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Successive Interference Cancellation for DS-CDMA Systems with Transmit Diversity

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We introduce a new successive interference cancellation (SIC) technique for direct sequence code division multiple access (DS-CDMA) systems with transmit diversity. The transmit diversity is achieved with a space-time block code (STBC). In our work we first consider hard decision SIC with an STBC, and then investigate the performance of soft decision SIC with an STBC. System performance over a Rayleigh fading channel is investigated and the analysis is confirmed by simulation.

Keywords and phrases: multiuser detection, space-time codes, CDMA, SIC.

1. INTRODUCTION

Code division multiple access (CDMA) systems allow multiple users to transmit information over the same physical channel [1]. However, the performance and capacity of CDMA systems are limited by multiple access interference (MAI). Multiuser detection (MUD) is a means to overcome MAI and the near-far effect. The optimal multiuser detector was proposed by Verdú in 1986 [2]. The drawback of the optimal multiuser detector is its complexity, hence much of the subsequent research in this area has considered suboptimal approaches. Several low-complexity multiuser detectors such as decorrelation, minimum mean squared error (MMSE), successive interference cancellation (SIC) [3], and parallel interference cancellation (PIC) [4] have been proposed. Among these techniques, SIC provides a serial approach to interference cancellation with relatively low complexity [5]. An SIC detector also has a simple structure that can easily be implemented in practical systems.

Diversity is a method to combat noise and fading. It provides the receiver with multiple copies of a signal generated by the same underlying data. Recently, space-time coding [6, 7] has gained much attention as an effective transmit diversity technique. Space-time coding can be thought of as a combination of channel coding and antenna arrays. There are two main types of space-time codes, namely, space-time block codes (STBCs) [6] and space-time trellis codes (STTCs) [8]. STBCs operate on a block of input symbols, producing a matrix output whose rows represent time and columns represent different transmit antennas. In contrast to the standard error correcting codes, STBCs do not generally provide coding gain, unless concatenated with an outer code. Their main feature is the provision of diversity gain with a very simple decoder. On the other hand, STTCs operate on one input symbol at a time, producing a sequence of vector symbols whose length represents the number of antennas. Like traditional trellis coded modulation (TCM) for a single-antenna channel, STTCs provide coding gain. Since they can also provide diversity gain, their key advantage over STBCs is the provision of coding gain. Their disadvantage is that they are very hard to design and in general the decoders are complex. This design problem is similar to that for TCM, convolutional codes, turbo codes, and so forth.

In this paper we introduce a new SIC technique for a STBC direct sequence code division multiple access (DS-CDMA) system with transmit diversity, and investigate its bit error rate (BER) performance over a Rayleigh fading channel. We first consider hard decision SIC with an STBC, then investigate soft decision SIC, and generalize the results to multiple antenna STBC systems. Computer simulation is used to verify the analysis which shows that the system has good performance with relatively low complexity.

The remainder of this paper is organized as follows. Section 2 introduces the system model. Section 3 presents the

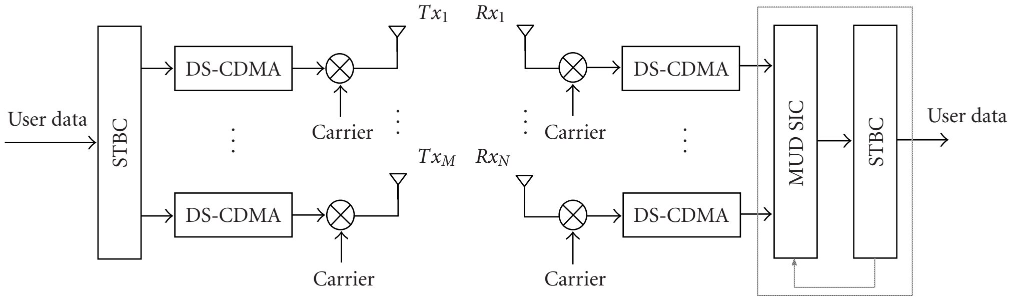


Figure 1: The model of a DS-CDMA system with an STBC and SIC.

performance analysis of the proposed hard decision SIC for DS-CDMA with the Alamouti STBC from [6]. Section 4 proposes hard/soft decision SIC with STBC and generalizes this to the case with M transmit antennas and N receive antennas. Section 5 presents the performance analysis of hard/soft decision SIC with STBC. Section 6 presents some simulation results on system performance, and finally, Section 7 presents a summary of our work.

2. SYSTEM DESCRIPTION

The system model is shown in Figure 1. We consider the multiuser DS-CDMA system introduced in [1] and the STBC introduced in [6, 7] to achieve space-time diversity. The transmitter is equipped with M transmit antennas and each transmit antenna sends STBC information for each user using DS-CDMA. We assume the desired user has N receive antennas and the system has K active users. For DS-CDMA, the spreading sequence is modulated directly with the user signal. The spreading ratio is denoted as G. We consider Gold codes for spreading. We assume a Rayleigh fading channel with additive white Gaussian noise (AWGN). The channel is flat during one STBC codeword. The effect of the near-far ratio, defined as the ratio of the power of the strongest user to the power of the weakest user, is also considered in this paper.

An SIC multiuser receiver is employed for DS-CDMA and STBC. The SIC decoder for CDMA was first introduced by Fazel and Papke (see [9]). The detector has V iterations in cascade, where $V = K$ with SIC. The first step is to rank the users in descending order of received power. Then each iteration of the detector makes a decision, regenerates the signal, and cancels out one more user from the received signal, so the remaining users have less MAI in the next iteration. Since the users are demodulated in decreasing order of power, the weak users will have more MAI reduction. The SIC detector offers significant performance improvements, especially when there is a large disparity amongst received user power levels. Details of the SIC algorithm can be found in [3, 9].

