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Performance Analysis of Multiuser DS-CDMA Receivers

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Abstract— **The DS-CDMA (Direct Sequence Code Division Multiple Access) technique is widely used in cellular systems where each user is assigned a unique spreading code. The growth in applications of DS-CDMA is due to its robustness to fading, its anti interference capability and the potential for multiple access. Spread spectrum signal occupies a large bandwidth, only a small portion of this signal undergoes fading due to multipath at any given time. DS-CDMA can reject narrowband interference, as narrowband interference affects only a small portion of the spread spectrum signal. In this paper the performance of a Multiuser DS-CDMA system is investigated in presence of multiple access interference (MAI) and AWGN. This paper also compares the performance of the conventional single user matched filter (SUMF) with the performance of suboptimal linear multiuser detector (MUD) and suboptimal non linear multiuser detector MUD. For this analysis the three types of receiver are proposed i.e. matched filter receiver, decorrelator receiver and Successive Interference Cancellation (SIC) MUD. The simulation result shows the better performance of SIC detector over conventional SUMF and Decorrelator receiver.**

Index Terms— **AWGN, decorrelator, DS-CDMA, MAI, MUD, SIC, SUMF.**

I. INTRODUCTION

The wireless personal communicator is as common as the wireline telephone used to be, and it provides reliable and affordable communication, anywhere and anytime. To bring this vision to fruition, major improvements in the current state of wireless technology are necessary. One type of wireless technology which has become very popular over the last few years is direct-sequence code-division multiple access (DS-CDMA). In this paper I review multi-user detection, an area of research with the potential to significantly improve DS-CDMA communications. Here has been great interest in improving DS-CDMA detection through the use of multi-user detectors. In multi-user detection, code and timing (and possibly amplitude and phase) information of multiple users are jointly used to better detect each individual user [5]. The important assumption That the codes of the multiple users are known to the receiver a priori.Verdu's seminal work published in 1986, proposed and analyzed the optimum multiuser detector, or the maximum likelihood sequence detector.

Unfortunately, this detector is much too complex for practical DS-CDMA systems. Therefore, over the last decade or so, most of the research has focused on finding suboptimal multiuser detector solutions which are more feasible to implement. Most of the proposed detectors can be classified in one of two categories: linear multi-user detectors and subtractive interference cancellation detectors. In linear multi-user 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 with lower complexity than optimum receiver[6]. In subtractive interference cancellation detection, estimates of the Interference are generated and subtracted out; the successive interference cancellation (SIC) detector takes a serial approach to cancel interference. Each stage of this detector decisions, regenerates, and cancels out one additional direct-sequence user from the received signal, so that the remaining users see less MA1 in the next stage.

In this paper Performance analysis of DS-CDMA system with binary phase shift keying (BPSK) modulation system is analyzed. It is assumed that there is coherent detection and perfect symbol synchronization in an AWGN channel. In section II, performance and block diagram DS-CDMA single user matched filter is presented. In section IV, the performance and block diagram of decorrelator receiver is presented, in section V concept and block diagram of Successive Interference Cancellation (SIC) MUD is evaluated. Section VI comprises of numerical results and MATLAB simulations which verify the theoretical expressions proved in section II, IV, V Finally, the conclusions are provided in section VII.

II. DS-CDMA PERFORMANCE ANALYSIS OF MULTIUSER DS-CDMA USING MATCHED FILTER

A model of the CDMA system under is shown in fig. A. It is assumed that there are K active users' transmissions. The received signal during one symbol interval, T_b has the following form:

$$r(t) = \sum_{k=1}^{K} g_k \sqrt{2P_k}\, C_k(t)\, b_k(t) \cos\omega_c t + n(t) \qquad (1)$$

where $b_k(t) \in \{-1,+1\}$ is the data symbol of the k^{th} user with equal probabilities 1 or -1 , P_k is the received power of k^{th} user,(assuming that all users transmits the same power so $p_1=P_2,\ldots,=P_k=P$) ,g_k is the channel gain of k^{th} user(assuming

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channel gain for each user is unit), n(t) is an AWGN with two sided power spectral density equal to $N_o/2$, ω_c is the carrier frequency .In (1) C_k is the signature sequence of +1 's and -1's assigned to the k^{th} user and it is given by

$$C_k(t) = \sum_{i=0}^{N} C_k \phi(t-iT_c) \quad (2)$$

Where ϕ (t) is the unit rectangular pulse of duration $T_c= T_b/N$ where N is the number of bits in the spreading sequence. The output of the matched filter is a dispread and demodulated signal. The dispread signal is obtained by applying the appropriate PN sequence.

