Non-Coherent Distributed Space-Time Processing for Multiuser Cooperative Transmissions

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***Abstract*— User cooperation can provide spatial transmit diversity gains, enhance coverage and potentially increase capacity. Existing works have focused on two-user cooperative systems with perfect channel state information at the receivers. In this paper, we develop several distributed space-time processing schemes for general N-user cooperative systems, which do not require channel state information at either relays or destination. We prove that full spatial diversity gain can be achieved in such systems. Simulations demonstrate that these cooperative schemes achieve significant performance gain.**

***Index Terms*— User cooperative diversity, unitary space-time modulation, differential unitary space-time modulation, distributed system, relaying protocol, diversity gain, coding gain.**

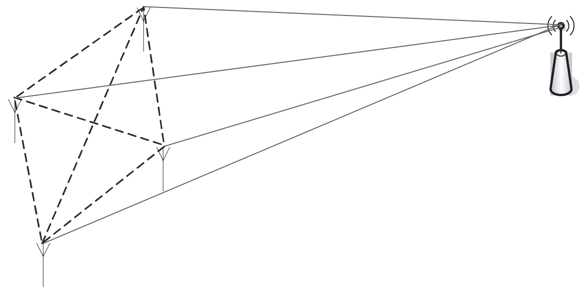

Fig. 1. Cooperative system model with $N = 4$ users.

I. INTRODUCTION

SPATIAL diversity enabled by multiple collocated antennas can mitigate the effects of channel fading and thus enhance error performance of wireless communication systems. Due to size limitation, mobile terminals are often unable to support multiple antennas. Spatial diversity gains, however, can still be achieved when single-antenna terminals effect a distributed antenna array through user cooperation [5], [6] [7], [8].

The concept of user cooperation was introduced in [8], for code division multiple access (CDMA) systems. In [5], a variety of simple relaying protocols were studied, and their outage probabilities in the high signal-to-noise ratio (SNR) regime were derived. A distributed space-time coded transmission scheme was developed in [6] and was shown to achieve full spatial diversity. For a comprehensive survey of relay and user cooperation techniques, we refer the readers to [7].

In most existing works, perfect channel state information (CSI) is assumed to enable coherent detection at the receiver. In some situations, however, it may be preferable to bypass channel estimation, either due to cost concerns or because the channels experience fast fading. In [9], schemes based on differential BPSK modulation and non-coherent detection were presented, and various relaying protocols were proposed for a single-relay system. However, these schemes still require knowledge of the average SNRs at the receiver.

In this paper, we develop several user cooperative schemes based on distributed non-coherent space-time processing and time-division-duplex (TDD) relaying protocols for general N-user systems. We derive the *distributed* counterparts of unitary space-time modulation (USTM) [3], [10] and differential unitary space-time modulation (DUSTM) [4], which do not require CSI at the source, the relays or the destination node. Four different relaying protocols are studied: fixed decode-and-forward (DF), selection relaying (SR), incremental DF (IDF) and incremental SR (ISR). Performance analysis and simulation results demonstrate that these user cooperative schemes achieve full diversity.

Notation: Upper and lower case bold symbols denote matrices and column vectors, respectively; $\mathbf{I}_M$ denotes an $M \times M$ identity matrix; $(\cdot)^T$ denotes transpose; $(\cdot)^\dagger$ denotes Hermitian transpose; $\mathcal{CN}(\mathbf{0}, \mathbf{I})$ denotes the symmetric multivariate complex Gaussian distribution with zero mean vector and covariance matrix $\mathbf{I}$; $Re\{\}$ denotes the real part of a complex number; $\mathrm{diag}(\cdots)$ denotes a diagonal matrix; $\mathrm{tr}\{\mathbf{A}\}$ and A_{mn} stand for the trace and the (m, n)th element of the matrix $\mathbf{A}$, respectively; finally, $x(m)$ denotes the m^{th} element of the vector $\mathbf{x}$.

