A Switching Mechanism Detection to Reduce Complexity in Multiuser Detection for DS-CDMA Systems

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Abstract: We present a reduced complexity switching mechanism which uses either matched filter or Parallel Interference Cancellation (PIC) detector based on channel characteristics. The main criterion of taking PIC detector is that it has less Bit Error Rate (BER) and less processing delay than other nonlinear multiuser detectors. This proposed detector reduces overall complexity while maintaining the same performance as PIC detector. The switching mechanism is exploited by performance complexity tradeoff between matched filter detector and PIC detector.

Key words: Multiple access interference, direct sequence code division multiple access, signal to noise ratio, signal interference ratio, parallel interference cancellation

INTRODUCTION

In a Code Division Multiple Access (CDMA) system, several users transmit their signals simultaneously over a common channel. The receiver has knowledge of the codes of all the users. It is then required to demodulate the information symbol sequences of these users, upon reception of the sum of transmitted signals of all the users in the presence of additive noise This situation arises in a variety of communication systems such as wireless communication and other multipoint to multipoint multiple access networks. However, since multiple users share the same bandwidth to transmit data in a typical CDMA system, users signal may interfere with each other if orthogonality is not maintained and causes Multiple Access Interference (MAI). MAI degrades the performance of the system. Conventional CDMA detectors such as matched filter[1] and RAKE combiner[2] are optimized for detecting the signal of a single desired user. These conventional detectors are inefficient, because the interference is treated as noise and there is no utilization of the available knowledge of spreading sequences of the interferers. The efficiency of these detectors is dependent on the cross correlation between the spreading codes of all users.

The optimal multiuser detector, discovered by Verdu[3] showed that a maximum likelihood receiver could be used to optimally decode multiple users in parallel, with dramatic gains. This receiver is unfortunately, extremely complex, with the computational needs increasing as $O(|A^K|)$, where $|A|$ is the alphabet size (2 for binary) and K is the number of users. While in many practical applications such performance complexity prohibits implementation of the Verdu algorithm, its performance is still of very much of interest since it serves as a benchmark against which to compare other schemes with less implementation complexity such as those that employ interference cancellation to be discussed shortly.

One approach is to employ a suitable linear transformation on the matched filter outputs. Belonging to this family are the decorrelating receiver and Minimum Mean Square Error (MMSE) detector[4-6]. In these methods, the different users are made uncorrelated by a linear transformation. This linear transformation is computed by measuring all cross correlations between pairs of user codes and then inverting the resulting huge matrix of cross-correlations. Since in practical systems each user is assigned a very long pseudonoise (PN) code, each bit has essentially a random code assigned to it. Thus, in this case, the above procedure would have to be repeated for each bit in succession.

Interference Cancellation (IC) schemes contribute another variant of multiuser detection and they can be broadly divided into two categories: successive cancellation and parallel cancellation. Interference cancellation should be interpreted to mean the class of techniques that demodulate and/or decode desired information and then use this information along with channel estimates to cancel received interference from the received signal. Lower computation and hardware related structures are the main advantages of these methods beside the main advantage of lower BER or better capacity than linear multiuser detectors[2,7]. With regard to former Patel and Holtzman[8] suggested coordinated processing of the received signal with a successive cancellation scheme in which the interference caused by remaining users is removed from each user in succession. The approach successively cancels strongest users by re-encoding the decoded bits and after making an estimate of the channel, the interfering signal is recreated at the receiver and subtracted from the received waveform. In this manner successive user does not have to encounter MAI caused

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by initial users. One disadvantage of this scheme is the fact that a specific geometric power distribution must be assigned to the users in order that each see the same signal power to the background plus interference noise ratio. Another disadvantage of this scheme has to do with the required delay necessary to fully accomplish the IC for all the users in the system. Since the IC proceeds serially, a delay on the order of M computation stages is required to complete the job. This delay becomes intolerable for large number of users and SIC method looses its advantage.