In this paper, the detector and sorting criterion are modified to work with STBC. Figure 2 shows the proposed algorithm. Since the output from the DS-CDMA correlator is an overlay of two or more space-time coded signals and AWGN, it does not provide the actual power of any of the signals, hence conventional SIC sorting is not suitable here. Taking

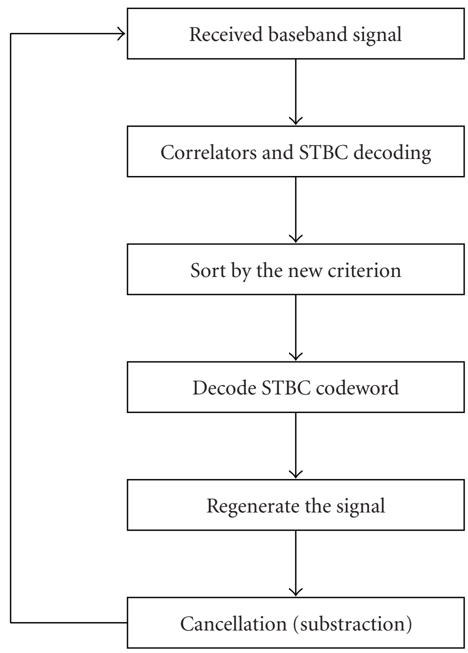


Figure 2: The new SIC technique for DS-CDMA with an STBC.

this into consideration, and also to avoid error propagation which can severely degrade the performance with SIC, we include an STBC in our decoding loop. Sorting is done after decoding the STBC, and this is performed every STBC period since we consider a flat Rayleigh fading channel.

In this paper, the initial sorting criterion is the combined power of the (two or more, depending on the number of transmit antennas) signals with the same underlying data which are transmitted in different time slots over different antennas. This provides an estimate of the user signal power. Consider the case with two transmit antennas in the system so that the received power from user k is

$$\delta = A^2_{s_0^k} + A^2_{s_1^k}, \tag{1}$$

where $A_{s_0^k}$ and $A_{s_1^k}$ are the amplitudes of the decorrelated signals s_0^k and s_1^k from the two transmit antennas. With a

Rayleigh fading channel, we have

$$\delta = \left| h_{k0}\sqrt{E_{k0}} \right|^2 + \left| h_{k1}\sqrt{E_{k1}} \right|^2, \tag{2}$$

where $h_{k0} = \alpha_{k0}e^{j\theta_{k0}}$ and $h_{k1} = \alpha_{k1}e^{j\theta_{k1}}$ are the complex channel (fading) impulse responses from the two transmit antennas to user k. Assuming every user has the same transmit energy E, and combining the near-far effect into the parameter α, we can ignore E and rewrite the criterion as

$$\delta = \left| \alpha_{k0} \right|^2 + \left| \alpha_{k1} \right|^2. \tag{3}$$

This criterion is justified by the analysis in the following section.

3. ANALYSIS OF HARD DECISION SIC WITH STBC

For simplicity, and without loss of generality, we assume here that the system has two transmit antennas and one receive antenna. The extension to other numbers of antennas is straightforward. In the transmitter, two signals s_0^k and s_1^k are simultaneously transmitted from the two antennas (Tx_0 and Tx_1, respectively), in the first of the two STBC symbol periods for each of the K users. In the following symbol period, $-s_1^{k*}$ is transmitted from antenna Tx_0 and s_0^{k*} is transmitted from antenna Tx_1, where $*$ denotes complex conjugation. Putting this in matrix form gives

$$\begin{bmatrix} Tx_0(t) & Tx_1(t) \\ Tx_0(t+T) & Tx_1(t+T) \end{bmatrix} = \begin{bmatrix} +s_0^k & +s_1^k \\ -s_1^{k*} & +s_0^{k*} \end{bmatrix}. \tag{4}$$

Here we let $h_{k0}(t)$ denote the channel response from antenna Tx_0 to the receiver of user k, and $h_{k1}(t)$ the channel response from antenna Tx_1 to the receiver of user k. We assume that the channel is constant across two consecutive symbols. The received signals for user k are

$$\begin{aligned} r_0^k &= r^k(t) = h_{k0}s_0^k + h_{k1}s_1^k + n_0, \\ r_1^k &= r^k(t+T) = -h_{k0}s_1^{k*} + h_{k1}s_0^{k*} + n_1, \end{aligned} \tag{5}$$

where r_0^k and r_1^k are the received signals at time t and $t+T$, respectively, T is the symbol period, and n_0 and n_1 are AWGN with zero mean and variance σ_n^2. The received signals are combined to give

$$\begin{aligned} \hat{s}_0^k &= h_{k0}^* r_0^k + h_{k1} r_1^{k*} = (\alpha_{k0}^2 + \alpha_{k1}^2)s_0^k + h_{k0}^* n_0 + h_{k1} n_1^*, \\ \hat{s}_1^k &= h_{k1}^* r_0^k - h_{k0} r_1^{k*} = (\alpha_{k0}^2 + \alpha_{k1}^2)s_1^k + h_{k1}^* n_0 - h_{k0} n_1^*, \end{aligned} \tag{6}$$

and are input to a maximum likelihood detector, which minimizes the decision metric

$$\left| r_0^k - h_{k0}s_0^k - h_{k1}s_1^k \right|^2 + \left| r_1^k + h_{k0}s_1^{k*} - h_{k1}s_0^{k*} \right|^2 \tag{7}$$

over all possible values of s_0^k and s_1^k.