II. SYSTEM MODEL

Consider a system of N single-antenna users, cooperating to transmit information to a distant destination node. A four-user system is illustrated in Fig. 1. We assume that the users are labeled from 1 to N and that each user knows its own label. At any time instant, one user will be the source, with others acting as relays. Source and relays form a distributed (virtual) antenna array to effect spatial diversity gains. Focusing only on transmit diversity, we suppose that the destination node is also equipped with a single antenna. The channels between any two users (inter-user channels) and between the users and the destination (user-destination channels) are independent of each other, and modeled as quasi-static flat Rayleigh fading plus additive white Gaussian noise (AWGN). We suppose that

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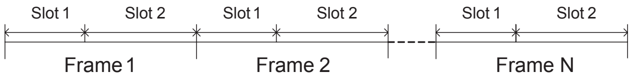

Fig. 2. TDD channel allocation mode.

the inter-user distance is much shorter than the user-destination distance. We also assume that the difference among different users' distances to the destination node is small enough to render timing synchronization errors negligible.

In practice, mobile terminals can not transmit and receive at the same time and over the same frequency band. For this reason, relays must operate either in a frequency-division-duplex (FDD), or in a TDD mode. In this paper, we suppose that relays operate in a TDD mode, but our schemes can be easily extended to systems employing an FDD mode. As depicted in Fig. 2, every transmission burst is divided into N time frames, each of which is further divided into two time slots. In slot 1 of frame n, only user n (source) transmits. In slot 2 of the same frame, all users form a "virtual array" to transmit user n's information to the destination using non-coherent space-time codes. We will denote the duration and bit rate of slot i ($i = 1, 2$) as T_i and R_i, respectively. If no additional error control is added at the relays, then R_i and T_i should satisfy $2^{R_1 T_1} = 2^{R_2 T_2} := L$, where L will denote the required constellation size. The total transmission rate is $R := R_1 T_1/(T_1 + T_2) = R_2 T_2/(T_1 + T_2)$.

III. Relaying Protocols

A. Fixed Decode-and-Forward

During slot 1 of this protocol, each relay performs non-coherent detection and decodes the source information; then forwards it during slot 2 to the destination node after re-encoding it using non-coherent space-time modulation. This is different from the DF protocol described in [5], where coherent detection is used. Furthermore, both source and relay transmissions in [5] employ identical constellations, while in our scheme, different constellations may be used for different transmissions.

B. Selection Relaying

In the DF protocol, when a detection error occurs at the relay, erroneous information will be forwarded to the destination, causing an increase in the probability of error at the destination. The selection relaying (SR) protocol seeks to mitigate this effect by relaying only when the relays determine that they have decoded the source information correctly. To enable detection of decoding errors at relays, cyclic redundancy check (CRC) bits are embedded in the source information. In this paper, we will assume that the CRC is perfect and causes negligible overhead [1], which will not affect the ensuring diversity gain analysis and will provide a lower bound on its practical error probability.[1]

[1] In the SNR range of interest, when the blocklength is long enough, CRC bits can be neglected. As pointed out in [1], standard codes, such as CRC-CCITT (used in X.25) and CRC-ANSI (used in DECNET), have been devised for blocklengths up to $2^{15} - 1 = 32767$. When CRC-16 bits are used, the reduction of the code rate can be less than 0.05%, with a detection-missing probability of $2^{-16} \approx 1.5 \times 10^{-5}$. In this case, the CRC can indeed be considered as perfect and the overhead does not have a significant effect on the error performance comparison of DF and SR in the SNR range of interest.

C. Incremental DF and Incremental SR

When the source transmits information to relays during slot 1, the destination node can also receive this information. When the source-destination link is reliable enough, the destination node can decode the information from the source-transmission (slot 1 copy) only, rendering the relay-transmission (slot 2 copy) unnecessary. Incremental relaying protocols seek to improve data throughput by eliminating these redundant relay transmissions. If the destination node determines from the CRC bits that the direct copy during slot 1 has been decoded correctly, it will send back an ACK for the users to start transmitting new information; otherwise, a NACK will inform them to send the relay copy during slot 2. If the relays use DF, this protocol will be called incremental DF (IDF). If SR is used at the relays, this protocol will be called incremental SR (ISR).

