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An Efficient Switched Detection Technique for DS-CDMA systems

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ABSTRACT: A dual-mode multiuser detector that dynamically switches its detection mode between matched filter and Minimum Mean Square Error (MMSE) detector operations based on channel characteristics is proposed. The main criterion of taking MMSE detector is that it has minimum Bit Error Rate (BER) among all linear multiuser detectors. This detector reduces overall computational complexity while maintaining the performance at tht same level as that of MMSE detector. The switching mechanism is exploited by the performance-complexity tradeoff, between matched filter and MMSE detector.

Key words: Multiple Access Interference, Minimum mean Square Error, Direct Sequence Code Division Multiple Access, Signal to Noise Ratio, Signal Interference Ratio, multiuser detector

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I. INTRODUCTION: Code Division Multiple Access (CDMA) implemented with Direct Sequence Spread Spectrum (DS/SS) signaling is among the most promising multiplexing technologies for cellular telecommunications. In DS-CDMA system, all users transmit at the same time and frequency but use distinct signature sequences to allow signal separation at the receiver [1]. 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 is the major factor limiting the performance and hence the capacity of DS-CDMA system when signal is detected using conventional detector [2]. Therefore, analyses of the effect of MAI on the system performance as well as ways to suppress MAI have been the focus of CDMA research. The Optimal multiuser detector proposed by Verdu [3] eliminates the MAI and offers a significant improvement over the conventional detector. The mechanism is to find Maximum Likelihood Sequence (MLS) for one user's received signal. However its complexity increases with the number of users [3]. A number of suboptimal detectors have been proposed to offer a compromise between performance and computational cost.[2,4]. These suboptimal detectors are further classified into linear and nonlinear type detectors. The linear detectors include decorrelating detectors and Minimum Mean Square Error (MMSE) detectors [4-7]. The detectors need to compute the inverse of cross-correlation matrix [1], the complexity of which is linear. The decorrelating detector chooses linear filter to eliminate the output MAI; and the MMSE detector uses linear filter to minimize the average mean square value of output MAI-plus-noise [7]. For complete literature survey on multiuser detectors; see [1] and [8].

Recently a dual-mode detector that dynamically switches between matched filter and decorrelator had been studied [9]. Our proposed dual-mode multiuser detector, instead switches between matched filter and MMSE detector . The reason of taking MMSE detector among two detectors (decorrelator and MMSE) is that it has minimum BER or maximum Signal to Interference Ratio (SIR) in all linear multiuser detectors[10]. As MMSE detector takes background noise into account, it performs better than the decorrelator . As the background noise goes to zero, the MMSE detector converges in performance to that of decorrelator [11]. It is shown in [12] that the MMSE detector offers significant practical advantage that it can be adapted blindly i.e. without the use of training sequences or knowledge of interfering signature waveforms. Thus adaptive form of this detector is among the most likely candidate for practical application of multiuser detection. However, for low value of Signal to Noise Ratio (SNR), MMSE detector behaves in the same manner as matched filter, which is simpler to implement. Hence by exploiting the performance-complexity tradeoff between matched filter and MMSE detector, we propose a new design based on MMSE detector.

The proposed detector switches between MMSE detector and matched filter based on SNR value. The matched filter in addition to being simpler than MMSE detector, offers same BER for low SNR. Therefore, at low SNR, the detector switches to matched filter and at high SNR it switches to MMSE detector where, its BER is significantly lower than the matched filter. Thus without degrading the performance, the complexity of overall circuit will be lower than if only MMSE detector is used at all time. The effectiveness is verified in simulations.

This paper is organized as follows. We introduce basic model of matched filter and MMSE detector in section II. In section III, we propose our dual-mode detector. The derivations for signal to interference ratio for proposed detector are carried out in section IV. The simulation results and conclusion is discussed in section V.

II. 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 Np. τ_i is the transmission delay for the ith user. In this paper, we will restrict attention to the synchronous CDMA systems, in which $\tau_1 = \tau_2 = \ldots = 0$. Since an asynchronous model can also 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 . It is shown in [16] that matched filter output in discrete form within symbol interval T can be written as

$$r_n = \sum_{i=1}^{K} A_i s_i{}^{n} b_i(n) + \sum_{i=1}^{K} A_i s_i{}^{m} b_i(n-1) + z \qquad (2)$$

where z is a complex gaussian random vector , s_i^n is effective spreading waveform that modulates symbol $b_i(n)$ in received signal, while s_i^m is the effective spreading waveform that modulates $b_i(n-1)$ in the received signal. Hence, signals modulated by s_i^n gives ISI, while by s_i^m gives multipath interference. We can view this system with K number of users in multipath channel as 2K users in AWGN channel. In more compact matrix vector form, the received signal vector can be represented as