Now we consider a multiuser DS-CDMA system with STBC. The modulation is QPSK which contains BPSK signals on the I and Q branches. For CDMA chip l, the received signal in the first STBC time slot at the receiver input is

$$\begin{aligned} r_{0l}(t) = {} & \sqrt{E_c}\sum_{k=1}^{K} h_{k0}C_{kl}(t-\tau_{k0})s_0^k(t-\tau_{k0}) \\ & + \sqrt{E_c}\sum_{k=1}^{K} h_{k1}C_{kl}(t-\tau_{k0})s_1^k(t-\tau_{k1}) + n_0(t), \end{aligned} \tag{8}$$

and in the next STBC time slot the received signal is

$$\begin{aligned} r_{1l}(t) = {} & \sqrt{E_c}\sum_{k=1}^{K} h_{k0}C_{kl}(t-\tau_{k0})s_1^{k*}(t-\tau_{k0}) \\ & - \sqrt{E_c}\sum_{k=1}^{K} h_{k1}C_{kl}(t-\tau_{k0})s_0^{k*}(t-\tau_{k1}) + n_1(t), \end{aligned} \tag{9}$$

where E_c is the energy of a CDMA chip, K is the number of active users, $h_{k0} = \alpha_{k0}e^{j\theta_{k0}}$ and $h_{k1} = \alpha_{k1}e^{j\theta_{k1}}$ are the complex channel responses from the two transmit antennas to user k, $\alpha \in R$ and $\theta \in [0, 2\pi)$, s_0^k and s_1^k are the transmitted signals from the two antennas for user k. $C_{kl}(t-\tau_{k0})$ is the lth chip of the DS-CDMA spreading code for the kth user. τ_{k0} and τ_{k1} are the system delays for the user k signals from the two transmit antennas. AWGN is denoted by $n_0(t)$ and $n_1(t)$. We consider uplink asynchronous transmission. Without loss of generality, we consider the performance of the first user. The demodulator lowpass filter (LPF) output for any l in the STBC time slots are (see [9])

$$\begin{aligned} d_{0l}(t) = {} & \sqrt{E_c}\sum_{k=1}^{K} \frac{h_{k0}C_{kl}(t-\tau_{k0})s_0^k(t-\tau_{k0})}{2} \\ & + \sqrt{E_c}\sum_{k=1}^{K} \frac{h_{k1}C_{kl}(t-\tau_{k1})s_1^k(t-\tau_{k1})}{2} + \frac{n_0(t)}{2}, \\ d_{1l}(t) = {} & \sqrt{E_c}\sum_{k=1}^{K} \frac{h_{k0}C_{kl}(t-\tau_{k0})s_1^{k*}(t-\tau_{k0})}{2} \\ & - \sqrt{E_c}\sum_{k=1}^{K} \frac{h_{k1}C_{kl}(t-\tau_{k1})s_0^{k*}(t-\tau_{k1})}{2} + \frac{n_1(t)}{2}. \end{aligned} \tag{10}$$

The decorrelator output for symbol s_0^1 is

$$Z_0 = \sum_{l=0}^{G-1} d_{0l}(t)C_{1l}(t-\tau_{10}). \tag{11}$$

For simplicity, we rewrite the decorrelator output as

$$Z_0 = S_0 + \mathrm{MAI}_0 + N_0, \tag{12}$$

where S_0 denotes the signal we want to decode, MAI_0 denotes the multiple access interference, and N_0 denotes AWGN. Since we consider flat fading, the fading for one STBC codeword is the same. For the second time slot we have

$$\begin{aligned} Z_1 &= \sum_{l=0}^{G-1} d_{1l}(t)C_{1l}(t-\tau_{11}) \\ &= S_1 + \mathrm{MAI}_1 + N_1. \end{aligned} \tag{13}$$

For $k = 1$, we have

$$
\begin{aligned}
S_0 &= \frac{\sqrt{E_s}}{2} h_{10} s_0^1(t-\tau_{10}) \\
&\quad + \frac{\sqrt{E_s}}{2} h_{11} s_1^1(t-\tau_{11}) I_{1,1}(\tau_{10}-\tau_{11}), \\
S_1 &= -\frac{\sqrt{E_s}}{2} h_{11} s_0^{1*}(t-\tau_{11}) \\
&\quad + \frac{\sqrt{E_s}}{2} h_{10} s_1^{1*}(t-\tau_{k0}) I_{1,1}(\tau_{10}-\tau_{11}),
\end{aligned} \tag{14}
$$

where

$$I_{i,k}(\tau) = \frac{1}{T}\int_0^T C_i(t-\tau)C_k(t)dt, \tag{15}$$

and E_s is the symbol energy with $E_s = GE_c$. Note that $I_{i,k}(\tau)$ is a real value so that (see [4])

$$\frac{\sqrt{E_s}}{2}(\alpha_{k0}^2 + \alpha_{k1}^2)s_0^k = h_{k0}^* S_0 - h_{k1} S_1^*, \tag{16}$$

and then

$$
\begin{aligned}
\hat{s}_0^1 &= h_{10}^*(S_0 + \mathrm{MAI}_0 + N_0) - h_{11}(S_1 + \mathrm{MAI}_1 + N_1)^* \\
&= \sqrt{E_s}(\alpha_{10}^2 + \alpha_{11}^2)s_0^1 + h_{10}^* \mathrm{MAI}_0 - h_{11} \mathrm{MAI}_1^* \\
&\quad + h_{10}^* N_0 - h_{11} N_1^*.
\end{aligned} \tag{17}
$$

The multiple access interference and noise in the first time slot of an STBC codeword are given by

$$
\begin{aligned}
\mathrm{MAI}_0 &= \frac{\sqrt{E_s}}{2}\sum_{k=2}^{K} h_{k0} s_0^k(t-\tau_{k0}) I_{k,1}(\tau_{10}-\tau_{k0}) \\
&\quad + \frac{\sqrt{E_s}}{2}\sum_{k=2}^{K} h_{k1} s_1^k(t-\tau_{k1}) I_{k,1}(\tau_{10}-\tau_{k1}), \\
N_0 &= \frac{1}{T}\int_0^T \frac{n_0(t)}{2} C_1(t-\tau_{10})dt,
\end{aligned} \tag{18}
$$

respectively, and for the next time period,

$$
\begin{aligned}
\mathrm{MAI}_1 &= \frac{\sqrt{E_s}}{2}\sum_{k=2}^{K} -h_{k1} s_0^{k*}(t-\tau_{k1}) I_{k,1}(\tau_{11}-\tau_{k1}) \\
&\quad + \frac{\sqrt{E_s}}{2}\sum_{k=2}^{K} h_{k0} s_1^{k*}(t-\tau_{k0}) I_{k,1}(\tau_{k0}-\tau_{11}), \\
N_1 &= \frac{1}{T}\int_1^T \frac{n_1(t)}{2} C_1(t-\tau_{10})dt.
\end{aligned} \tag{19}
$$