The demodulated signal simply obtained by applying a modulating tone to provide a coherent detection .The output of the receiver can be written a

$$Z_k=\int_0^{Tb} r(t)\, C_k(t) \cos\omega_c t\, dt \quad (3)$$
$$= B_k + I + \eta$$

Where B_k is the information of the aimed user, I is the multiple access interference, η is an AWGN .The output of the matched filter provides the following information:

1-The aimed user information B_k:

$$B_k= \int_0^{Tb} \sqrt{2P}\; C_k^2(t)\; b_k(t)\cos^2\omega_c\, dt \quad (4)$$
$$= \pm\sqrt{\frac{P}{2}}\, T_b$$

Where $\cos^2\omega_c t = \frac{1}{2}(1 + \cos 2\,\omega_c t)$, $C_k^2(t) = 1$. Since the multiplication of ω_c and t was selected as the integer number, the integration of $\cos\omega_c t$ and $\sin\omega_c t$ functions over one period is always zero. Likewise the integration of b_k (t) over one period is 1 because the number of 1's and -1's is assumed to be the same.

2-The multiple access interference I which is represented as:

$$I=\int_0^{Tb} \sum_{i=1\; i\neq K}^{K} \sqrt{2P}\, C_k(t)\, C_i(t) b_k(t) \cos 2\omega_c t\, dt \quad (5)$$

$$= \sum_{i=1\; i\neq K}^{K} \sqrt{\frac{P}{2}}\, T_b \int_0^{Tb} C_k(t) C_i(t)\, dt$$

3 – The AWGN power η is given by:

$$\eta=\int_0^{Tb} n(t)\, C_k(t)\, \cos\omega_c t\, dt \quad (6)$$

The decision statistic of the output of the matched filter, Zk can be modeled as Gaussian random variable with a mean value of $\dot{Z}$ and variance of σ_z^2 is

$$E\{Z\} = \dot{Z} = E\{B_K + I + \eta\}$$
$$\dot{Z}=E\{B_k\} +E\{I\} +E\{\eta\} = \pm\sqrt{\frac{P}{2}}\, T_b \quad (7)$$

E {I} is the multiple access interference term mean that is defined in [4] as zero mean, E {η} is the noise power mean which equal to zero. While $E\{B_k\} = \pm\sqrt{\frac{P}{2}}\, T_b$.

The variance of Z, σ_z^2 is the sum of variance of the multiple access interference term and noise, which are assumed to be independent, therefore, σ_z^2 can be written as:

$$\sigma_z^2=\sigma_i^2+\sigma_\eta^2 \quad (8)$$

Assume transmitted power from all user is same and gain of the channel is same for each user. The variance of multiple access interference term, σ_i^2 is defined in [3] as

$$\sigma_i^2=T_c^2(k-1)\; PN/6 \quad (9)$$

as the variance of noise term,

$$\sigma_\eta^2 = E\{\eta^2\} - E\{\eta\}$$
$$=E\left\{\int_0^{Tb} n(t) C_k(t) \cos\omega_c t\, dt \int_0^{Tb} n(\lambda) C_k(\lambda) \cos\omega_c\lambda\, d\lambda\right\}$$
$$=E\int_0^{Tb}\int_0^{Tb} n(t) C_k(t) n(\lambda) C_k(\lambda) \cos\omega_c t\, \cos\omega_c\lambda\, dt\, d\lambda \quad (10)$$