$$\mathbf{r_n = SAb+z} \qquad (3)$$

where S =[s_1 … s_{2K}] is effective spreading waveform matrix, A= diag(A_1 … A_K, A_1 … A_K), and 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. As already described in section I, several demodulators have been studied for this channel (see [1]), including the conventional detector

$$b_k=\mathrm{sgn}(y_k) \qquad (4)$$

the optimum multiuser detector

$$\hat{b} = \arg \min_{b\in\{-1,+1\}} P(y/b) \qquad (5)$$

and

$$\hat{b}_k = \arg \min_{\beta \in \{-1,+1\}} P(\beta \neq b_k) \qquad (6)$$

the decorrelating detector

$$\hat{b}_k = \mathrm{sgn}((\mathbf{R}^{-1}\mathbf{y})_k), \qquad (7)$$

and the MMSE detector $\hat{b}_k = \mathrm{sgn}((\mathbf{My})_k)$ with,

$$\mathbf{M} = (\mathbf{R}+\sigma^2\mathbf{A}^{-2})^{-1}, \qquad (8)$$

which minimizes the second moment of the difference between the transmitted bit and the output of the linear transformation **M**. We can easily note that the conventional, decorrelating and MMSE detector are linear detectors of the form

$$\hat{b}_k = \mathrm{sgn}((\mathbf{Ly})_k) \qquad (9)$$

where **L** is a K x K matrix , whose value depends on the type of detector used. We can easily note that the output signal consists of three terms: a desired signal term which could be present even in a single user channel, the second term comprising of MAI at the output and third term which is correlation of noise with the signal. The advantage of the conventional detector is that its implementation requires knowledge of only signature waveform of the users being demodulated. However, the conventional detector suffers from very significant performance degradation in presence of significant MAI, resulting in inefficiency of overall communication system. The decorrelator, on the other hand, eliminates much of this degradation by forcing the MAI to zero. The MMSE detector enjoys the favorable performance property of decorrelator [11], but it too requires knowledge of signature waveforms, as well as signal to noise ratios of all users. Thus it would appear more cumbersome than decorrelator, but note that MMSE works better than decorrelator in presence of background noise. One more point to be noted is that the MMSE detector minimizes the energy of the quantity which the receiver has access, and therefore it can be found adaptively for a given user k with the knowledge of only the signature waveform of that user; that is, the MMSE detector admits an adaptive implementation that uses only the knowledge required by the conventional detector [6].

III. DUAL MODE DETECTOR: The MMSE detector implements the linear mapping which minimizes the mean squared error between the actual data and the soft output of the conventional detector. As we have already seen in eq. (8) the MMSE detector implements partial modification in inverse of correlation matrix. The amount of modification is directly proportional to background noise; the higher the noise level, the less complete an inversion of R can be done without noise enhancement causing performance degradation. Thus, MMSE detector balances the desire to decouple the users (and completely eliminate MAI) with the desire not to enhance the background noise [1]. In particular MMSE detector is shown to be the most efficient in all three linear multiuser receivers [13] in terms of maximum SIR and minimum BER. It operates more likely to be same as conventional detector when SIR is small, but when SIR is large it gives less BER. The performance gain afforded by the MMSE detector over the conventional detector depends on the SIR at which the system is to be operated, and this in turn depends on the data rate, amount of coding and symbol size [13]. It is shown in [14] that for a DS-CDMA system with random spreading codes, the spectral efficiency of matched filter and MMSE detector is same. Therefore, at low SNR matched filter can be used, which is less computationally complex (does not require matrix multiplication and also knowledge of SNR of all other users) than

MMSE detector. It is therefore, inefficient to apply MMSE detector in a situation where it does not significantly outperform the matched filter.

However, due to superior performance of MMSE detector over large range of SNR, it prompted us to use the switching criterion between matched filter detector and MMSE detector. The block diagram of our dual mode detector is shown in fig. 1.The received signal is first processed by bank of matched filters (anyway, it is also required in case of MMSE detector). After this, some estimation is done to take the decision to perform MUD or not. If multiuser detection is required, the signal is passed to a block where matrix multiplication is done for MMSE detector, otherwise it is directly passed to the symbol decision block.

The key functioning of this detector depends on the SNR value. In a real cellular environment, where, background interferences are sometimes very strong, this detector will take MMSE detector path. Also due to multipath fading, the amplitude of the received signal of each user may vary over time significantly. Hence, there will be a significant portion of time this detector will take matched filter path. We expect that this dual mode detector would be a better option to use, since none of both the detectors, if used alone at all time will give the better performance.