Now let

$$
\begin{aligned}
\mathrm{MAI} &= h_{k0}^* \mathrm{MAI}_0 - h_{k1}^* \mathrm{MAI}_1^*, \\
N &= h_{k0}^* N_0 - h_{k1}^* N_1^*.
\end{aligned} \tag{20}
$$

The amplitude of the STBC decoded signal is then

$$A_{s_0^1} = \frac{\sqrt{E_s}}{2}(\alpha_{k0}^2 + \alpha_{k1}^2), \tag{21}$$

so that the power of the received signal s_0^1 is

$$\sigma_A^2 = \frac{E_s(\alpha_{10}^2 + \alpha_{11}^2)^2}{4}. \tag{22}$$

Based on [10], and assuming that every user has the same transmit power, we can estimate the MAI power. For an asynchronous system, the variance of the signal cross-correlations is given by

$$\sigma_I^2 = \mathrm{Var}[I(\tau_{11}-\tau_{k1})] = \frac{1}{3G}, \tag{23}$$

The interfering MAI signal power is

$$\sigma_{\mathrm{MAI}}^2 = \frac{E_s(\alpha_{10}^2 + \alpha_{11}^2)\sum_{k=2}^{K}(\alpha_{k0}^2 + \alpha_{k1}^2)}{12G}, \tag{24}$$

and the AWGN power is

$$\sigma_N^2 = \frac{(\alpha_{10}^2 + \alpha_{11}^2)N_0}{8}. \tag{25}$$

According to [1], the SNR is then

$$
\begin{aligned}
\gamma &= \frac{\sigma_A^2}{\sigma_{\mathrm{MAI}}^2 + \sigma_N^2} \\
&= \frac{\alpha_{10}^2 + \alpha_{11}^2}{\sum_{k=2}^{K}(\alpha_{k0}^2 + \alpha_{k1}^2)/3G + 1/2(E_s/N_0)},
\end{aligned} \tag{26}
$$

and the BER of the STBC DS-CDMA system is

$$P_e = \int_{-\infty}^{0} f_{\hat{s}}(t)dt = Q(\sqrt{\gamma}), \tag{27}$$

where $Q(\cdot)$ is the Q-function.

Now we consider the system performance with SIC. At iteration v (after $k-1$ cancellations), the decision variable for the kth user is (see [9])

$$\hat{s}_0^k = \frac{E_s}{2}(\alpha_{k0}^2 + \alpha_{k1}^2) + \mathrm{MAI}_k + N_k, \tag{28}$$

where $v = k$, and

$$
\begin{aligned}
\gamma &= \frac{\sigma_{A_k}^2}{\sigma_{\mathrm{MAI}_k}^2 + \sigma_{N_k}^2} \\
&= \frac{\alpha_{k0}^2 + \alpha_{k1}^2}{\sum_{k=k+1}^{K}(\alpha_{k0}^2 + \alpha_{k1}^2)/3G + 1/2(E_s/N_0)}.
\end{aligned} \tag{29}
$$

From (29), we see that MAI and noise cause poor performance, and the spreading gain G is important to combat multiuser interference. Here we assume the interference cancellation in the previous iterations is perfect. Note that in the later iterations, when the remaining signals are weak, we have less MAI. Also note that the power of the decoded signal $\alpha_{k0}^2 + \alpha_{k1}^2$ fits the requirements of our technique since $\alpha_{k0}^2 + \alpha_{k1}^2$ is the signal power used as the criterion for the initial sorting.

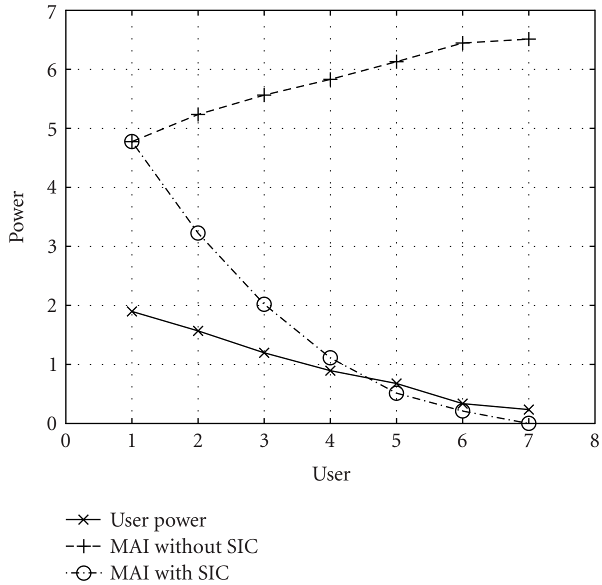


Figure 3: Signal and MAI power versus number of users with and without SIC.