Assuming that n (t) is a wide sense stationary random process. Thus the autocorrelation of the white Gaussian random process was defined in [7] as:

$$E\{n(t)\, n(\lambda)\} =N_0\delta(t-\lambda)/2 \quad (11)$$

So

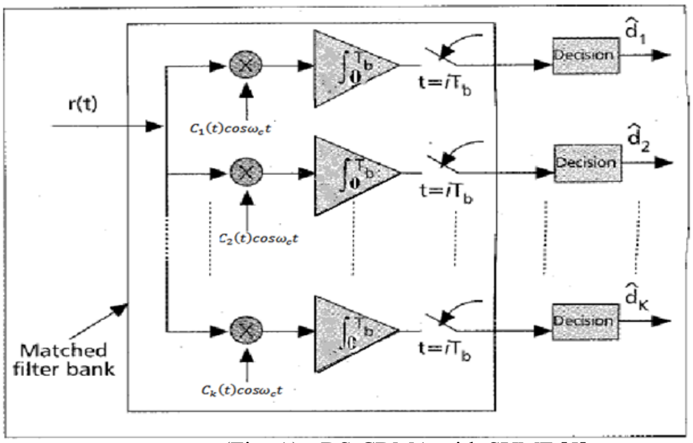
$$\sigma_\eta^2 = \frac{N_0}{2}\int_0^{Tb} C_k^2(t)\, \frac{1}{2}(1 + \cos 2\omega_c t)\, dt$$
$$= \frac{N_0\, T_b}{4} \quad (12)$$

So $\sigma_\eta^2 = N_0 T_b/4$ The bit error probability for this system P_e , is defined according to the Gaussian approximation [4,8]as

$$P_e=Q\left(\sqrt{\frac{\dot{Z}^2}{\sigma_z^2}}\right)$$
$$= Q\left(\sqrt{\frac{\left(\sqrt{\frac{P}{2}}T_b\right)^2}{\frac{N_0 T_b}{4} + \frac{T_c^2(k-1)PN}{6}}}\right) \quad (13)$$

The Gaussian approximation of the MAI has limitation when used to predict system performance .In a typical CDMA system when the user number M is not sufficiently large, the Gaussian approximation of the MAI may be highly inaccurate, particularly in a near far problem.

Where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{\left(-\frac{u^2}{2}\right)} du$ is the standard Q function, $T_c N = T_b$.



(Fig. A) - DS-CDMA with SUMF [5]

III. NEAR –FAR ENVIRONMENT:

In multiuser scenario conventional detection fails if the spreading sequences are not perfectly orthogonal and is exacerbated by large variations between each user's received signal powers. This phenomenon is commonly known as the near –far problem and is major concern for specific application [1].

IV. DECORRELATOR RECEIVER:

Verdu's seminal work published in 1986, proposed and analyzed the optimal multiuser detector, or the maximum likelihood sequence detector. Unfortunately, this detector is much too complex for practical DS-CDMA systems [6]. Therefore, over the last decade or so, most of the research has focused on finding suboptimal multiuser detector solutions which are more feasible to implement. Most of the proposed detectors can be classified in one of two categories: linear

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multi-user detectors and subtractive interference cancellation detectors.

The decorrelator MUD is a linear method that simply uses matrix multiplication to remove the MAI among different users. The received signal at the input of the decorrelator receiver during one bit interval, T_b has the following form

$$r(t) = \sum_{k=1}^{K} g_k \sqrt{2P_k}\, C_k(t)\, b_k(t) \cos\omega_c t + n(t) \quad (14)$$

the output of the kth matched filter is given by

$$Y_k = \int_0^{Tb} r(t)\, C_k(t) \cos\omega_c t \; dt \quad (15)$$

This could be rewritten as:

$$Y_1 = \sum_i A\, b_k\, R_{1i} + n$$
$$Y_2 = \sum_i A\, b_k\, R_{2i} + n$$
$$Y_3 = \sum_i A\, b_k\, R_{3i} + n$$
$$\vdots \qquad \vdots$$
$$Y_K = \sum_i A\, b_k\, R_{ki} + n \quad (16)$$