IV. Distributed Space-Time Modulations

A. Distributed USTM and DUSTM

Suppose there are M transmit antennas and the channels remain constant for T symbol periods. USTM consists of L complex space-time matrices: $\mathbf{S}_l = \sqrt{T}\mathbf{\Phi}_l$, $l = 1, \ldots, L$, where $\mathbf{\Phi}_l$ is a $T \times M$ unitary matrix, that is, $\mathbf{\Phi}_l^\dagger \mathbf{\Phi}_l = \mathbf{I}$, $l = 1, \ldots, L$. The received signal can be written as: $\mathbf{x} = \sqrt{\rho}\mathbf{Sh} + \mathbf{w}$, where $\rho := \rho_b RT/M$ stands for the average SNR per symbol at the receive antenna and ρ_b stands for the average output SNR per bit, $\mathbf{h} := [h(1), \ldots, h(M)]^T \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_M)$ and $\mathbf{w} := [w(1), \ldots, w(T)]^T \sim \mathcal{CN}(\mathbf{0}, \mathbf{I}_T)$ denote the vectors of fading coefficients and AWGN components respectively, while $\mathbf{h}$ and $\mathbf{w}$ are independent of each other. The maximum-likelihood (ML) receiver is [3]:

$$\widehat{\mathbf{\Phi}}_{ml} = \arg \max_{\mathbf{\Phi}_l \in \{\mathbf{\Phi}_1, \ldots, \mathbf{\Phi}_L\}} \operatorname{tr}\{\mathbf{x}^\dagger \mathbf{\Phi}_l \mathbf{\Phi}_l^\dagger \mathbf{x}\}. \quad (1)$$

In our multiuser cooperative schemes, we implement USTM and DUSTM[2] in a distributed manner: user m corresponds to the m^{th} "virtual" antenna of the M-element "virtual array" formed by M cooperating users; therefore, it will transmit the m^{th} column of the space-time code matrix. Consider an N-user cooperative system. Suppose that during each slot, a sequence of K space-time matrices is transmitted. In the DF protocol, during slot 1 of frame n, user n (source) transmits information; thus, we have $T = T_1/K$ and $M = 1$. At the end of slot 1, every relay performs non-coherent detection and obtains an estimate of the source sequence. In slot 2, user m maps this estimated source sequence into a sequence of space-time matrices $[\hat{\mathbf{S}}^{(m)}(1), \ldots, \hat{\mathbf{S}}^{(m)}(K)]$ and transmits the m^{th} column of each of these matrices, that is, $\hat{\mathbf{s}}_m^{(m)}(k)$, $k = 1, \ldots, K$. (Note that, for user n, $\hat{\mathbf{S}}^{(m)}(k) = \mathbf{S}^{(m)}(k)$, but for other users, they may be different.) So all N users cooperate to transmit a sequence of matrices of the form $\tilde{\mathbf{S}}(k) := [\hat{\mathbf{s}}_1^{(1)}(k), \ldots, \hat{\mathbf{s}}_N^{(N)}(k)]$. Notice that during slot 2, we have $T = T_2/K$ and $M = N$.

In the SR protocol, the only difference is that during slot 2 of each frame, some columns in the signal matrix $\tilde{\mathbf{S}}(k)$ may not be transmitted due to detection errors at the corresponding relays, resulting in $\hat{\mathbf{s}}_m^{(m)}(k) = \mathbf{0}$ for some values of m.

[2] The encoding and decoding processes for DUSTM can be found in [4] and will not be repeated here due to the space limit.

B. Combining Copies from Both Slots

In the DF and SR protocols of Section III, the destination relies only on the transmissions during slot 2 to perform non-coherent detection. But the destination can also make use of the direct transmission during slot 1. To improve performance, we may combine the received waveforms at the destination during both slots. In the following, we describe such an equal gain combining (EGC) scheme for systems using USTM. A similar combiner can be applied to systems using DUSTM. Suppose that the space-time code matrices used in the direct transmission during slot 1 are $\mathbf{\Phi}_l^{(1)}, l \in \{1, \ldots, L\}$, and those used during slot 2 are $\mathbf{\Phi}_l^{(2)}, l \in \{1, \ldots, L\}$. Let $\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$ denote the copies received by the destination during slot 1 and 2, respectively. The non-coherent detector combining both copies is given by