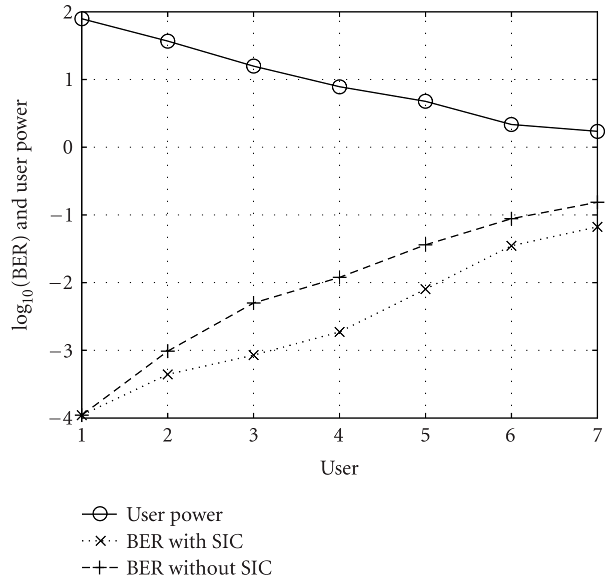
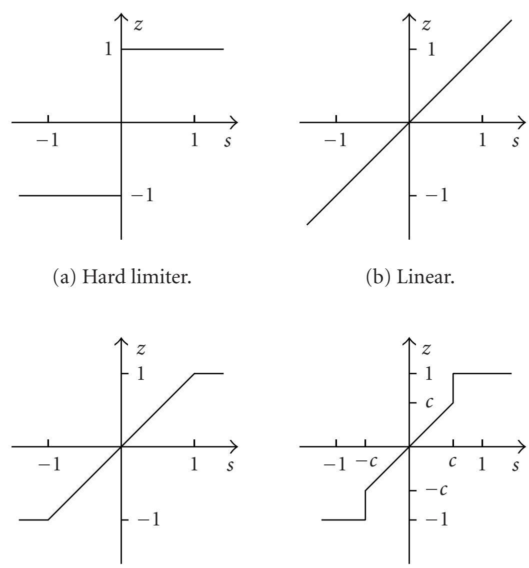


Figure 4: BER versus number of users for DS-CDMA with SIC and an STBC.

We now consider an example of our SIC technique. The spreading gain is $G = 31$ and there are 7 active users. The near-far ratio is 8 dB, and E_b/N_0 is 7 dB. We consider a Rayleigh fading channel which is flat during one codeword of the STBC. Figure 3 presents the MAI power after different stages of SIC cancellation. In the figure the solid line is the power of the individual users in decreasing order, the dashed line is the MAI for each user without SIC, and the dashed-dotted line is the MAI for each user with SIC. From Figure 3, it is clear that the MAI is greatly reduced by the new SIC technique, the weak user signals have less MAI interference, and hence will have better performance. The simulation results are identical to those obtained via the analysis (29).

Figure 4 shows the BER performance of the system. In the figure the solid line is the power of the individual users in decreasing order, the dashed line is the BER for each user without SIC, and the dotted line is the BER for each user with SIC. Figure 4 shows that the BER is greatly improved by our SIC technique except for the strongest user. Since weak user signals have less MAI interference, their BER performance will be limited to a large extent by AWGN.



(a) Hard limiter. (b) Linear.

(c) Unit clipper. (d) Zha's decision function.

Figure 5: Hard, soft, and hybrid decision SIC functions.

4. SOFT DECISION SIC FOR DS-CDMA WITH STBC

Much effort has been expended since the first SIC algorithm was proposed to improve the performance of CDMA systems. Hard decision SIC, as shown in Figure 5a [11], can completely cancel the MAI interference when the hard decisions are correct, but error propagation is a significant problem since weak users will by definition have a high BER. Soft techniques such as linear decision [3], shown in Figure 5b, produce no error propagation but cannot significantly reduce the MAI interference, so the performance is often inadequate. To get both good MAI reduction for strong user signals and good SIC cancellation for weak users, many hybrid algorithms have been proposed. As shown in Figure 5c [11] and Figure 5d [10], these algorithms combine the advantages of hard and soft decision functions, so that when the signal is strong, a hard decision is made and SIC cancels all the MAI, but when the signal is weak, a soft decision is made to cancel part of the MAI and avoid error propagation.

The results in Section 3 show that the BER of weak users is relatively poor, and this may cause error propagation with

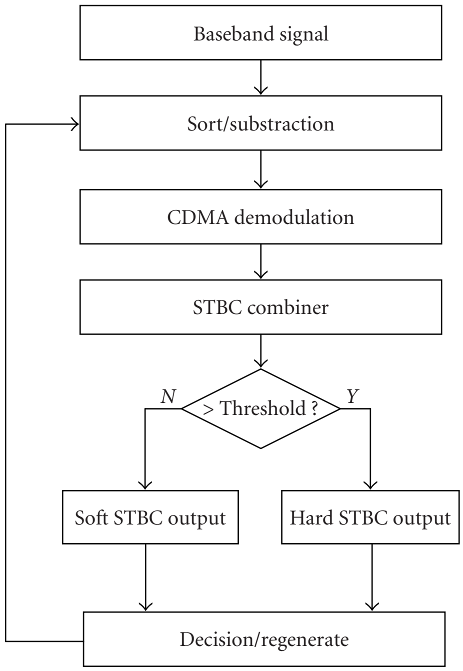


Figure 6: Soft-decision SIC for DS-CDMA with a soft STBC decoder.

SIC, which will degrade performance. To improve the performance and prevent error propagation, we introduce a soft-decision multistage STBC SIC scheme based on Sections 2 and 3, as well as the work of Zha and Blostein [10]. We use the system architecture described in Section 2 and apply the new sorting criterion to this system. The SIC algorithm employed combines soft and hard decisions to get better BER performance. The new technique is shown in Figure 6 for one user within one stage.

Now consider an STBC system with M transmit antennas and N receive antennas, and use the STBC introduced in [6, 7]. An STBC codeword is a matrix with M columns and L rows. After DS-CDMA decorrelation, the transmitted data block is a matrix with GL rows and M columns. The received signal for antenna j is

$$r_j = \sum_{l=1}^{GL}\sum_{k=1}^{K}\sum_{i=1}^{M} h_{ij}s_i^k(t-lP-\tau_i^k)C(t-lP-\tau_i^k)+n_j(t), \tag{30}$$

where P is the CDMA chip time, $s_0^k(t)$ is the transmitted signal, $C(t)$ is the CDMA spreading code, and h_{ij} is the complex channel gain between transmit antenna i and receive antenna j. From Figure 6, after sorting, all signals other than the user being detected are cancelled using the previous results from the current stage for those users stronger than the desired user, and the results from the previous stage for those users weaker than the desired user (if after the first stage). Next, the CDMA signal is decorrelated and passed to the STBC decoder. The STBC decoder outputs soft values to the decision function. According to the threshold, a hard or soft decision is made, and the algorithm continues with the next user.