The above equation could be written in vector representation as follows

$$Y = RAb + n \quad (17)$$

Where a is a diagonal matrix with a vector [$A_1, A_2, A_3, \ldots, A_k]^T$ represents it is main diagonal ,$A_k = \sqrt{\frac{P}{2}}\, T_b$,$1 \leq K \leq k$ assuming a constant power for all users=[$b_1, b_2, \ldots b_k$] are the data bits from the k user ,n= [$n_1, n_2, n_3, \ldots, n_k$] is a vector of the Gaussian noise samples with zero mean and a covariance matrix $\sum n = \sigma_n^2 R$ (where $\sigma_n^2 = NT_b/4$ is the noise power after despreading)R is the non negative definite matrix of the cross correlations between the waveforms of the different users that's given by[2]

$$R_{ij} = \int_0^{Tb} C_i(t) C_j(t) dt \quad (18)$$

The estimated value of the transmitted bit is given by

$$\hat{b} = sign\; R^{-1}\, Y \quad (19)$$

The decision matrix z is is equal to $R^{-1}\, Y$, and the covariance matrix $\sum_z$ is computed

$$\textstyle\sum_z = E\{zz^T\} - E\{z\}\, E\{z^T\}$$
$$= E\{(Ab+R^{-1}n)\,(Ab+R^{-1}n)^T\} - (Ab)\,(Ab)^T$$
$$= E\{Ab(Ab)^T + Ab(R^{-1}n)^T + R^{-1}n(A\,b)^T + R^{-1}n(R^{-1}n)^T\} - (Ab)(Ab)^T$$
$$= AbE\{n^T\}(R^{-1})^T + R^{-1}E\{n\}b^TA^T + R^{-1}E\{nn^T\}(R^{-1})^T$$
$$= \sigma_n^2 (R^{-1})^T \quad (20)$$

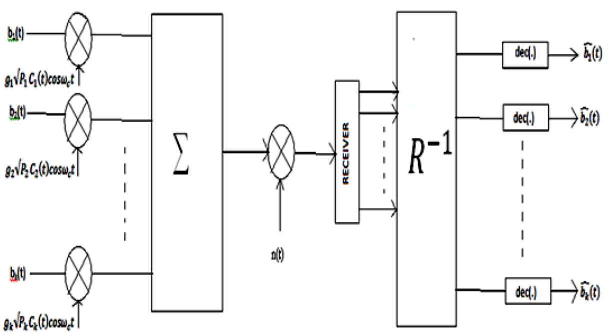
Where $E\{n\} = 0$ and $E\{nn^T\} = \sigma_n^2 R$ and σ_n^2 is the power of the AWGN at the output of the matched filter.

The probability of bit error of the k^{th} user can be written as

$$P_e = Q\left(\sqrt{\frac{E(Z_k|b_k)^2}{var(z)}}\right)$$

$$= Q\left(\sqrt{\frac{(\sqrt{\frac{P}{2}}\, Tb)^2}{\sigma_n^2 (R^{-1})^T}}\right) \quad (21)$$

Where $\sigma_n^2 = N_0\, T_b/4$ as calculated in eq.12



(Fig.B)- Decorrelator MUD

V. SUCCESSIVE INTERFERENCE CANCELLATION

In subtractive interference cancellation detection, estimates of the Interference are generated and subtracted out; the successive interference cancellation (SIC) detector takes a serial approach to canceling interference. Each stage of this detector decisions, regenerates, and cancels out one additional direct-sequence user from the received signal, so that the remaining users see less MA1 in the next stage [5]. The first stage is preceded by an operation which ranks the signals in descending order of received powers. The reasons for canceling the signals in descending order of signal strength are straightforward. First, it is easiest to achieve acquisition and demodulation on the strongest users. Second, the removal of the strongest users gives the most benefit for the remaining users. The result of this algorithm is that the strongest user will not benefit from any MAI reduction; the weakest users, however, will potentially see a huge reduction in their MAI.

If power reordering is done properly than SIC proves to be best technique of multiuser detection in fading environment and acquire less hardware component [5].

The first stage is preceded by an operation which ranks the signals in descending order of received powers. The first stage implements the following steps:

1. Detect with the conventional detector the strongest signal b_1.
2. Make a hard data decision on b_l.
3. Regenerate an estimate of the received signal for user One,$\widehat{b_1}(t)$, using:

   a) Data decision from step 2
   b) Knowledge of its PN sequence
   c) Estimates of its timing and amplitude (and phase)

4. Cancel (subtract out) $\widehat{b_1}(t)$ from the total received signal, r (t), yielding a partially cleaned version of the received signal, $r_1(t)$.