Parallel processing of multiuser interference simultaneously removes from each user the interference produced by the remaining users accessing the channel. In this way, each user in the system receives equal treatment insofar as the attempt is made to cancel multiple user interference. As compared with the serial processing scheme, since the IC is performed in parallel for all the users, the delay required to complete the operation is at most a few bit times. Varanasi and Aazhang[9] proposed a multistage detector for an asynchronous system, where the outputs from a matched filter bank were fed into a detector that performed MAI cancellation using a multistage algorithm. At each stage in the detector, the estimates of all other users from the previous stage were used for reconstructing an estimate of the MAI and this estimate was then subtracted from the interfered signal representing the wanted bit. The computational complexity of this detector was linear with respect to number of users and delay introduced was much less than serial method[10]. This prompts us to take PIC detector for switching mechanism in our paper.

A dual-mode detector that dynamically switches between matched filter and decorrelator had been studied[11]. With the above discussion in mind, this paper presents a switching mechanism that significantly reduces the complexity in multiuser detection. The proposed detector switches between matched filter detector and PIC detector . In realistic situations, where the channel conditions are randomly changing, using one detector alone all the time will not be advantageous. However, if an arrangement can be made to use another detector as channel conditions change, will be definitely a better solution. The proposed detector use conventional detector for less number of users (i.e. less MAI) as the performance of conventional detector and PIC detector is same and complexity of conventional method is much lower than PIC method. For large number of users it switches to PIC detector because multiuser detection is required to reduce BER or to increase the capacity. Therefore in practical situations, when only few users are present on the channel, complexity can be saved by not using PIC method. This detector does not degrade the performance as the output will be same as PIC detector even if it is not used all the time and computational complexity will also be reduced. The efficiency of this

detector will be definitely better than if any of the two detectors is alone used all the time. Hence by exploiting the performance-complexity tradeoff between matched filter and PIC, better capacity and less BER can be achieved.

Basic model: We begin with the mathematical description of the typical DS-CDMA system. Assuming that there are K active users sending data over the same channel, then the received baseband signal over one data interval can be expressed as

$$r(t) = \sum_{i=1}^{K} A_i s_i(t - \tau_i) b_i(t - \tau_i) + n(t) \qquad (1)$$

where A_i, $s_i(t)$ and $b_i(t)$ are the received amplitude, signature code waveform and data symbol (-1 or +1 for the duration of data interval) of the ith user, respectively and n(t) is additive white Gaussian noise with variance σ^2 and power density No. τ_i is the transmission delay for the ith user. An asynchronous model can be viewed as a synchronous model with different number of users [6], this restriction is not significant for the purpose of bit error rate analysis.In downlink CDMA, the common channel is always frequency selective fading channel. We assume that channel parameters vary slowly with time, so that for sufficiently short interval channel is assumed to be a Linear Time Invariant (LTI) system. In more compact matrix vector form, the received signal vector can be represented as

r= SAb+z   (2)

where **S** =[s_1 … s_{2K}] is effective spreading waveform matrix, **A**= diag(A_1 … A_K, A_1 … A_K), matrix **b** =[$b_1(n)$ … $b_K(n)$ $b_1(n-1)$ … $b_K(n-1)$] is the symbol vector whose elements are independent and identically distributed and z is a complex gaussian random vector.

Switched mode detector: The computational complexity of the detection scheme used in a system is vital for both implementation and simulation. High complexity receiver structure will require high speed processors for implementation as well as high run time. The complexity is given in terms of no. of users K, the frame length N_b., the no. of Rake fingers L, the spreading factor N, the number of samples per chip N_s and the number of stages for multistage receiver s. The computational complexity of PIC detector C_{PIC} can be expressed as given below[12]:

$$C_{PIC} = KLN_b(s(6NN_s + 7) - 4NN_s - 1) \qquad (3)$$

The Complexity of conventional detector is linear with number of users K. It is clear that the computational requirement of PIC method is much more than conventional method. Therefore, in situations, when BER of both the detectors is same, this computational requirement can be saved by making a judicious choice to conventional detector.
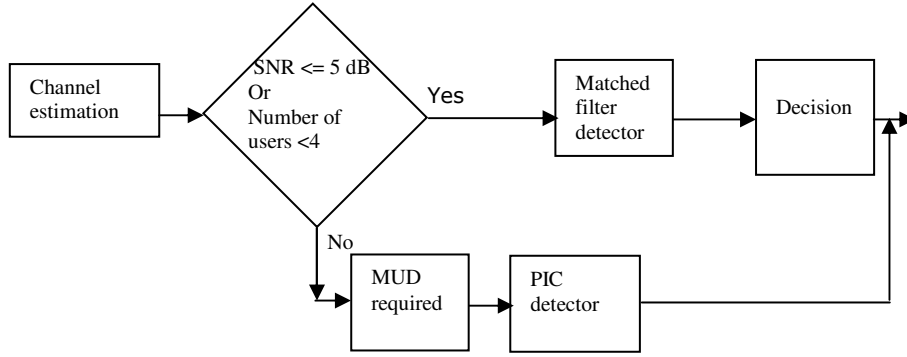
Fig. 1: Block Diagram representation of switched mode detector