In our system, the control parameter q is defined as the normalized amplitude of the STBC decoder output. As shown in Figure 5d, the decision function is (see [10])

$$f(s)=\begin{cases}1, & q>c,\\ q, & q\in[-c,c],\\ -1, & q<-c.\end{cases} \tag{31}$$

When q is greater than the threshold c, hard decision SIC is used to get the best interference cancellation, and when q is lower than the threshold c, we use soft decision SIC to improve the performance and at the same time avoid error propagation. Hard SIC was discussed in Section 3, so here we introduce the soft output portion of the proposed SIC technique.

A normalized soft output STBC decoder is employed here. The proposed SIC algorithm requires a soft output without the channel effects, hence the normalized outputs are

$$\begin{aligned}\hat{q}_0^k &= \frac{h_{k0}^* r_0^k + h_{k1} r_1^{k*}}{\alpha_{k0}^2+\alpha_{k1}^2} = s_0^k + \frac{h_0^*}{\alpha_{k0}^2+\alpha_{k1}^2}n_0 + \frac{h_{k1}}{\alpha_{k0}^2+\alpha_{k1}^2}n_1^*,\\ \hat{q}_1^k &= \frac{h_{k1}^* r_0^k - h_{k0} r_1^{k*}}{\alpha_{k0}^2+\alpha_{k1}^2} = s_1^k + \frac{h_1^*}{\alpha_{k0}^2+\alpha_{k1}^2}n_0 - \frac{h_{k0}}{\alpha_{k0}^2+\alpha_{k1}^2}n_1^*.\end{aligned} \tag{32}$$

Note that we have assumed perfect knowledge of the channel so that amplitude estimation is not considered. Assuming there are V stages in the receiver, in the νth stage ($1 \le \nu \le V$), the steps of the new SIC algorithm are as follows [10].

(1) Estimate the received signal for the desired user bit by bit in one STBC codeword. For any bit, the received signal is estimated by subtracting the regenerated signals for all other users from the received signal. The bit is then decorrelated in the CDMA decoder. Let Γ^ν denote the signal after the νth stage of SIC cancellation:

$$\begin{aligned}\Gamma^\nu = \Gamma^0 &- \sum_{l=1}^{GL}\sum_{k=1}^{k-1}\sum_{i=1}^{M} h_{ij}s_0^k(t-lP-\tau_i^k)^\nu C(t-lP-\tau_i^k)\\ &- \sum_{l=1}^{GL}\sum_{k=k+1}^{K}\sum_{i=1}^{M} h_{ij}s_0^k(t-lP-\tau_i^k)^{\nu-1} C(t-lP-\tau_i^k).\end{aligned} \tag{33}$$

In the equation above, $s_0^k(t)^\nu$ is the amplitude of the regenerated signals from the previous iteration of the same stage for those users stronger than the νth user, and $s_0^k(t)^{\nu-1}$ is the amplitude of the regenerated signals from the results of the previous stage for those users weaker than the νth user.

(2) STBC decoding is performed; details of the algorithm can be found in [6, 7]. The soft output is normalized and passed on to the decision function.

(3) For each bit, the decision function makes a decision, either soft (except for the last stage) or hard, according to the threshold. The signal is regenerated for the next user or for the next SIC stage.

5. ANALYSIS OF SOFT DECISION SIC WITH STBC

In this section, we analyze the performance of hard/soft decision multistage SIC introduced in Section 4. We consider the system performance after convergence, which is typically reached after 4–5 stages as shown by the simulation results in the next section. After the system converges, the residual interference can be assumed to be Gaussian distributed, and the interference from individual users to be mutually independent [10, 12]. We denote the interference variance of user k by σ_k^2, and the channel noise variance by σ_n^2. The total interference and noise variance at the input of the CDMA correlator is (see [10, 12])

$$\sigma^2 = \sum_{k=1}^{K} \sigma_k^2 + \sigma_n^2, \tag{34}$$

where σ_k^2 includes the interference power of user k from all M transmit antennas. After decorrelation, the variance of the reconstructed signal of user k is

$$\sigma_k^2 = \frac{\sigma^2}{G}. \tag{35}$$

After STBC decoding, and noting that it is a linear algorithm, we have

$$\hat{\sigma}_k^2 = \frac{1}{\sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2} \sigma_k^2 = \frac{1}{\sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2} \frac{\sigma^2}{G}, \tag{36}$$

and after convergence, we have

$$\sigma^2 = \sum_{k=1}^{K} \frac{1}{\sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2} \frac{\sigma^2}{G} + \sigma_n^2. \tag{37}$$

Rearranging (37) gives

$$\begin{aligned} \sigma^2 &= K \frac{1}{G \sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2} \sigma^2 + \sigma_n^2 \\ &= \frac{1}{1 - K/G \sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2} \sigma_n^2. \end{aligned} \tag{38}$$

Note that $\sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2$ is the power due to the transmit diversity.

Next the MAI power is calculated [8]. Assume the amplitude of the soft output from the STBC decoder for user k is a_k. Without loss of generality, we can assume the transmitted signal is +1. The normalized output of the STBC decoder can be modeled as a Gaussian random variable with mean a_k and variance σ^2. As in [8], we have three different possibilities, namely, when $a_k > c$, a hard and correct decision is made; when $-c \le a_k \le c$, a soft decision is made, and when $a_k < -c$, a hard decision is made but it is a wrong decision. These possibilities are considered below.