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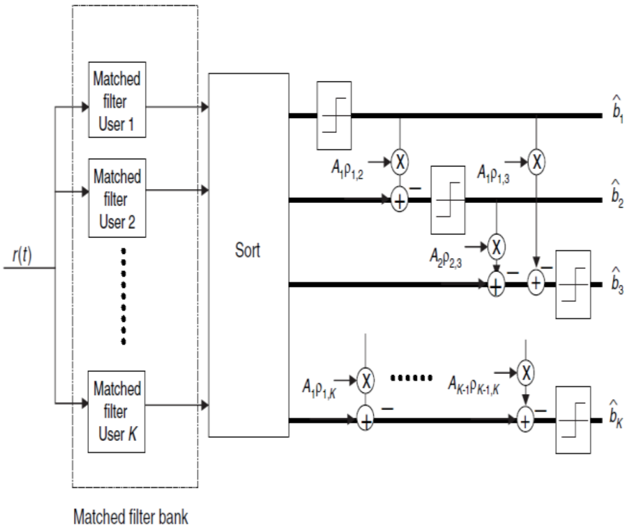

(Fig.C)- SIC MUD [3]

VI. MATLAB SIMULATION AND RESULTS:

The theoretical expressions are derived in the presence of AWGN and MAI. Gold sequences of length 31 are taken and BPSK modulation scheme is used. In Fig.1 bit error rates of four users for SUMF receiver are shown individually, Thus it is clear that all users have different bit error rates under same conditions just because of different spreading codes. In Fig.2 BER performance comparison between the conventional SUMF and suboptimal linear multiuser detector Decorrelator is conducted for two users and individual comparison for two users is plotted. In Fig.3 performance comparison between the conventional SUMF and suboptimal nonlinear detector SIC is conducted for two different users. In Fig. 4 performance comparison among the conventional SUMF, Decorrelator and SIC is conducted, in this average bit error rate for two user is plotted and compared.

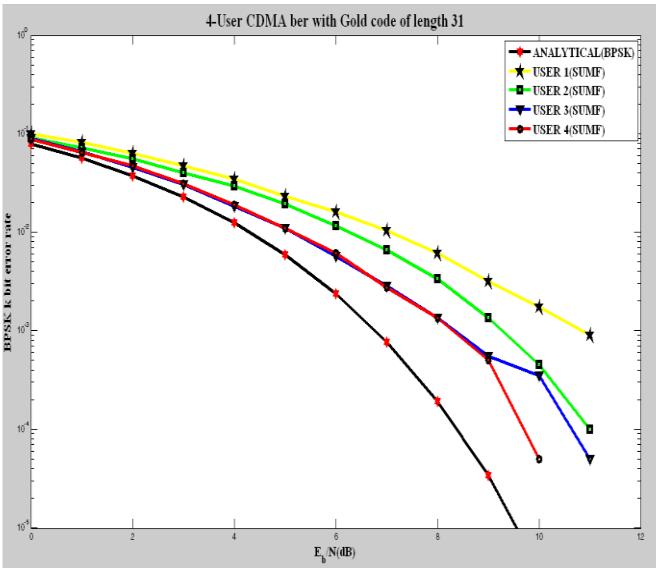

Fig.1 Four user CDMA BER with Gold code of Length31

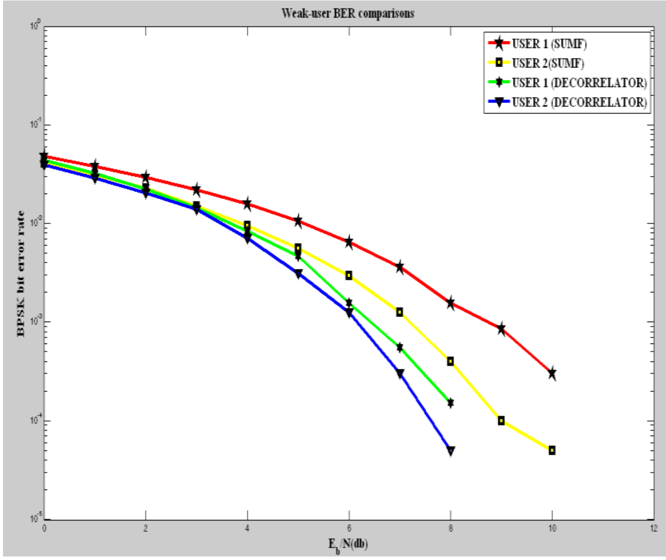

Fig.2 Performance comparison of the single user matched filter with Decorrelator multiuser detector.

