# THE PERFORMANCE OF SPACE-TIME CODED COOPERATIVE DIVERSITY IN AN ASYNCHRONOUS CELLULAR UPLINK

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## ABSTRACT

*Most of the prior work on cooperative diversity assumes allocation of orthogonal channels to multiple users (inter-user orthogonality) and synchronous communication between the signals transmitted from different cooperating terminals in the network. Both of these assumptions may require an accurate coordination among the cooperating users causing significant overhead in wireless networks. The main purpose of this paper is to investigate the impact of inter-user non-orthogonality and asynchronous communication on the information-outage probability performance of multi-user space-time coded cooperative diversity in a cellular uplink. We also present a practical system design and we provide bit-error-probability simulations under the practical adaptive receiver design.*

## INTRODUCTION

Recently, cooperative diversity, which generalizes the conventional multiple-antenna system, has generated a great deal of interest in the research community. It virtually creates an antenna array via cooperation of single antenna mobile units.

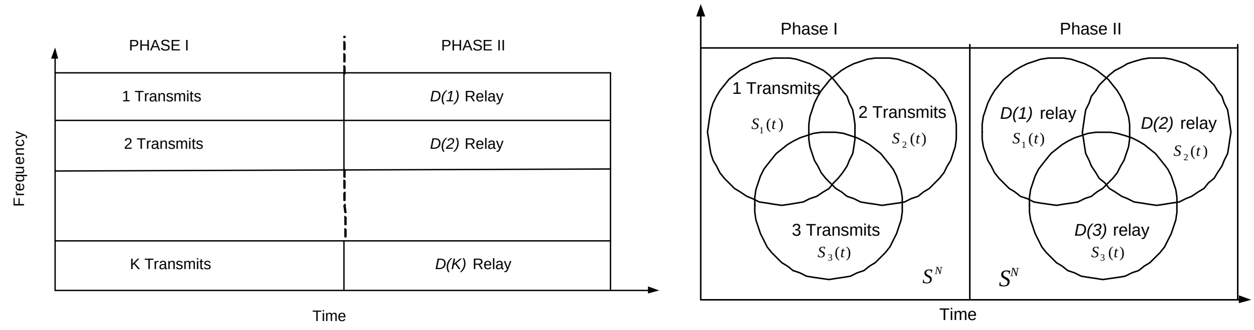
In [1], the authors develop a full-duplex, two-user sharing protocol for the code-division-multiple access (CDMA) cellular uplink. But the assumption of orthogonal spreading codes limits flexibility of the scheme. Also choosing orthogonal codes does not achieve orthogonality in asynchronous channels. In [2], the authors develop space-time coded decode-and-forward (DF) protocols for combating multipath fading in wireless networks and present information-outage probability analysis of these protocols. The medium access control protocol suggested in [2] allocates orthogonal (frequency) channels to the transmitting terminals. The authors in [3, 4, 5] present various channel coding schemes for cooperative networks. The previously established work on cooperative communication is based upon orthogonal channel allocation to different users, i.e., inter-user orthogonality and an assumption of synchronous communication between the signals transmitted from different cooperating terminals in the network. The issue of non-orthogonal channel allocation in the context cooperation has been addressed in [6, 7]. The authors in [6] consider cooperative schemes with single source-destination pair and multiple relays that do not require orthogonal channelization between relays and symbol-level timing synchronization and design a minimum-mean-squared-error (MMSE) receiver. In [7], the authors employ adaptive DF schemes in the absence of orthogonal channelization.

Our main contributions in this paper are as follows:

1. We propose a space-time coded cooperative diversity protocol that operates in an asynchronous CDMA cellular uplink while relaxing the inter-user orthogonality constraint.
2. We analyze the information-outage probability performance of the proposed protocol in three special cases: underloaded CDMA, fully-loaded CDMA and overloaded CDMA system configuration.
3. We present a practical system design including design of adaptive base-station receiver structure and provide bit-error-rate (BER) simulations for practical, noisy inter-user channels.

We compare the outage probability performance of the proposed scheme with that of Laneman's space-time coded protocol [2][1] which builds upon inter-user orthogonality and accurate synchronous communication assumptions. The comparison demonstrates the loss in spectral efficiency of the proposed protocol with respect to Laneman's space-time coded protocol due to non-orthogonal spreading code assignment to each user (which introduces inter-user non-orthogonality) and sub-optimal space-time coding and reception method used in our scheme. But these assumptions make our system practical and more flexible. The

[1] Since we compare the performance of our space-time coded protocol with that of Laneman, we will use similar terminology as given in his paper [2].