(1) $a_k > c$, with probability $1 - Q((1-c)/\sigma)$. Since we assume perfect knowledge of the channel, we can estimate the amplitude accurately. Thus complete interference cancellation can be obtained and

$$\mathrm{Var}_1 = 0. \tag{39}$$

(2) $-c \le a_k \le c$, with probability $Q((1-c)/\sigma) - Q((1+c)/\sigma)$. Since the output is linear, we have

$$\mathrm{Var}_2 = \frac{\sigma^2}{G \sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2}. \tag{40}$$

(3) $a_k < -c$, with probability $Q((1+c)/\sigma)$. In this case, the resulting noise variance is a function of twice the amplitude of the received signal. After decorrelation, the interference noise power is

$$\mathrm{Var}_3 = \frac{(2a_k)^2}{G \sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2}. \tag{41}$$

Combining all three possibilities, and letting

$$\alpha = \sum_{m=1}^{M} \sum_{n=1}^{N} \alpha_{m,n}^2, \tag{42}$$

gives

$$\begin{aligned} \sigma_k^2(a_k) &= \left[Q\left(\frac{1-c}{\sigma}\right) - Q\left(\frac{1+c}{\sigma}\right) \right] \frac{\sigma^2}{G\alpha} \\ &\quad + Q\left(\frac{1+c}{\sigma}\right) \frac{(2a_k)^2}{G\alpha}, \end{aligned} \tag{43}$$

so that

$$\begin{aligned} \sigma^2 &= \sum_{k=1}^{K} \left\{ \left[Q\left(\frac{1-c}{\sigma}\right) - Q\left(\frac{1+c}{\sigma}\right) \right] \frac{\sigma^2}{G\alpha} \right. \\ &\quad \left. + Q\left(\frac{1+c}{\sigma}\right) \frac{(2a_k)^2}{G\alpha} \right\} + \sigma_n^2. \end{aligned} \tag{44}$$

Assuming perfect power control, that is, all user signals have the same amplitude $a_k = a$, results in

$$\begin{aligned} \sigma^2 &= K \left\{ \left[Q\left(\frac{1-c}{\sigma}\right) - Q\left(\frac{1+c}{\sigma}\right) \right] \frac{\sigma^2}{G\alpha} \right. \\ &\quad \left. + Q\left(\frac{1+c}{\sigma}\right) \frac{(2a)^2}{G\alpha} \right\} + \sigma_n^2. \end{aligned} \tag{45}$$

Using the above results, Figure 7 shows the equivalent system SNR loss due to MAI, with $E_b/N_0 = 3$ dB, $G = 31$, 20 users in the system ($K = 20$), and the threshold of the hard/soft SIC algorithm set to $c = 0.7$. In the figure, the dashed line is SNR loss with one receiver, and the dotted line is the loss with two receivers. From Figure 7 we see that the SNR loss is lower with an STBC because the STBC decoder reduces the interference noise.

6. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed hard/soft SIC algorithm. We use two-branch transmit diversity with the two-branch receiver introduced in [6]. DS-CDMA as given in [9] and QPSK modulation are employed with a spreading gain of $G = 31$. The near-far ratio

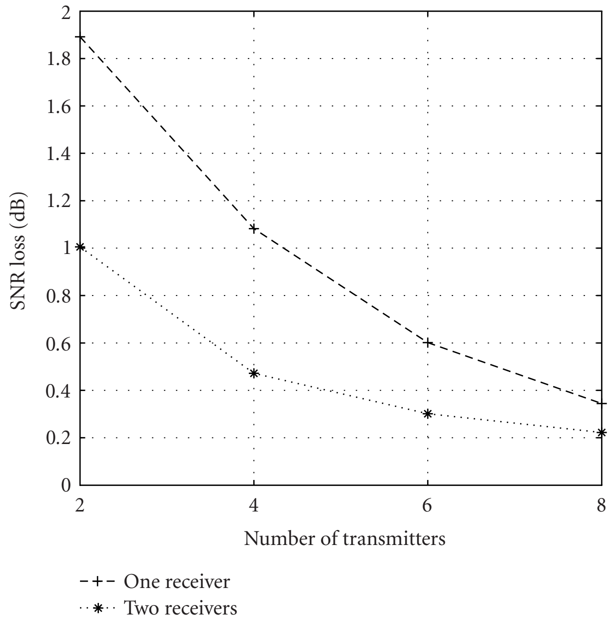


FIGURE 7: SNR loss due to multiple access interference.

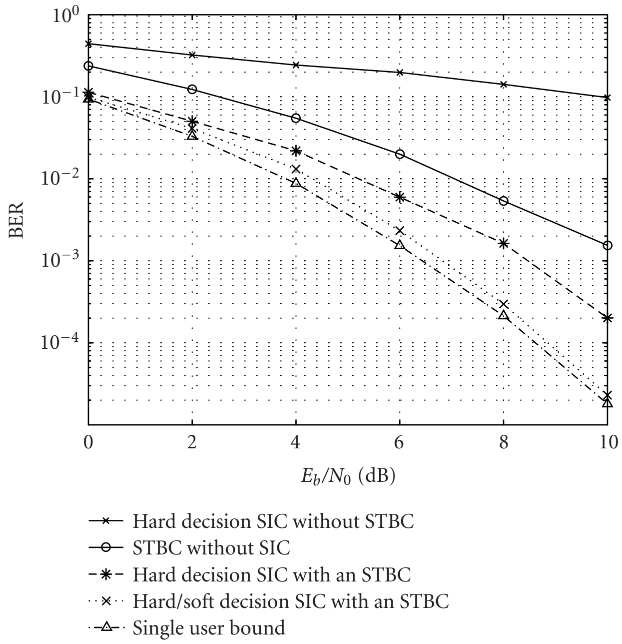


FIGURE 8: BER performance of hard/soft SIC with DS-CDMA and an STBC.

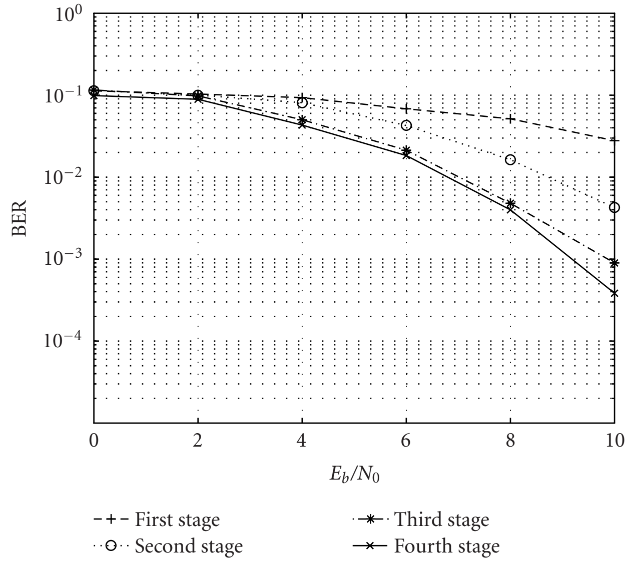


FIGURE 9: BER performance of 1–4 soft SIC stages with DS-CDMA and an STBC.