$$\hat{l} = \arg\max_{l=1,\ldots,L} \left\{ \mathrm{tr}\{\mathbf{x}^{(1)\dagger}\mathbf{\Phi}_l^{(1)}\mathbf{\Phi}_l^{(1)\dagger}\mathbf{x}^{(1)}\} + \mathrm{tr}\{\mathbf{x}^{(2)\dagger}\mathbf{\Phi}_l^{(2)}\mathbf{\Phi}_l^{(2)\dagger}\mathbf{x}^{(2)}\} \right\}. \quad (2)$$

Compared with incremental protocols, DF and SR protocols with EGC do not require feedback from the destination. Furthermore, the DF protocol with EGC does not need CRC either. On the other hand, since the ISR and IDF protocols may not need to use slot 2 (when the destination can correctly decode the source information during slot 1), they may result in higher transmission rates than their non-incremental counterparts.

V. Performance Analysis

In this section, we will analyze the diversity gain of our non-coherent multiuser cooperative schemes. As usual, we define diversity gain as:

$$G_d := \lim_{\mathrm{SNR}\to+\infty} \frac{-\log P_e\,(\mathrm{SNR})}{\log \mathrm{SNR}}, \quad (3)$$

where P_e denotes the probability of error. This diversity gain, which is determined by the channel and the relaying protocol, will dominate the error performance at high SNR. Unless noted otherwise, P_e means average Symbol Error Rate (SER), but the results on diversity gain also hold for bit error rate (BER). For simplicity, we assume that all channels have the same average output SNR per bit (symmetric system), although our results are applicable to asymmetric systems as well. We will focus on SR-based protocols in this paper. A diversity gain analysis of the DF-based relaying for the special case of BFSK signaling and orthogonal relaying can be found in [2], where the average error probabilities at the relays are assumed to be known at the destination.

A. SR Protocol

Let $P_{e,m}, m = 1, \ldots, M-1$ denote the probability of detection error at the m^{th} relay. Since we assume that the inter-user channels are symmetric, we have $P_{e,1} = \cdots = P_{e,M-1} := P_{er}$. The probability of error at the destination node, denoted by P_{ed}, should satisfy

$$P_{ed} = \sum_{k=0}^{M-1} \binom{M-1}{k} P_{er}^{\,k}(1-P_{er})^{M-1-k}\widetilde{P_{ek}}, \quad (4)$$

where $\widetilde{P_{ek}}$ is the error probability at the destination node when k relays experience decoding errors and, as a consequence, k columns of the space-time code matrix are not transmitted. Let $\widetilde{P_{ek}}^{l,l'}$ denote the pairwise probability of mistaking $\mathbf{\Phi}_l$ for $\mathbf{\Phi}_{l'}$, where $l \neq l'$. The probability of error $\widetilde{P_{ek}}$ satisfies the union bound

$$\begin{aligned} \widetilde{P_{ek}} &= \frac{1}{L}\sum_{l=1}^{L} \Pr\left(\text{destination error} |\ \mathbf{\Phi}_l \text{ transmitted}\right) \\ &\leq \frac{1}{L}\sum_{l=1}^{L}\sum_{l'\neq l} \widetilde{P_{ek}}^{l,l'}. \end{aligned} \quad (5)$$