(a) (b)

Figure 1: Space-time coded medium access control for a) Laneman's protocol, and b) the proposed cooperation scheme. Figure indicates example channel allocations across spreading codes and time for the 3 user case. For user $k \in \{1, 2, \ldots, K\}$, $\mathcal{D}(k)$ denotes the decoding set. $\mathcal{S}^N$ is the $N$ dimensional code space, where $N$ is the processing gain. The non-orthogonal spreading waveforms of 3 users are denoted by $s_1(t), s_2(t)$, and $s_3(t)$.

protocol developed here leads to fully distributed cooperation where no inter-user coordination is required and greatly simplifies the medium access control protocol design.

## PROTOCOL DESIGN

We consider a CDMA cellular uplink consisting of $K$ users. The protocol description differs from [2] in medium-access control requirements and also in multiple access strategy. Each user is assigned a single spreading code. The spreading codes provide processing gain $N$ and are not assumed orthogonal. Fig. 1(b) depicts channel and subchannel allotments for the space-time coded CDMA cooperative scheme. The channel representing a single spreading code spans two time-phases and when split into individual time phases corresponds to subchannels. The transmission between users and the base station is accomplished in two orthogonal time-phases. In the first phase, user $k \in \{1, 2, ..K\}$ transmits to the base-station on its spreading code (i.e., in the appropriate subchannel). In the second phase, the users that can decode $k$-th user's transmission form a decoding set $\mathcal{D}(k)$ and serve as relays ($r$). The relays then transmit to the base-station asynchronously on source terminal's spreading code using a space-time code or delay diversity technique. Thus for space-time coded cooperative diversity, all relay transmissions occur in the same subchannel. Note that since spreading codes are non-orthogonal, and we assume asynchronous communication between signals transmitted from cooperating users, we have non-orthogonality across the subchannels and also within a subchannel[2]. The crux of the problem is then to evaluate performance under these conditions and to design practical coding and reception schemes.

[2]But note that we still have time-phase orthogonality.

## SIGNAL MODEL

The proposed sharing scheme operates in an asynchronous CDMA uplink in the presence of multiple-access interference (MAI) and intersymbol interference (ISI). The specified use of decorrelating multiuser detection at the base station effectively transforms the resulting MAI channel into parallel interference-free scalar flat fading channels with increased background noise. Using this scalar channel model with an appropriate signal-to-noise ratio ($\mathsf{SNR}$) parameterization, the proposed scheme can be compared to [2] via outage probability, i.e., the probability that average mutual information (in bits/sec/Hz) falls below a given threshold. We now develop a signal model for the second phase of transmission but we note that the signal model for the first phase of transmission can be obtained in a similar manner. The users that can decode $k$-th terminal's transmission form a decoding set $\mathcal{D}(k)$ and serve as relays. The received signal at the base-station with total $K$ users and $K' \triangleq |\mathcal{D}(k)|$ cooperating users is given by

$$r(t) = \sum_{k=1}^{K} \sum_{l \in \mathcal{D}(k)} \sum_{i=0}^{B-1} x_{l,k}[i] \alpha_l s_k(t - iT_s - \tau_l) + n(t)$$

where $B$ is the block length, $T_s$ is the symbol period, $n(\cdot)$ is the additive white Gaussian noise process, $x_{l,k}[i]$ is $k$-th user's space-time coded symbol transmitted from $l$-th cooperating user with $\mathsf{E}\{x_{l,k}^2[i]\} = P$, $\alpha_l$ (or $\alpha_{l,d}$) is the flat fading Rayleigh channel coefficient for the channel between $l$-th user and the destination (base-station) with variance $1/\lambda_l$ (or $1/\lambda_{l,d}$), $s_k(t) = \sum_{j=0}^{N-1} c_k[j]\psi(t - jT_c)$ is the spread-