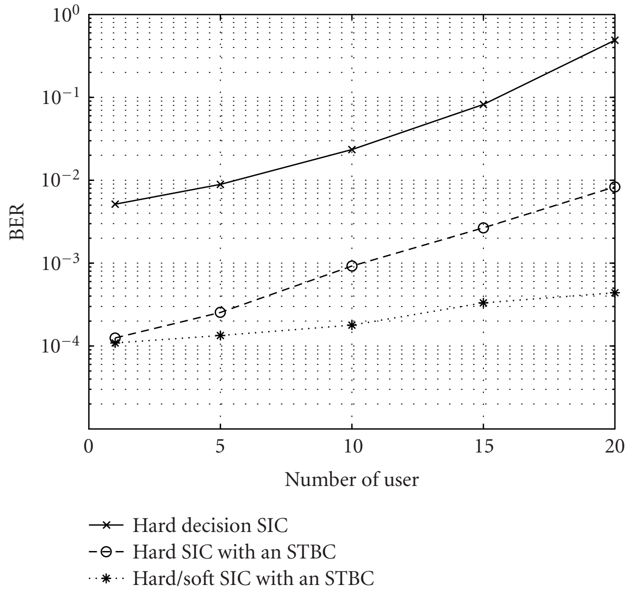


FIGURE 10: BER performance versus number of users.

is 10 dB, which is defined as the ratio between the power of the strongest user and that of the weakest user. The threshold for hard/soft SIC is set to $c = 0.7$. We consider the performance of the weakest user. We assume a Rayleigh fading channel which is flat during one codeword of the STBC.

Figure 8 shows the BER performance with 20 users ($K = 20$). In this figure, the solid line with "x" is the BER of hard decision SIC without an STBC; the solid line with "o" is the BER without SIC in the CDMA system, but with an STBC; the dashed line is the BER of hard decision SIC with STBC; and the dotted line is the BER of hard/soft decision SIC with an STBC. The dashed-dotted line is the single user bound, which shows that when E_b/N_0 is 3 dB, the equivalent SNR loss is about 1 dB, which fits well with the analysis in the previous section. Figure 8 clearly shows a BER improvement with an STBC and soft decision SIC.

Figure 9 presents the BER at different stages of hard/soft SIC with 30 users ($K = 30$). This shows that the system convergences after four stages.

Figure 10 shows the BER versus the number of users in the system with $E_b/N_0 = 7$ dB. In the figure, the solid line is the BER of hard decision SIC without an STBC; the dashed line is the BER of hard decision SIC with an STBC, and the dotted line is the BER of hard/soft decision SIC with an STBC. From this figure we see that the BER increases as the number of users increases, but an STBC and SIC greatly improve performance.

With conventional SIC, system performance is very sensitive to the initial bit estimates. Also, the sorting operation (which needs to be performed at the beginning of each bit interval) results in significant computational requirements. Our technique increases the reliability of the SIC algorithm by introducing an STBC in the interference cancellation loop, and also lowers the MUD complexity by halving the number of sorting operations. If accurate channel estimation is available, and every user has approximately the same transmit power, the sorting can be done with very little effort since the received power can easily be estimated from the channel information.

7. SUMMARY

In this paper we have introduced a new SIC technique for a DS-CDMA system with transmit diversity. An analysis of the performance of this system was presented. Simulation was used to verify the analysis. This algorithm can also be used for similar systems such as parallel interference cancellation.

REFERENCES

[1] J. G. Proakis, *Digital Communications*, McGraw-Hill, New York, NY, USA, 3rd edition, 1995.

[2] S. Verdú, "Minimum probability of error for asynchronous Gaussian multiple-access channels," *IEEE Transactions on Information Theory*, vol. 32, no. 1, pp. 85–96, 1986.

[3] P. Patel and J. M. Holtzman, "Analysis of a simple successive interference cancellation scheme in a DS/CDMA system," *IEEE Journal on Selected Areas in Communications*, vol. 12, no. 5, pp. 796–807, 1994.

[4] D. Koulakiotis and A. H. Aghvami, "Data detection techniques for DS/CDMA mobile systems: a review," *IEEE Personal Communications*, vol. 7, no. 3, pp. 24–34, 2000.

[5] M. K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," *IEEE Trans. Communications*, vol. 38, no. 4, pp. 509–519, 1990.

[6] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[7] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[8] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *IEEE Transactions on Information Theory*, vol. 44, no. 2, pp. 744–765, 1998.

[9] P. R. Patel and J. M. Holtzman, "Analysis of a DS/CDMA successive interference cancellation scheme using correlations," in *Proc. IEEE Global Telecommunications Conference*, pp. 76–80, Houston, Tex, USA, November 1993.

[10] W. Zha and S. D. Blostein, "Soft-decision multistage multiuser interference cancellation," *IEEE Trans. Vehicular Technology*, vol. 52, no. 2, pp. 380–389, 2003.

[11] L. B. Nelson and H. V. Poor, "Iterative multiuser receivers for CDMA channels: an EM-based approach," *IEEE Trans. Communications*, vol. 44, no. 12, pp. 1700–1710, 1996.

[12] R. M. Buehrer and B. D. Woerner, "Analysis of adaptive multistage interference cancellation for CDMA using an improved Gaussian approximation," *IEEE Trans. Communications*, vol. 44, no. 10, pp. 1308–1321, 1996.

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