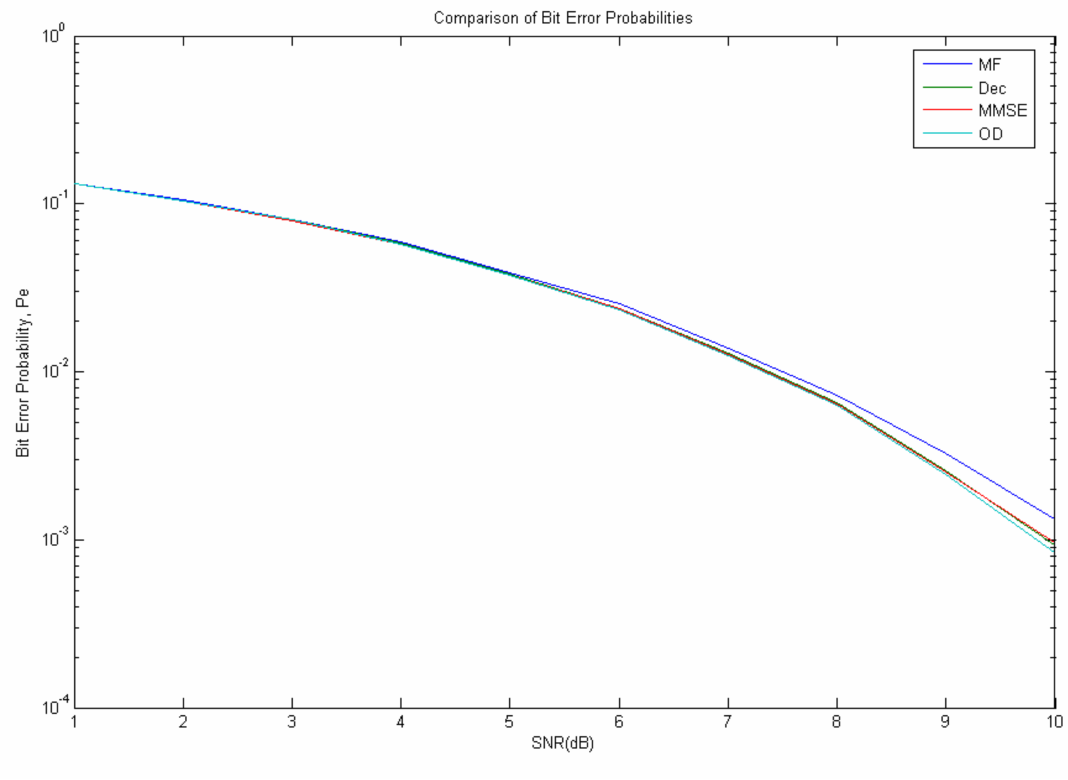

Figure 8: BER performance comparison versus SNR between detectors

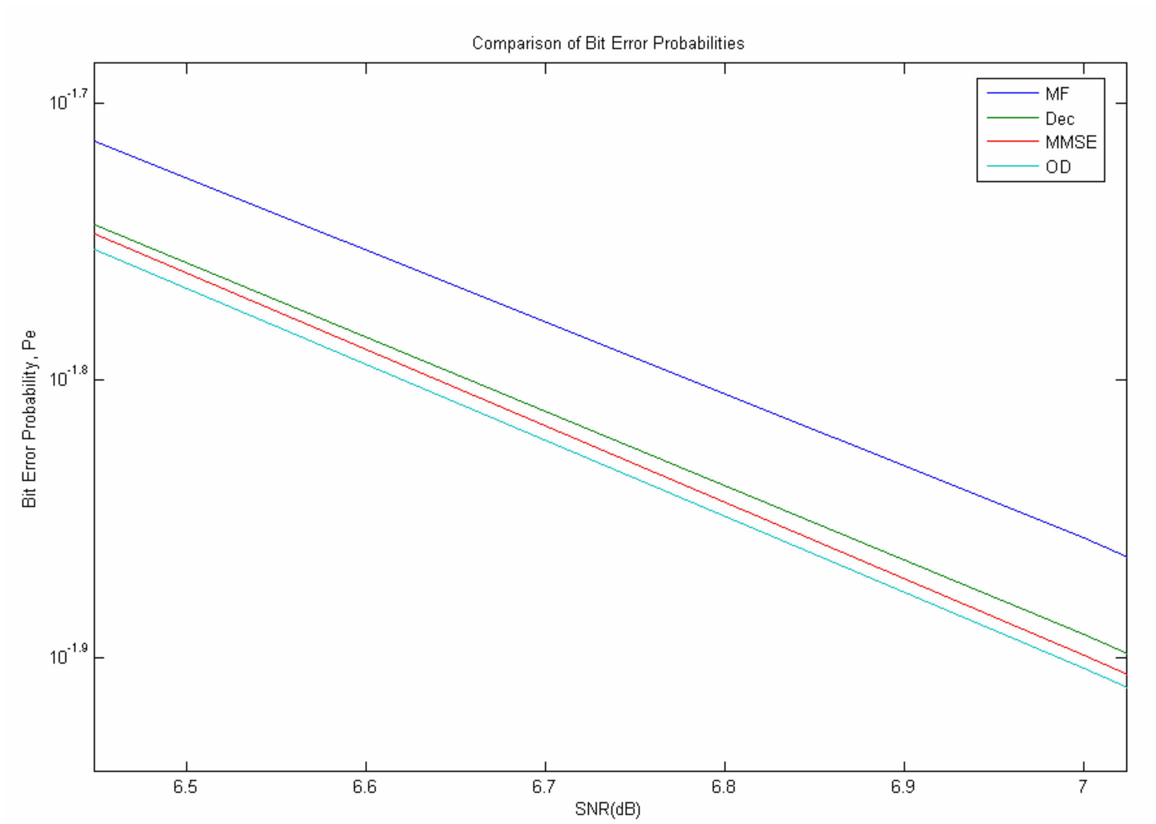

Figure 9: Enlarged graph of Figure 8

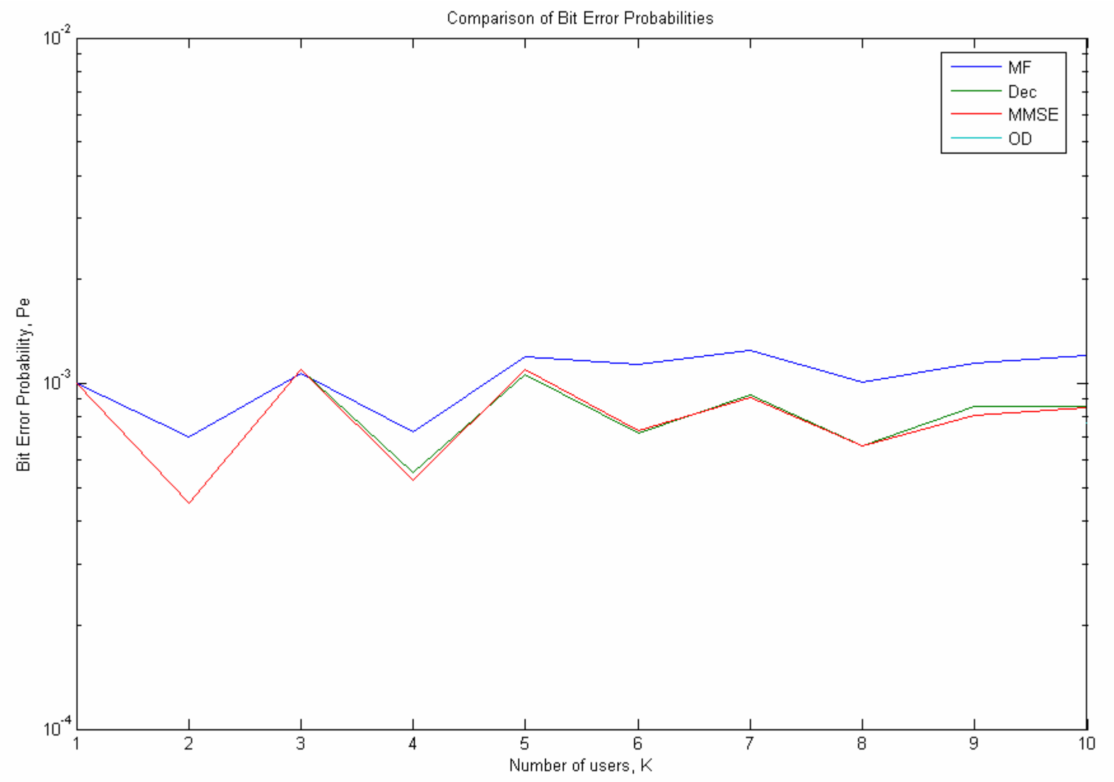

Figure 10: BER performance comparison versus number of users between detectors

Figure 11 shows the BER performances of the detectors are investigated for increasing number of active users in the same channel. All interfering users, from K=1 through K=25 are signaling at SNR=10dB. 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.