$$\tilde{\boldsymbol{H}}=\begin{bmatrix} \alpha_1^*\alpha_1\rho_{11}^{11} & \cdots & \alpha_1^*\alpha_1\rho_{11}^{1K} & \cdots & \alpha_1^*\alpha_m\rho_{11}^{K1} & \cdots & \alpha_1^*\alpha_m\rho_{11}^{KK'} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_1^*\alpha_1\rho_{1K}^{11} & \cdots & \alpha_1^*\alpha_1\rho_{1K}^{1K} & \cdots & \alpha_1^*\alpha_m\rho_{1K}^{K1} & \cdots & \alpha_1^*\alpha_m\rho_{1K}^{KK'} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_m^*\alpha_1\rho_{K1}^{11} & \cdots & \alpha_m^*\alpha_1\rho_{K1}^{1K} & \cdots & \alpha_m^*\alpha_m\rho_{K1}^{K1} & \cdots & \alpha_m^*\alpha_m\rho_{K1}^{KK'} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_m^*\alpha_1\rho_{KK'}^{11} & \cdots & \alpha_m^*\alpha_1\rho_{KK'}^{1K} & \cdots & \alpha_m^*\alpha_m\rho_{KK'}^{K1} & \cdots & \alpha_m^*\alpha_m\rho_{KK'}^{KK'} \end{bmatrix}, \boldsymbol{r}=\begin{bmatrix} r_{1,1} \\ \vdots \\ r_{1,K} \\ \vdots \\ r_{K,1} \\ \vdots \\ r_{K,K'} \end{bmatrix}, \boldsymbol{x}=\begin{bmatrix} x_{1,1} \\ \vdots \\ x_{1,K} \\ \vdots \\ x_{K,1} \\ \vdots \\ x_{K,K'} \end{bmatrix} \quad (1)$$

ing waveform of $k$-th user where $c_k[j]$ is the $j$-th element of user $k$'s spreading code and $\psi(t)$ is a unit-energy transmit pulse shape waveform. Also, $\tau_l$ is the delay for the channel between $l$-th user and the destination. $\tau_l$ includes a random transmit delay for delay diversity. At the base-station, the received signal is match filtered with respect to the received waveform over the channel. By Cameron-Martin formula, this process generates sufficient statistics, $r_{k,l}[i]$ [8]. These are given by

$$r_{k,l}[i] = \alpha_l^* \int_{-\infty}^{\infty} r(t) s_k(t-\tau_l - iT_s) dt \quad (2)$$

$$= \sum_{k'=1}^{K} \sum_{l' \in \mathcal{D}(k)} \sum_{i'=0}^{B-1} x_{k',l'}[i'] \alpha_l^* \alpha_{l'} \rho_{kl}^{k'l'} \quad (3)$$

where $\rho_{kl}^{k'l'} \triangleq \int_{-\infty}^{\infty} s_k(t-\tau_l - iT_s) s_{k'}(t-\tau_{l'} - i'T_s) dt$ is the cross-correlation between delayed spreading waveforms. Stacking all match filtered outputs, we get $\boldsymbol{r} = \tilde{\boldsymbol{H}}\boldsymbol{x} + \boldsymbol{n}$ where $\boldsymbol{n} \sim \mathcal{N}_c(0, \sigma^2 \tilde{\boldsymbol{H}})$. This can further be expressed as

$$\boldsymbol{r} = \underbrace{\boldsymbol{A}\boldsymbol{R}\boldsymbol{A}^{\mathsf{H}}}_{\tilde{\boldsymbol{H}}} \boldsymbol{x} + \boldsymbol{n} \quad (4)$$

where $\boldsymbol{A}$ is a diagonal matrix and is a function of only channel gains $\alpha_i$'s, $\boldsymbol{R}$ is a function of cross-correlations between delayed signature waveforms. Applying the decorrelating detector to the discrete-time received vector $\boldsymbol{r}$, we get $\boldsymbol{y} = (\boldsymbol{A}\boldsymbol{R})^{-1}\boldsymbol{r} + \boldsymbol{v}$ where $\boldsymbol{v} \sim \mathcal{N}_c(0, \sigma^2 \boldsymbol{R}^{-1})$. Thus we get a parallel flat fading scalar channel model similar to [2],

$$y_i \triangleq [\boldsymbol{y}]_i = \alpha_i x_i + v_i, \quad (5)$$

but with enhanced noise distributed as $v_i \sim \mathcal{N}_c(0, \sigma^2 [\boldsymbol{R}]_{i,i}^{-1})$.