IV Switching Criterion: The switching criterion of our dual mode detector is based on the random channel conditions. The SIR for user 1 with total K users in matched filter detector can be expressed as [9]

$$\beta_1^{mf} = \frac{A_1^2}{\sum_{j=2}^{K} \rho_{1,j}^2 A_j^2 + \sigma^2} \tag{8}$$

where σ^2 is the variance of noise and $\rho_{1,j}$ are the elements of cross correlation matrix. The SIR for user 1 in MMSE detector can be expressed as (the proof of which is given in Appendix)

$$\beta_2^{MMSE} = \frac{A_1^2}{((\mathbf{A}^2 + \sigma^2 \mathbf{R}_{\mathbf{S}}^{-1})_{1,1})^{-1} - A_1^2} \tag{9}$$

The matched filter detector is computationally simpler than MMSE detector, hence when received SNR is below 5 dB, the proposed detector will switch to it, otherwise it will use MMSE detector .The MMSE detector is advantageous only in the case when SIR1 MMSE is more than SIR1 of matched filter, i.e.

$\beta_2^{MMSE} > \beta_1^{mf}$

V. Simulation Results and Conclusion:

Simulation results are shown here to verify that at low SNR range MMSE detector and matched filter detector have same BER while for large SNR, MMSE detector performs significantly better than matched filter detector (Figure 2). Note that at high SNR decorrelator and MMSE detector work almost similar and and at very low range they have almost same BER. Therefore we have taken MMSE detector instead of decorrelator to take advantages of MMSE detector over decorrelator. This can be verified mathematically. From eq.(8) MMSE matrix is $\mathbf{M} = (\mathbf{R}+\sigma^2\mathbf{A}^{-2})^{-1}$. At low SNR (or very high σ^2), it approximately becomes $\mathbf{M} = (\sigma^2\mathbf{A}^{-2})^{-1}$ which is same as the matched filter. At high SNR (or very low σ^2) it approximates to $\mathbf{M} = (\mathbf{R})^{-1}$, which is nothing but decorrelator matrix. Thus MMSE detector works in between these limits.

The MMSE detector has minimum BER among all linear multiuser detectors. In figure 2, the proposed dual mode detector's switching criterion is shown, which switches to matched filter at low SNR and to MMSE detector at high SNR. The overall complexity of the proposed detector will depend on the percentage of total time it uses matched filter or MMSE detector . In figure 3, BER is plotted against number of users which also shows that BER of matched filter increases sharply with number of users, which is not so much critical in case of MMSE detector. In figure 4, we have shown the near-far effect, which is worse in matched filter detector. As the power difference increases, the BER increases sharply in matched filter, while the effect is less serious in MMSE detector.

The value of SNR is also dependent on the random behavior of channel noise and background interferences and therefore behavior and complexity will be different for each case. We have taken random noise function to simulate random channel conditions. The nominal SNR of all users are taken in the range of -2 to 12 dB. In practical situations, where channel behavior is unpredictable, if this detector takes matched filter most of the time (because of low SNR), then it will be computationally simpler than that if only

MMSE detector is alone used just to take its advantages. Also an option available in this detector is that if SNR becomes high it can use MMSE detector which provides less BER but computationally complex.

Appendix A (Proof):

In the MMSE detector, the adaptive weight vector is calculated using various algorithms based on MSE criterion. The output is then taken by multiplying the received signal by weight vector, which minimizes the mean square error. Without loss of generality, we take user 1 cross correlation vector between the desired symbol and received samples, which will be

$$\mathbf{X}=E[\mathbf{r}\, A_1 b_1] = A_1^2\, \mathbf{s_1} \qquad \text{(A-1)}$$

In MSE criterion the cost function $E[|y_1^n - A_1\, b_1|^2]$ is minimized . The wiener solution weight vector of which for user 1 is given by [15] as

$$\mathbf{c}=\mathbf{R}^{-1}\mathbf{P}= A_1^2\, [\mathbf{SA^2S^t}+\sigma^2\,]^{-1}\, \mathbf{s_1} \qquad \text{(A-2)}$$

where $\mathbf{R}=E[\mathbf{rr^t}] = \mathbf{SA^2S^t}+\sigma^2$ (A-3)

is the cross correlation matrix of received samples. In practical system the number of users is always much less than the processing gain N. So practically we can assume that all 2K combined spreading waveforms are uncorrelated with each other. We now define a cross correlation matrix of combined spreading waveforms as $\mathbf{R_s} = \mathbf{SS^t}$. This matrix $\mathbf{R_s}$ is positive Hermitian matrix with full rank. The weight vector for any user will be located in the complex space with 2K dimensions ($\boldsymbol{\alpha}=\mathbf{C}^{2K}$). Therefore, we can write any weight vector c satisfies $\mathbf{c}=\mathbf{S}\boldsymbol{\alpha}$. The output signal of user 1 (or any user k) is then obtained by multiplying the code vector of user 1 with the received signal i.e.