Next, we will evaluate $\widetilde{P_{ek}}^{l,l'}$. Suppose that because of decoding errors at k relays, instead of a $T \times M$ matrix $\mathbf{\Phi}_l$, a $T \times (M-k)$ matrix $\mathbf{\Phi}'_l$ is transmitted. Without loss of generality, suppose that the last k columns of $\mathbf{\Phi}_l$ have been removed, that is, $\mathbf{\Phi}'_l = \mathbf{\Phi}_l \begin{bmatrix} \mathbf{I}_{M-k} \\ 0 \end{bmatrix}_{M\times(M-k)}$. Then, we can write $\widetilde{P_{ek}}^{l,l'} = P_{e|l} := \Pr\left(\mathrm{tr}\{\mathbf{x}^\dagger(\mathbf{\Phi}_{l'}\mathbf{\Phi}_{l'}^\dagger - \mathbf{\Phi}_l\mathbf{\Phi}_l^\dagger)\mathbf{x}\} > 0 |\ \mathbf{\Phi}'_l\right)$. Since $\mathbf{x} = \sqrt{\rho T}\mathbf{\Phi}'_l\mathbf{h}' + \mathbf{w}$, where $\mathbf{h}' := [h(1), \ldots, h(M-k)]^T$, and recalling that $\mathbf{\Phi}_l^\dagger\mathbf{\Phi}'_l = \begin{bmatrix} \mathbf{I}_{M-k} \\ 0 \end{bmatrix}_{M\times(M-k)}$ and $\mathbf{\Phi}_l'^\dagger\mathbf{\Phi}'_l = \mathbf{I}_{M-k}$, as $\rho \to +\infty$, we find

$$P_{e|l} \to P'_{e|l} := \Pr\left(\mathrm{tr}\{\mathbf{x}^\dagger(\mathbf{\Phi}_{l'}\mathbf{\Phi}_{l'}^\dagger - \mathbf{\Phi}'_l\mathbf{\Phi}_l'^\dagger)\mathbf{x}\} > 0 |\ \mathbf{\Phi}'_l\right). \quad (6)$$

Using the singular value decomposition $\mathbf{\Phi}_{l'}^\dagger\mathbf{\Phi}'_l = \mathbf{\Theta}\mathbf{D}\mathbf{\Upsilon}^\dagger$, where $\mathbf{\Theta}$ is an $M \times M$ unitary matrix, $\mathbf{\Upsilon}$ is an $(M-k) \times (M-k)$ unitary matrix, $\mathbf{D} = [\mathbf{D}', \mathbf{0}]^T$ and $\mathbf{D}' = \mathrm{diag}(d_1, \ldots, d_{M-k})$, whose diagonal elements are real and nonnegative, we can rewrite (6) as

$$\begin{aligned} P'_{e|l} &= \Pr\left(\mathrm{tr}\{\mathbf{x}^\dagger(\mathbf{\Phi}_{l'}\mathbf{\Theta}\mathbf{\Theta}^\dagger\mathbf{\Phi}_{l'}^\dagger - \mathbf{\Phi}'_l\mathbf{\Upsilon}\mathbf{\Upsilon}^\dagger\mathbf{\Phi}_l'^\dagger)\mathbf{x}\} > 0 |\ \mathbf{\Phi}'_l\right) \\ &= \Pr\left(\mathrm{tr}\{\mathbf{y}_{l'}^\dagger\mathbf{y}_{l'} - \mathbf{y}_l^\dagger\mathbf{y}_l\} > 0 |\ \mathbf{\Phi}'_l\right), \end{aligned} \quad (7)$$

where $\begin{bmatrix} \mathbf{y}_l \\ \mathbf{y}_{l'} \end{bmatrix} := \left(\frac{\rho T}{1+\rho T}\right)^{1/2} \begin{bmatrix} \mathbf{\Upsilon}^\dagger\mathbf{\Phi}_l'^\dagger \\ \mathbf{\Theta}^\dagger\mathbf{\Phi}_{l'}^\dagger \end{bmatrix} \mathbf{x} := \mathbf{y}$. Following procedures similar to [3, Appendix B], it can be shown that, as $\rho \to \infty$,

$$P'_{e|l} \leq \prod_{m=1}^{M-k} \left[\frac{1}{\frac{1}{4}\rho T(1-d_m^2)}\right] \mathcal{A}, \quad (8)$$

where $\mathcal{A} := \left\{-\frac{1}{2\pi i}\int_{-\infty}^{\infty} \mathrm{d}w \frac{1}{w+i/2}\left[\frac{1}{\frac{1}{2}+iw}\right]^k\right\}$. Since $P'_{e|l}$ is real-valued, we find

$$\begin{aligned} P'_{e|l} &\leq \prod_{m=1}^{M-k}\left[\frac{1}{\frac{1}{4}\rho T(1-d_m^2)}\right] Re\{\mathcal{A}\} \\ &= \left(\frac{4}{\rho T}\right)^{M-k} \prod_{m=1}^{M-k}\left[\frac{1}{1-d_m^2}\right] Re\{\mathcal{A}\}. \end{aligned} \quad (9)$$