The main aim of this proposed switched detector is to select the detector according to channel conditions. As channel conditions continuously fluctuate, taking one detector for all the situations will not be certainly a good solution. Therefore, our proposed detector instead of using single type of detector in all the situations, makes a choice between two detectors. When number of users or SNR at the channel is less, it uses conventional detector (no multiuser detection, existing and simple method), which gives least computational complexity. As the number of users or SNR increase (MAI and BER will be more), it uses PIC multiuser detection method to give minimum BER or increase in capacity. Therefore, in the output we can achieve the better capacity than if any of the above detectors is used independently all the time irrespective of channel conditions. It will require both the detectors and a logical switch to select the path but at the same time it will maintain the BER of signal to its minimum value.

The switching criterion of our switched mode detector is based on the random channel conditions. In a CDMA system with K users and processing gain G, bit error probability is given by

$$P_{b1} = Q\left(\sqrt{\cfrac{1}{\cfrac{1}{2\cfrac{E_b}{N_o}} + \cfrac{(K-1)}{G}}}\right) \qquad (4)$$

Where $\dfrac{E_b}{N_o}$ is signal to noise ratio and Q(.) is the complementary Gaussian error function. The bit error probability in a PIC detector consisting of s stages is given by [9]:

$$P_{b2} = Q\left\{\left[\left[\left[\frac{1}{2E_b/N_o}\frac{1-\left(\frac{K-1}{3N}\right)^s}{1-\left(\frac{K-1}{3N}\right)}\right]\right] + \frac{1}{(3N)^s}\left(\frac{(K-1)^s - (-1)^s}{K}\left(\frac{\sum_{k=1}^{K} P_k}{P_k}\right) + (-1)^s\right)\right]^{-1/2}\right\} \qquad (5)$$

The proof of eq. (5) is given in Appendix A. The matched filter detector is an existing and simpler detector than PIC detector, hence when received SNR is below 5 dB, the proposed detector will switch to it, otherwise it will use PIC detector .The PIC detector is

advantageous only in the case when BER of it is less than BER of matched filter detector, i.e. $P_{b2} < P_{b1}$.

RESULTS AND CONCLUSION

In Fig. 2, we have shown the simulation results for comparing the linear and nonlinear multiuser detection algorithms with the conventional method. As clear from the figure, for low SNR value, the BER of conventional method is almost same as any multiuser detection method, therefore conventional method can be used, as it is least complex among all and already in use. For higher SNR values, BER of nonlinear methods i.e. SIC or PIC is lower than linear methods i.e. decorrelator and Minimum Mean Square Error (MMSE). We consider nonlinear multiuser detector method i.e. PIC detector in our switching detector as nonlinear methods give less BER than linear methods. Out of two nonlinear methods, PIC detector gives less BER and delay requirement over SIC method. Therefore, it prompts us to take PIC detector as multiuser detector in our proposed algorithm.
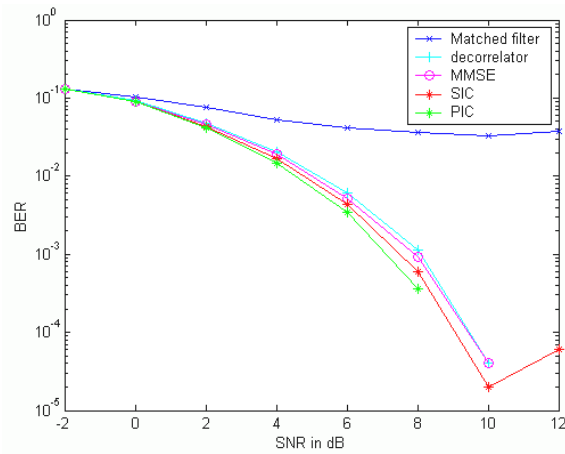