## COOPERATION IN CELLULAR UPLINK

We now formulate the outage probability expressions for the space-time coded cooperative diversity in an underloaded, fully-loaded and overloaded CDMA cellular uplink. We indicate different parameters such as degrees of freedom utilized by each cooperating terminal, normalized spectral efficiency and normalized discrete-time power in Table 1. Because we compare the performance of the proposed scheme to Lanneman's space-time coded protocol, we express normalized discrete-time power constraint and normalized spectral efficiency for our scheme in terms of the parameters of Laneman's protocol [2]. In Table 1, $r$ is the transmission rate in bits/sec, $R$ as defined in [2], is the spectral efficiency in bits/sec/Hz and is nothing but the transmission rate normalized by the number of degrees of freedom utilized by each terminal under Laneman's non-cooperative medium access scheme. Also, $R_{\text{CDMA}}$ is the normalized spectral efficiency in bits/sec/Hz in case of the proposed scheme and is expressed in terms of $R$ for fair comparison.

## UNDERLOADED CDMA UPLINK

For an underloaded system, $K < N$, where $K$ and $N$ are the number of users and the processing gain respectively. Each user is assigned a single spreading code. Since each user sends its own data on its spreading code in the first time phase and also sends other user's data on that user's spreading code, each user effectively uses $K$ spreading codes while the total number of linearly independent spreading codes available in the system is $N$. Thus each cooperating terminal utilizes $K/2N$ of available degrees of freedom in the channel. The $1/2$ factor is due to time-phase orthogonality. Conditioned on the decoding set $\mathcal{D}(k)$, the mutual information between $k$-th user and destination can be shown to be

$$I_{\text{u-CDMA}} = \frac{K}{2N} \log\left(1 + \frac{2N\mathsf{SNR}}{K^2} \frac{|\alpha_{k,d}|^2}{[\boldsymbol{R}^{-1}]_{1,1}}\right) + \frac{K}{2N} \log\left(1 + \frac{2N\mathsf{SNR}}{K^2} \sum_{r \in \mathcal{D}(k)} \frac{|\alpha_{r,d}|^2}{[\boldsymbol{R}^{-1}]_{r,r}}\right). \quad (6)$$

where $\mathsf{SNR} \triangleq \frac{P}{\sigma^2}$. The mutual information in (6) is the sum of the mutual informations for two parallel channels, one from the source to the destination

| | Laneman[2] | Underloaded CDMA | Fully-loaded CDMA and Overloaded CDMA |
|---|---|---|---|
| DOF utilized by each cooperating terminal | 1/2 | $K/2N$ | 1/2 |
| Normalized discrete-time power constraint | $2P/K$ | $2NP/K^2$ | $2P/K$ |
| Normalized spectral efficiency (bits/sec/Hz) | $R \triangleq Kr/W$ | $R_{\text{CDMA}} \triangleq Nr/W = NR/K$ | $Nr/W = NR/K$ |

Table 1: Normalized (by the number of degrees of freedom utilized by each cooperating user) transmit power and normalized (by the number of degrees of freedom utilized by each user under noncooperative transmission) spectral efficiency parameterizations inspired by Laneman [2]. $r$ is the transmission rate in bits/sec.

and other from the set of decoding relays to the destination. The expression for outage probability under high-$\mathsf{SNR}$ approximation conditioned on $\boldsymbol{R}$, is given by[3]

$$\begin{aligned}
&\Pr[I_{\text{u-CDMA}} < R_{\text{CDMA}}|\boldsymbol{R}] \sim \\
&\left[\frac{2^{(\frac{2N^2R}{K^2})}-1}{2N\mathsf{SNR}/K^2}\right]^K \times \sum_{\mathcal{D}(k)} \lambda_{k,d}[\boldsymbol{R}^{-1}]_{1,1} \\
&\times \prod_{r\in\mathcal{D}(k)} \lambda_{r,d}[\boldsymbol{R}^{-1}]_{r,r} \times \prod_{r\notin\mathcal{D}(k)} \lambda_{k,r}[\boldsymbol{R}^{-1}]_{r,r} \\
&\times A_{|\mathcal{D}(k)|}\left(2^{(\frac{2N^2R}{K^2})}-1\right) \qquad (7)
\end{aligned}$$

where $A_n(t) = \frac{1}{(n-1)!}\int_0^1 \frac{w^{n-1}(1-w)}{1+tw}dw, \quad n > 0$. Thus the final expression for outage probability is

$$\Pr[I_{\text{u-CDMA}} < R_{\text{CDMA}}] = \mathsf{E}_{\boldsymbol{R}}\left\{\Pr[I_{\text{u-CDMA}} < R_{\text{CDMA}}|\boldsymbol{R}]\right\}.$$

The expected value is found using Monte-Carlo simulations by averaging (7) over realizations of $\boldsymbol{R}$.