Because $Re\{\mathcal{A}\}$ is finite and does not depend on ρ, the probability of error decays as $(1/\rho)^{M-k}$ for large ρ. So, the diversity gain (high-SNR slope of $\widetilde{P_{ek}}^{l,l'}$ in a log-log scale) is $M-k$. From (5), we can see that the diversity gain of $\widetilde{P_{ek}}$ is also $M-k$. Since P_{er} has a diversity gain of one, from (4), the diversity gain of P_{ed} is $(M-k)+k = M$.

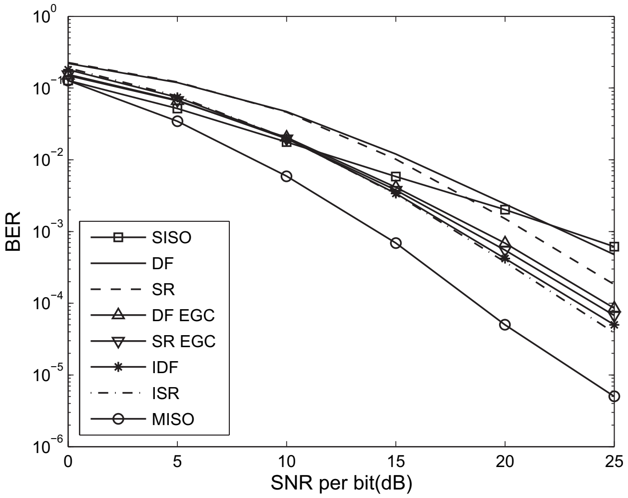

Fig. 3. USTM with $R = 1$ bits/s, $N = 2$.

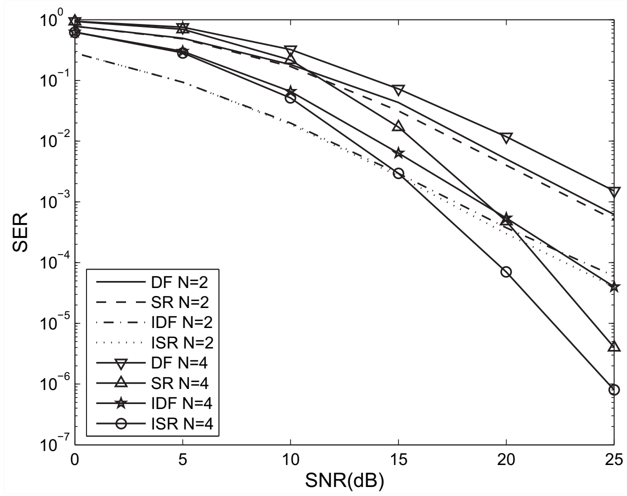

Fig. 4. USTM with $R = 1/2$ bits/s.

When a DUSTM constellation is used, the ML receiver is equivalent to the ML receiver for a USTM constellation applied to two successive received blocks. Therefore, SR protocols using a DUSTM constellation will also achieve a diversity gain of M.

B. ISR Protocol

Let us define $E_{SR} := \{$ destination error using SR $\}$, and $E_{direct} := \{$ direct transmission error during slot 1 $\}$. For the SR protocol, we have

$$P_{e,SR} = P_{e,direct}\Pr\left(E_{SR}|E_{direct}\right) + \left(1 - P_{e,direct}\right)\Pr\left(E_{SR}|\overline{E_{direct}}\right), \quad (10)$$

where $P_{e,direct}$ is the probability of E_{direct}. For the ISR protocol, a destination error will occur only when the direct source-channel copy in slot 1 is not decoded correctly. Hence

$$\begin{aligned} P_{e,ISR} &= P_{e,direct}\Pr\left(E_{SR}|E_{direct}\right) + \left(1 - P_{e,direct}\right)0 \\ &= P_{e,direct}\Pr\left(E_{SR}|E_{direct}\right). \end{aligned} \quad (11)$$