$$\mathbf{y}=\mathbf{c_1}'\,\mathbf{r} \qquad \text{(A-4)}$$

Another performance measure, which is more often used is the signal to interference (SIR), which is defined as

$$\mathrm{SIR} = \frac{E^2[c_k^{'} r]}{\mathrm{var}[c_k^{'} r]} \qquad \text{(A-5)}$$

where $c_k' = [c_{k,1} \ \ c_{k,2} \ \ \ldots \ c_{k,N}]$ .This ratio is nothing but the ratio of the signal of desired user and the total interference, which is the sum of interferences from signals of other users and the channel noise power. From equation (A-2), we can rewrite wiener solution for weight vector as

$$\mathbf{S}\boldsymbol{\alpha} = \mathbf{c}=\mathbf{R}^{-1}\mathbf{P}= A_1^2 \, [\mathbf{SA^2S^t}+\boldsymbol{\sigma}^2]^{-1} \, \mathbf{s_1} \qquad \text{(A-6)}$$

If we multiply both sides by the factor $(\mathbf{SA^2S^t}+\boldsymbol{\sigma}^2)\,\mathbf{S^t}$, we get

$$\mathbf{S}\boldsymbol{\alpha}(\mathbf{SA^2S^t}+\boldsymbol{\sigma}^2)\,\mathbf{S^t} = A_1^2 \, [\mathbf{SA^2S^t}+\boldsymbol{\sigma}^2]^{-1} \, \mathbf{s_1}.\,(\mathbf{SA^2S^t}+\boldsymbol{\sigma}^2)\,\mathbf{S^t} \qquad \text{(A-7)}$$

After substituting $\mathbf{R_s} = \mathbf{SS^t}$ and $\mathbf{s_1}=\mathbf{S_1e_1}$, the above equation can be further simplified to

$$\mathbf{R_s}\,\boldsymbol{\alpha}(\mathbf{SA^2S^t}+\boldsymbol{\sigma}^2) = A_1^2 \ \mathbf{R_s}\,\mathbf{e} \qquad \text{(A-8)}$$

where $\mathbf{e}=[1 \ 0 \ \ldots \ 0]'$. Using (A-2) and (A-6), we thus get

$$\mathbf{c}=A_1^2 \, \mathbf{S^t} \, (A^2\mathbf{R_s}+\boldsymbol{\sigma}^2)^{-1} \, \mathbf{e} \qquad \text{(A-9)}$$

On comparison of equation (A-5) and (A-9), we see that

$$\mathbf{c} = \frac{A_1^2 \mathbf{S_t}}{((\mathbf{A}^2 \mathbf{R_s} + \sigma^2)_{1,1}{}^{-1})^{-1}} \qquad (\mathrm{A}-10)$$

The SIR can thus be obtained as

$$\beta_2^{\mathrm{MMSE}} = \frac{A_1^2}{((\mathbf{A}^2 + \sigma^2 \mathbf{R}_{\mathbf{S}}^{-1})_{1,1})^{-1} - A_1^2} \qquad (A-11)$$

Where $(.)_{1,1}^{-1}$ denotes element of first row and first column of the inverse matrix. This equation can again be seen as ratio of the signal of user 1 and the variance from the output (the total signal minus the signal of user1 will be the total interference)

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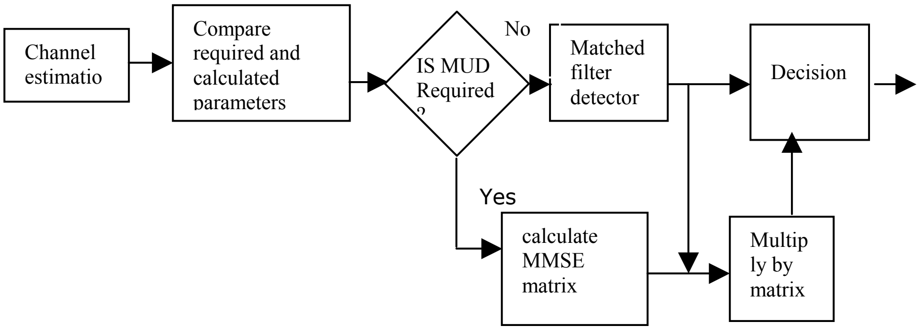