## FULLY-LOADED CDMA UPLINK

The mutual information and outage probability expressions for the fully-loaded case can be obtained by substituting $K = N$ in (6) and (7) respectively.

## OVERLOADED CDMA UPLINK

For an overloaded CDMA system, we have $K > N$. Notice that we can generate only $N$ linearly independent spreading waveforms. The remaining $K-N$ signatures waveforms are linear combinations of the first $N$ spreading waveforms. Each user thus utilizes up to all available spreading codes. Hence each cooperating terminal utilizes 1/2 of the available degrees of freedom. We consider the following two special subcases:

**Case I** : Up to $K-1$ users cooperate
Here we consider the case where the allowed maximum number of relays in the decoding set is $K-1$. Since we also have $K > N$, random delays are inserted before each cooperating user in $\mathcal{D}(k)$ transmits $k$-th user's data to the destination. This allows us to identify each user and each relay transmission i.e., it allows us to maintain a full-rank signature matrix $\boldsymbol{R}$. The addition of random delays induces the delay diversity effect which is a form of space-time code but is not an optimal space-time code. Though it is not optimal, it is attractive since it is simple in implementation, fully distributed, and scales with increasing numbers of cooperating users [6]. As indicated in Table 1, each cooperating terminal utilizes 1/2 of total degrees of freedom in the channel. Conditioned on the decoding set $\mathcal{D}(k)$, the mutual information between $k$-th user and destination can be shown to be

$$\begin{aligned}
I_{\text{o-CDMA}} &= \frac{1}{2}\log\left(1 + \frac{2\mathsf{SNR}}{K}\frac{|\alpha_{k,d}|^2}{[\boldsymbol{R}^{-1}]_{1,1}}\right) \\
&+\frac{1}{2}\log\left(1 + \frac{2\mathsf{SNR}}{K}\sum_{r\in\mathcal{D}(k)}\frac{|\alpha_{r,d}|^2}{[\boldsymbol{R}^{-1}]_{r,r}}\right) \qquad (8)
\end{aligned}$$

and the corresponding formulation for outage probability conditioned on $\boldsymbol{R}$ is

$$\begin{aligned}
&\Pr[I_{\text{o-CDMA}} < R_{\text{CDMA}}|\boldsymbol{R}] \sim \\
&\left[\frac{2^{(\frac{2NR}{K})}-1}{2\mathsf{SNR}/K}\right]^K \times \sum_{\mathcal{D}(k)} \lambda_{k,d}[\boldsymbol{R}^{-1}]_{1,1} \\
&\times \prod_{r\in\mathcal{D}(k)} \lambda_{r,d}[\boldsymbol{R}^{-1}]_{r,r} \times \prod_{r\notin\mathcal{D}(k)} \lambda_{k,r}[\boldsymbol{R}^{-1}]_{r,r} \\
&\times A_{|\mathcal{D}(k)|}\left(2^{(\frac{2NR}{K})}-1\right) \qquad (9)
\end{aligned}$$

and the final expression for outage probability is

$$\Pr[I_{\text{o-CDMA}} < R_{\text{CDMA}}] = \mathsf{E}_{\boldsymbol{R}}\left\{\Pr[I_{\text{o-CDMA}} < R_{\text{CDMA}}|\boldsymbol{R}]\right\}.$$

**Case II** : Up to $N$ users cooperate
Here we deal with the case where the allowed maximum number of relays in the decoding set is $N$. The remaining $(K-N)$ users do not participate in the cooperation but continue transmitting their

[3] The proof is similar to [2].