Fig. 2: BER vs SNR of linear and nonlinear multiuser detection methods

As shown in Fig. 3, for low value of SNR, BER offered by conventional and SIC method is almost same. Therefore, at low values switched mode detector
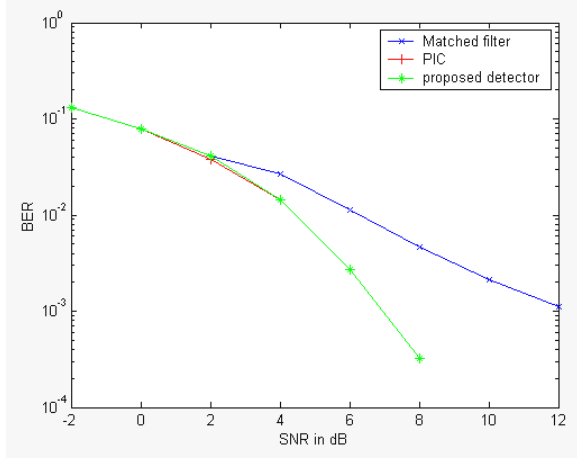
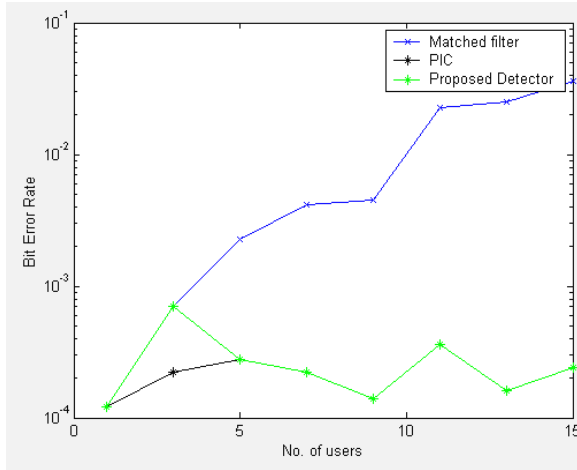Fig. 3: BER vs. SNR comparison for proposed detector with conventional detector and nonlinear detector

Fig. 4: BER vs. Capacity of proposed detector with conventional detector and nonlinear detector

switches to conventional method keeping complexity to minimum level. When SNR increases, then switched mode detector uses PIC method to minimize BER or increasing capacity, but at the expense of increase in computational complexity. In Fig. 4, BER vs. number of users is plotted. It is clear that when number of users is less, the BER offered by conventional method is almost same as PIC method and therefore, conventional method may be used to minimize the computational requirement. But as the number of users increase, effect of MAI will be more and in this situation multiuser detection method (i.e. PIC method) is used to minimize BER or increasing capacity. In real situations, when traffic on the channel e.g. during morning and late night hours or channel is less noisy, our proposed detector will use conventional method to save the computational requirements. This can be seen that the computational complexity will be certainly less than if PIC detector is used always irrespective of channel conditions.

Therefore, this detector will reduce complexity by making a choice between two detectors.

Appendix A: PIC uses the matched filter detector to detect all of the signals. The decision variables Z_i, as seen in Fig. A-1, are the decision variables used for decoding by the conventional receiver. These decision variables are then used to regenerate the user signals and cancel it from the received signal to isolate the user of interest. The modified received signals are once again fed through the matched filter of the user of interest and another set of decision variables $Z_i^{'}$ is obtained. This process forms the first stage of parallel-cancellation. Multiple stages can be performed to increase the performance of the system as shown in Fig. A-1.

$$r(t) = \sum_{k=1}^{K} \frac{1}{2} A_k a_k (t - \tau_k) b_k (t - \tau_k) e^{j\phi_k} + \frac{1}{2} n_z(t)$$

The Z_i represents the decision variable for the ith user at the output of the conventional detector and is given by

$$Z_i = \text{Re}\left\{ \frac{1}{T} \int_{\tau_i}^{\tau_i + T} r(t) a_i (t - \tau_i) e^{-j\phi_i} dt \right\}$$

$$= \frac{1}{2} A_i b_i + \sum_{\substack{k=1 \\ k \neq i}}^{K} \frac{1}{2} A_k I_{k,i} + \frac{1}{2} N_i$$