Figure 1: Block Diagram of proposed dual mode detector

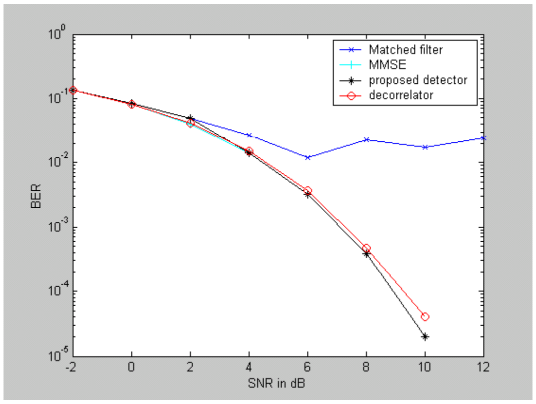

Figure 2 : Bit error rate comparison for matched filter , decorrelator , MMSE detector and proposed detector .

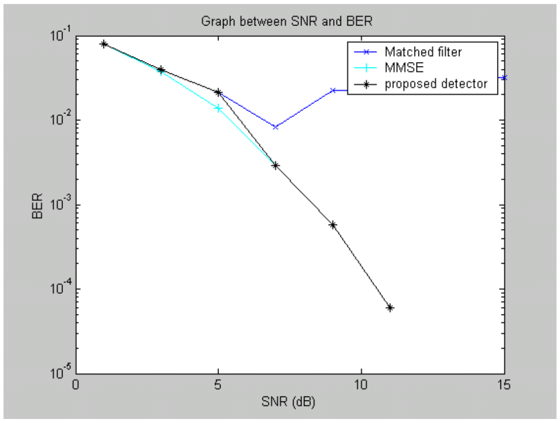

Figure 3: Switching criterion of proposed detector in between matched filter and MMSE detector .

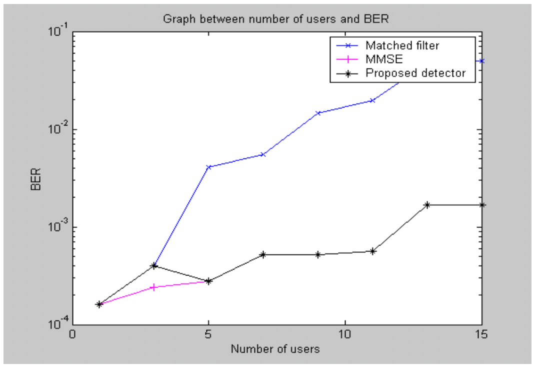

Figure 4:BER vs. number of users for matched filter , MMSE detector and proposed detector

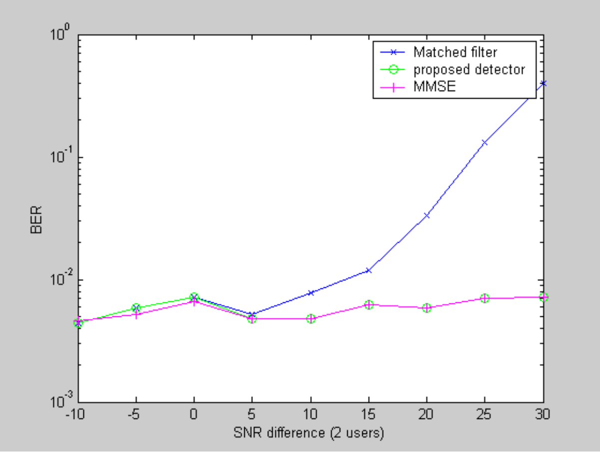

Figure 5: Illustration of near-far effect in matched filter, MMSE detector and proposed detector.

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Prof. Aggarwal was honored by the Reliability Society of IEEE, USA for his services as Guest Editor for the special issue on "State of Reliability Effort of the Indian sub-Continent". He was also declared as the Man of Decade by American Bibliographical Institute, USA and was conferred L.C. Verman Award by the Institute of Electronics and Tele-Communication Engineers, India. It is India's leading professional society with more than 40,000 members. He received this honour for his outstanding contribution in Electronics and Telecommunication. He got Indira Gandhi "Priyadarshini award" for his outstanding services, achievements & contribution in the field of education. He has been listed as one of the first five hundred personalities of the new millenium worldover, by American Bibliographical Institute, U.S.A.