own data to the base-station hence just add interference to the users that cooperate. Again, each cooperating terminal utilizes 1/2 the total degrees of freedom. The expression for outage probability in this case is similar to the case where all users cooperate but only differs in the exponent of the first term in (9) which depends upon $\mathsf{SNR}$. The exponent of the first term in equation (9) indicates the diversity gain which is equal to $N$ in this case. Since the mutual information formula is the same as in case I, we present the outage probability conditioned on $\boldsymbol{R}$ which is given as

$$\begin{aligned}&\Pr[I_{\text{o-CDMA}} < R_{\text{CDMA}}|\boldsymbol{R}] \sim \\ &\left[\frac{2^{\left(\frac{2NR}{K}\right)}-1}{2\mathsf{SNR}/K}\right]^{N} \times \sum_{\mathcal{D}(k)} \lambda_{k,d}[\boldsymbol{R}^{-1}]_{1,1} \\ &\times \prod_{r\in\mathcal{D}(k)} \lambda_{r,d}[\boldsymbol{R}^{-1}]_{r,r} \times \prod_{r\notin\mathcal{D}(k)} \lambda_{k,r}[\boldsymbol{R}^{-1}]_{r,r} \\ &\times A_{|\mathcal{D}(k)|}\left(2^{\left(\frac{2NR}{K}\right)}-1\right). \qquad (10)\end{aligned}$$

Unconditional outage probability can then be found by taking expectation of (10) with respect to signature matrix $\boldsymbol{R}$.

## NUMERICAL RESULTS

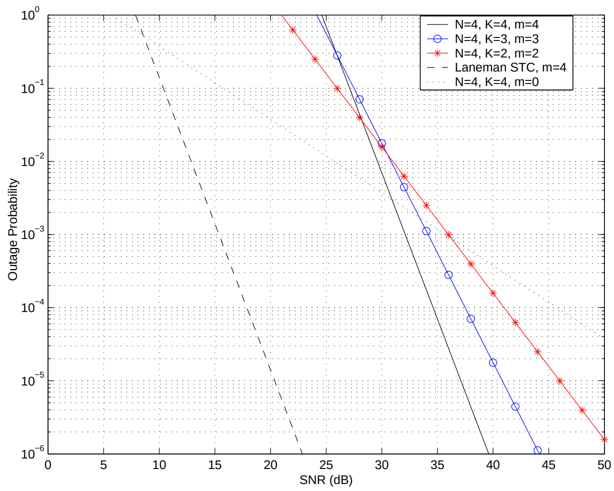



Figure 2: Outage probability performance of space-time coded scheme in an asynchronous underloaded CDMA uplink.

In Figs. 2, 3 and 4, $N = 4$ is the processing gain, $K$ denotes the total number of users in the system and $m$ denotes the allowed maximum number of cooperating users. All curves are plotted for $R = 1$ bits/sec/Hz and $\lambda_{i,j} = 1$. The $\mathsf{SNR}$ gain or loss of these curves indicates the spectral (bandwidth) efficiency/inefficiency of the protocols and slope of the curves indicates the spatial diversity gain. Fig. 2 indicates the outage probability performance of space-time coded cooperative diversity

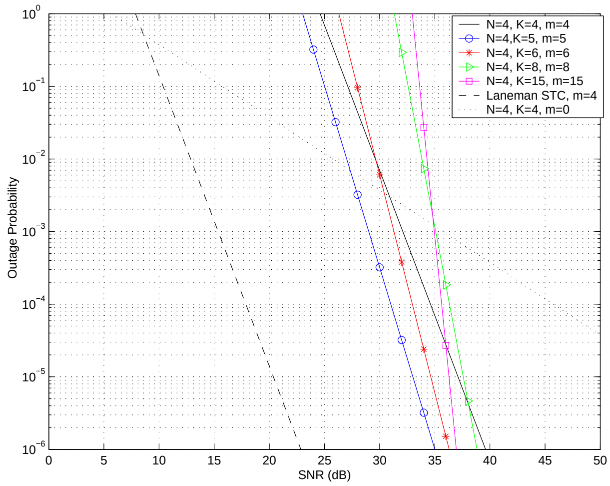



Figure 3: Outage probability performance of space-time coded scheme in an asynchronous overloaded CDMA uplink ($K > N$) assuming $m = K - 1$.