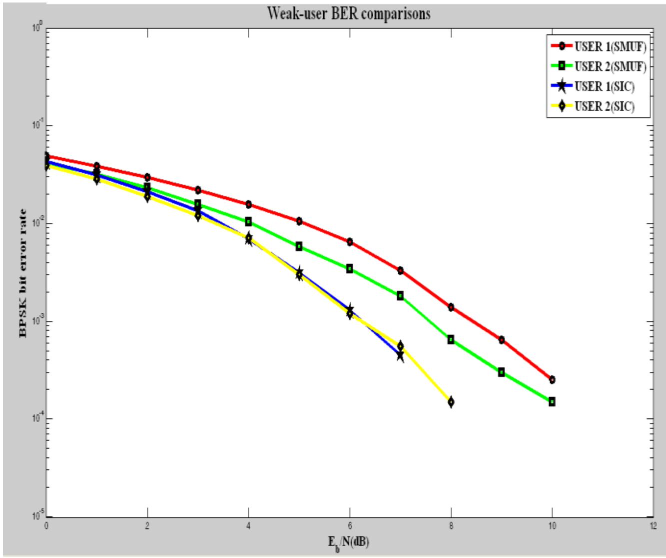

Fig.3 Performance comparison of the single user matched filter with SIC

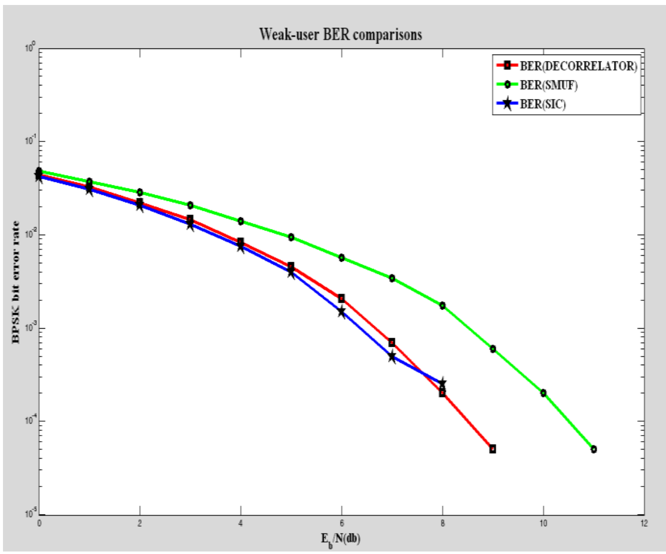

Fig.4 Performance comparison of the single user matched filter, SIC, Decorrelator (Gold sequence length 31 and No. of users =2)

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VII. CONCLUSION

The DS-CDMA receivers are divided into single user and multi user detectors. Single user receiver detects the data of one user at a time whereas a multi user receiver jointly detects several users' information. This paper focuses on Suboptimal MUD. Firstly suboptimal linear detector Decorrelator is taken to improve BER performance .From Fig.2 it is clear that decorrelator performs better than SUMF, as comparisons are made between two different users having different spreading codes that are why both users have different performance improvements. Secondly suboptimal interference cancellation MUD SIC is taken for Gaussian interference cancellation in Fig.3. Unlike the interference –ignorant detector this joint detector exploits knowledge of the distribution of the interference rather than interference as Gaussian noise. From Fig.3 it is clear that SIC performs better than SUMF. Furthermore the bit error rate performance of SIC was compared analytically with SUMF and decorrelator receiver, average bit error rate for two users is plotted in Fig.4. Simulation plot shows for this particular set of Gold codes SIC provides 4 % bit error rate improvement than decorrelator receiver and 40 % improvement than SUMF. This SIC multiuser detector holds promise for improving DS-CDMA performance. Although SIC is currently in research stage, The SIC detector faces the problems of power reordering. Efforts to commercialize multiuser detectors are expected in the coming years as DS-CDMA systems are more widely deployed .The success of these efforts will depend on the outcome of careful performance and cost analysis for the realistic environment.

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