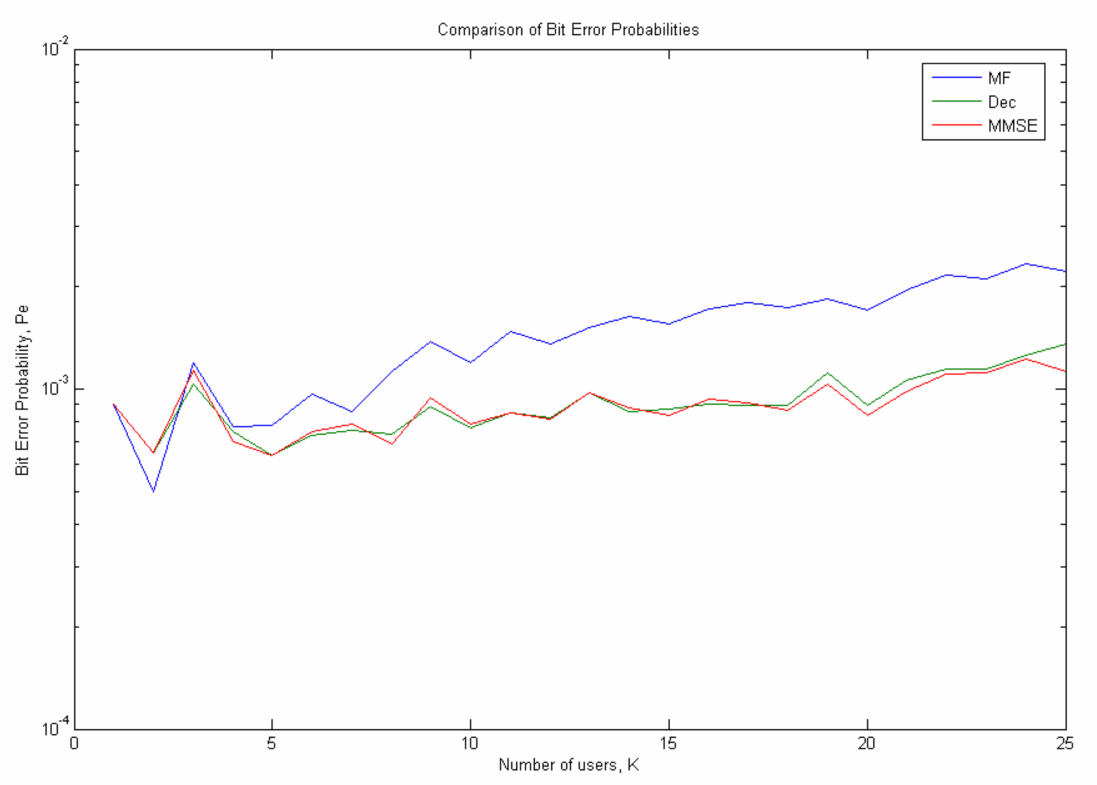

Figure 11: BER performance in increasing active K-users and SNR=10dB

Figures 12 – 14 show that the BER performance in increasing number of users with conventional matched filter, decorrelating and MMSE detector respectively. From these figures, we can also draw a conclusion that the interference suppression capability in conventional detector is very low and susceptible to the MAI effect. Decorrelating detector provides best interference suppression capability since it completely eliminates the MAI [15]. This is proven in Figure 13, where there is a slight difference in performance between number of users. MMSE can provide interference suppression capability as good as decorrelating detector when the background noise is very small compared to interference effect.

Conclusion

The optimal multiuser detector performs better than the conventional matched filter and also the linear multiuser detectors. However, this detector is too complex for practical DS-CDMA system. MMSE detector generally performs better than the decorrelating because it takes the background noise into account. With increasing in the number of users, the performance of all detectors will degrade as well. This is because as the number of interfering users increases, the amount of MAI becomes greater as well.