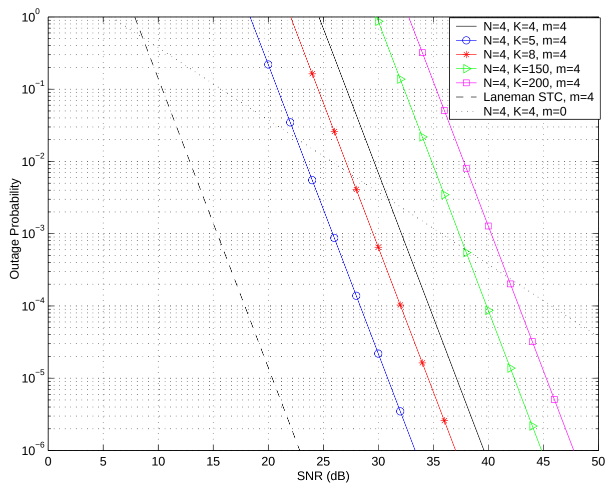



Figure 4: Outage probability performance of space-time coded scheme in an asynchronous overloaded CDMA uplink ($K > N$) assuming $m = N$.

in an underloaded CDMA system. It can be seen that the underloaded system is bandwidth inefficient when compared to fully loaded system. This is because not all available degrees of freedom in the channel are utilized in this system configuration. Fig. 3 compares the outage probability results of the proposed space-time coded scheme that operates in the overloaded CDMA ($K > N$) uplink. The curves are plotted assuming $m = K - 1$ users cooperate in the second phase of transmission. It can be seen that overloading the system is advantageous in terms of the bandwidth efficiency until certain threshold ($K = 6$ in this case). But if the number of users exceed a certain threshold, then it exhibits a loss in band-

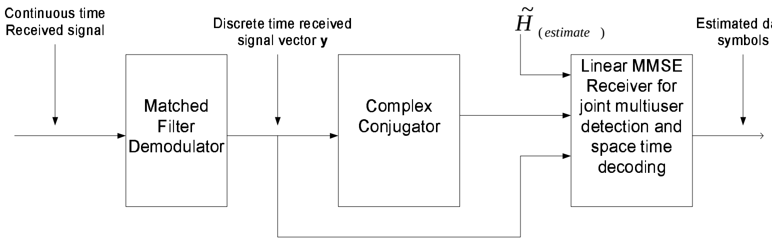



Figure 5: Block diagram of the receiver structure

width efficiency. This is because keeping $N$ constant, if we increase the number of users $K$ without bound, then $\boldsymbol{R}$ tends towards singularity and leads to large SNR loss. The outage probability curve for Laneman's space-time coded protocol is also plotted for comparison. Note that Laneman's protocol can only be treated as the fully-loaded scenario ($N = K = m$), where $m$ is the number of users [2]. The proposed scheme with fully-loaded configuration demonstrates loss in spectral efficiency with respect to space-time coded protocol developed in [2] which assumes inter-user orthogonality and the optimal decoding at the destination. This loss accounts for the inter-user non-orthogonality (use of non-orthogonal spreading codes) issue addressed in our scheme. The other reason for the SNR loss is the use of decorrelating multiuser detector to generate parallel channels at the base-station and the use of suboptimal space-time code (arising from delay diversity effect). But delay diversity has advantages as pointed out earlier. The SNR loss with respect to Laneman could be reduced using alternative receiver structures, e.g., MMSE-DF detection, perhaps, as long as post-interference suppression parallel channels can be assumed and modeled. Fig. 4 illustrates the outage probability performance of the proposed space-time coded scheme in overloaded CDMA system assuming $m = N (< K)$ users cooperate in the second phase of transmission. Here, the slope of all outage probability curves is the same because even if we vary total number of users in the system, the number of users that cooperate remains fixed which decides the diversity gain and hence the slope of the outage probability. All numerical results via slope of the curves indicate that the protocol achieves full spatial diversity in number of cooperating users.

## PRACTICAL SYSTEM DESIGN

In the previous sections, we demonstrated the performance of the proposed scheme through an information-theoretic approach. Now we will present a practical approach to system design. Here we consider specific coding scheme, modulation type and present practical pseudo-linear receiver design for the cooperative diversity in an asynchronous cellular uplink.