These decision variables are then used to regenerate the user signals, which are cancelled from the received signal to form a modified received signal. The modified received signal becomes

$$r_i^{(1)}(t) = r(t) - \sum_{\substack{m=1 \\ m \neq i}}^{K} z_m a_m (t - \tau_m) e^{j\phi_{mk}}$$

$$= \frac{1}{2} A_i a_i (t - \tau_i) b_i (t - \tau_i) e^{j\phi_i} + \frac{1}{2} n_z(t)$$

$$- \sum_{\substack{m=1 \\ m \neq i}}^{K} \sum_{\substack{k=1 \\ k \neq m}}^{K} \frac{1}{2} A_k I_{k,m} a_m (t - \tau_m) e^{j\phi_{mk}}$$

$$- \sum_{\substack{m=1 \\ m \neq i}}^{K} \frac{1}{2} N_i a_m (t - \tau_m) e^{j\phi_{mk}}$$

The decision variable for the first stage for the ith user now becomes

$$Z_i^{'} = \text{Re}\left\{ \frac{1}{T} \int_{\tau_i}^{\tau_i + T} r_i^{(1)}(t) a_i (t - \tau_i) e^{-j\phi_i} dt \right\}$$

$$= \frac{1}{2} A_i b_i + \sum_{\substack{m=1 \\ m \neq i}}^{K} \sum_{\substack{k=1 \\ k \neq m}}^{K} \frac{1}{2} A_k I_{k,m} I_{i,m} - \sum_{\substack{m=1 \\ m \neq i}}^{K} \frac{1}{2} N_i I_{i,m}$$

This completes the first stage cancellation. To cascade one more stage of cancellation, the new decision variables obtained above are used in the same manner as before to regenerate a more accurate version of the user signals, which are then cancelled from the
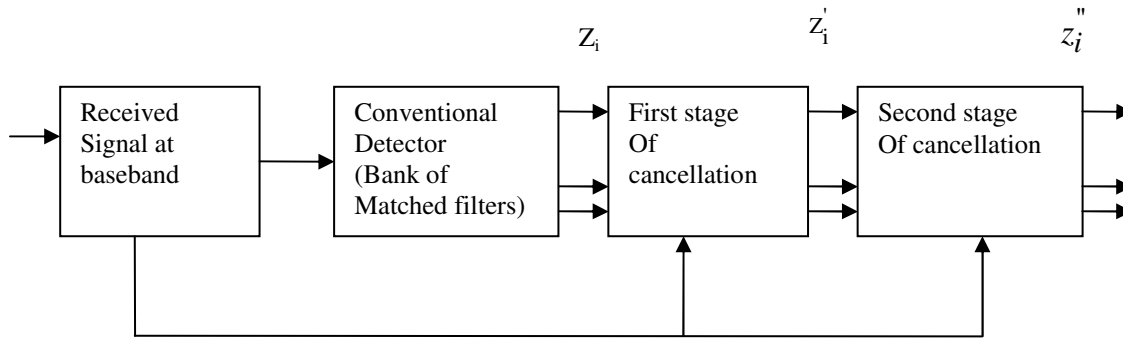
$$Z_i \qquad Z_i' \qquad z_i''$$

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┌──────────┐   ┌──────────┐   ┌──────────┐   ┌──────────┐
│ Received │   │Conventional│ │First stage│  │Second stage│
│Signal at │──▶│ Detector │──▶│   Of    │──▶│   Of     │──▶
│ baseband │   │(Bank of  │   │cancellation│ │cancellation│
│          │   │Matched filters)│ │       │  │          │
└──────────┘   └──────────┘   └──────────┘   └──────────┘
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Fig. A-1: Cascade of parallel cancellers

received signal. This process can be repeated for *s* stages to obtain better results. Further analysis of the decision variables become very difficult and very complicated to follow.

The BER can be expressed as:

$$P_{b2} = Q\left\{ \left[\left[\frac{1}{2E_b/N_o} \frac{1-\left(\frac{K-1}{3N}\right)^s}{1-\left(\frac{K-1}{3N}\right)} \right] \right] + \frac{1}{(3N)^s}\left(\frac{(K-1)^s - (-1)^s}{K}\left(\frac{\sum_{k=1}^{K} P_k}{P_k} \right) + (-1)^s \right) \right]^{-1/2} \right\}$$

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