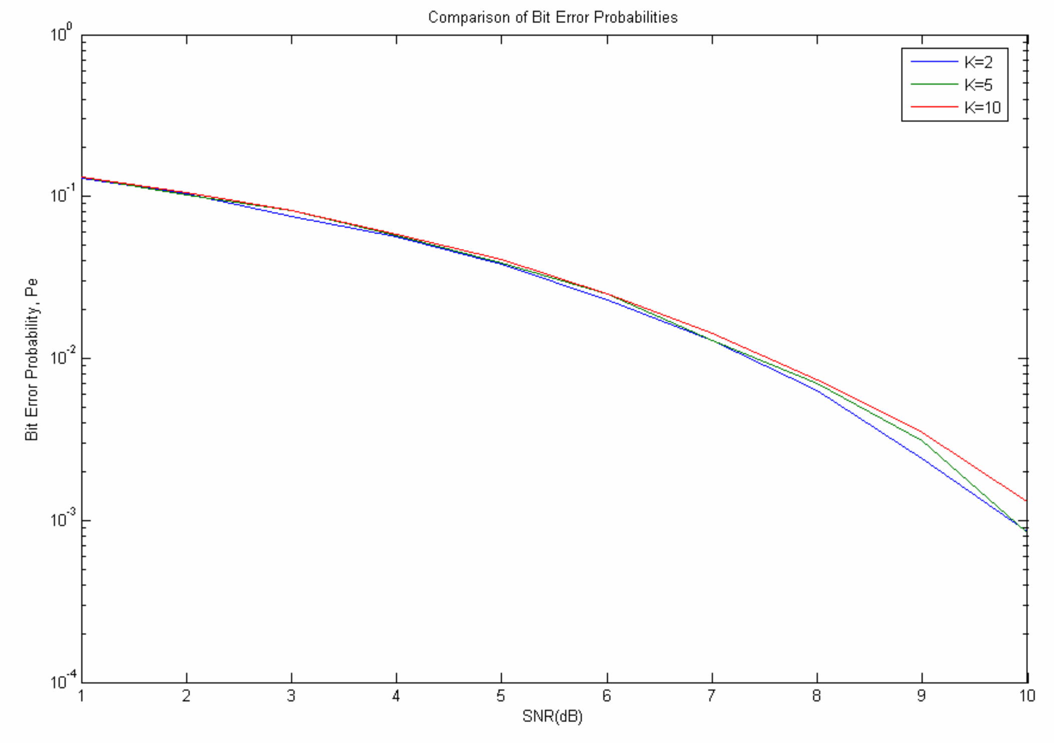

Figure 12: BER performance in matched filter with increasing active K-users

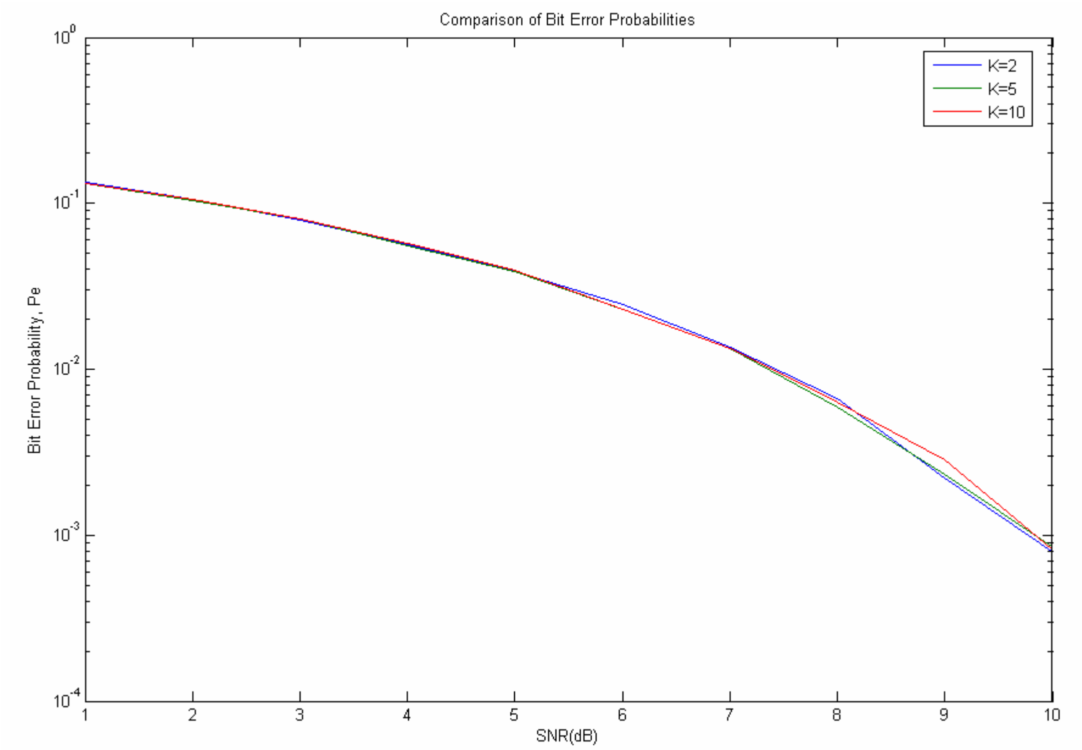

Figure 13: BER performance in decorrelating