**A. DF User Cooperation:** We develop a specific protocol for three-or-more cooperating users that makes use of space-time block codes [9]. As an example, we consider a BPSK modulated CDMA system whose users have been assigned to groups of three. Each user sends its own new data in every time slot. Simultaneously, upon successful reception, each user transmits the other user's previous data using a distributed space-time code. For three-user sharing, we use Alamouti's space-time code in our simulations. Note that orthogonal space-time block codes cannot provide full diversity in asynchronous environments for some delay profiles (e.g., if the relative uplink delay between users is exactly one symbol interval), but these profiles occur with probability zero. Because of asynchronism, ML decoding of the orthogonal block codes is no longer linear, but we will see that linear reception, together with a non-linear complex conjugation receiver front-end, still provides full diversity. We also present the bit-error-rate (BER) performance with the delay diversity technique for comparison purpose.

**B. Adaptive Receiver Design:** We present an adaptive structure based on existing MMSE channel estimation schemes using periodically-inserted pilot symbols. Joint space-time decoding and multiuser detection is accomplished using the receiver structure in Fig. 5. The continuous time received signal is matched filtered for one extra time slot (assuming delays very between 0 and 1 symbol periods) with respect to transmit pulse shape waveform. Stacking of discrete-time received vector with it's complex conjugate is critical to obtaining full diversity with linear reception in asynchronous communication environments. We then MMSE filter the stacked version of the received signal vector using a channel matrix obtained via training data and MMSE channel estimation [10] to form bit estimates.

## SIMULATION RESULTS

We use random spreading codes of length 8. The normalized total transmit power of each user during each time slot is 1. The base-station receiver uses a set of 150 frames of data to estimate the effective channel. The results are included for an estimated channel but we note in passing that an estimated channel case suffers from 1 dB SNR loss when compared to perfectly known channel case. Fig. 6 illustrates the BER and diversity performance of the three-user DF sharing scheme in asynchronous uplink environments for various inter-user channel qualities. It is seen that the three-user sharing scheme provides full diversity with 0.1% inter-user demodulation errors, and provides no diversity with errors $\geq 25\%$. BER and diversity performance comparison of three-user sharing using Alamouti code and delay diversity technique (under perfect inter-user channel assumption) indicates that delay diversity is only 1dB worse when compared to Alamouti space-time code and is much simpler to implement, i.e., it's purely distributed.

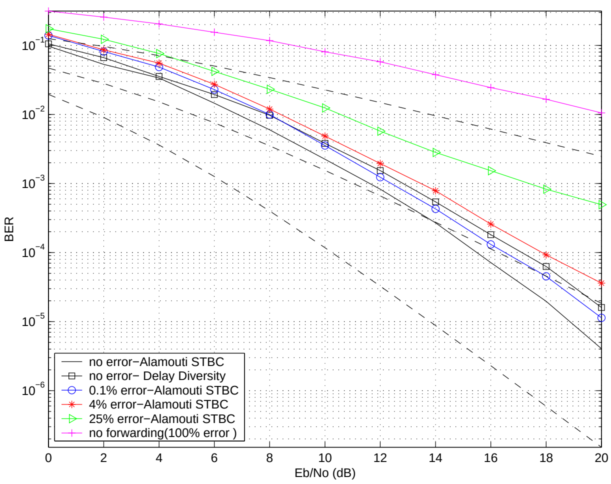



Figure 6: BER and diversity performance of three-user DF sharing in an asynchronous uplink for various inter-user channel qualities. Performance of maximum-ratio-combining (MRC) with 1,2 and 3 antennas is plotted for comparison (dotted lines).

## CONCLUSIONS

In this work, we have analyzed the performance of space-time coded cooperative diversity protocol while relaxing the inter-user orthogonality and synchronous communication constraints. We have evaluated its performance in underloaded CDMA, fully-loaded CDMA and an overloaded CDMA system configurations through information-outage probability calculations. The outage probability results indicate that an underloaded CDMA system is bandwidth inefficient when compared to a fully loaded CDMA system. Also, overloaded system is bandwidth efficient up to certain number of users but then exhibits worse performance than fully loaded system as number of users exceed a certain threshold, due to multiple access interference. We also presented a practical system design including design of an adaptive base-station receiver. The simulation results indicated that if the inter-user channel quality is poor, the benefits from cooperation are limited. We also demonstrated that delay diversity is nearly as good as orthogonal space-time block codes in asynchronism.

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