detector with increasing active K-users

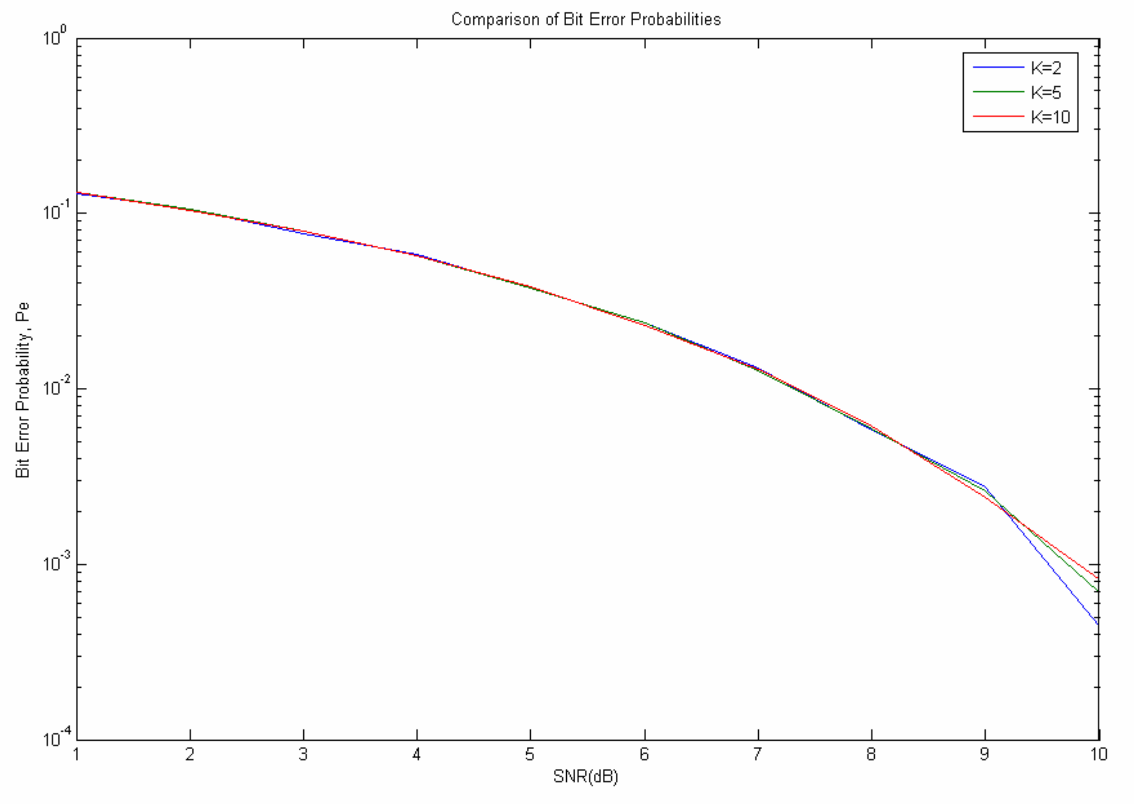

Figure 14: BER performance in MMSE detector with increasing active K-users

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