The diversity gain of $P_{e,ISR}$ depends on the channel setting. If the source-destination channels during slots 1 and 2 are independent, it is easy to show that $P_{e,ISR} = P_{e,direct}P_{e,SR}$. Therefore, we have $G_{\mathrm{d},ISR} = G_{\mathrm{d},SR} + 1$, where $G_{\mathrm{d},ISR}$ and $G_{\mathrm{d},SR}$ are the diversity gains of ISR and SR protocols, respectively. Since we focus on spatial diversity gains in this paper, we assume that source-destination channel does not change from slot 1 to slot 2. Under this assumption, we have $G_{\mathrm{d},ISR} = G_{\mathrm{d},SR} = M$. However, comparing (10) with (11), we can see that the ISR protocol still outperforms the SR protocol in this setting.

VI. Simulations

In this section, we compare the error performance of various multiuser cooperative schemes using Monte-Carlo simulations. Our comparisons will focus on the error performance of these protocols at moderate-to-high SNR values.

A. Performance of Various Cooperative Schemes

In Fig. 3, we compare the BER of various non-coherent multiuser cooperative schemes. We also plot as benchmark the BER of a single-input-single-output (SISO) system and a system with multiple collocated transmit antennas (i.e., a multi-input-single-output, or MISO, system). In our simulation, we assume that the channel between each user and the destination (user-destination channel) has the same average output SNR per bit, shown in dB along the x-axis. We also assume that the average received SNRs per bit are the same for all inter-user communications, and are set to be 10dB higher than those of user-destination channels. We observe that the slope of the BER curve of the SR protocol coincides with that of the MISO benchmark at high SNR. This verifies our conclusion in Section V that the SR protocol achieves the full diversity gain, $G_{\mathrm{d},SR} = 2$. Compared with the SR protocol, the error performance of DF is slightly worse, due to the propagation of decoding errors from relays to the destination.

In Fig. 3, we also plot the BER curves of the EGC-based schemes (2). We observe that these schemes substantially outperform their counterparts without EGC.

Also shown in Fig. 3 are the BER performance of incremental protocols. We observe that they achieve the best performance among all user cooperative schemes. Although these protocols incur overhead due to CRC and feedback bits, their superior error performance along with their higher throughput makes them attractive design choices.

B. Effects of Network Size

In Fig. 4, we test the dependence of the SER performance of various USTM-based user cooperative schemes on the number of cooperating users. In this simulation, we set the received SNR of the inter-user communication to be the same as that of the user-destination communication. We also adjust the transmission power of each individual user so that the total transmission power for a two-user system is the same as that of a four-user system. As expected, for SR and ISR protocols, increasing the number of cooperating users improves the error performance of multiuser cooperative schemes at high SNR, because it effects a higher diversity gain. We observe that SR

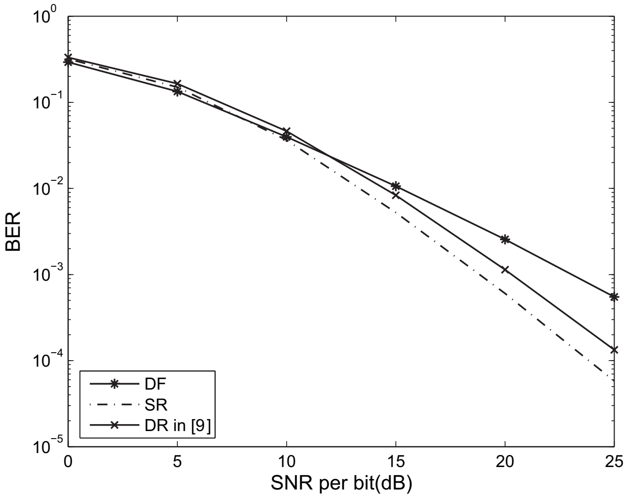

Fig. 5. DUSTM, $N = 2$. (For DR, $R = 1/2$ bits/s; for DF and SR, $R = 2/3$ bits/s.)

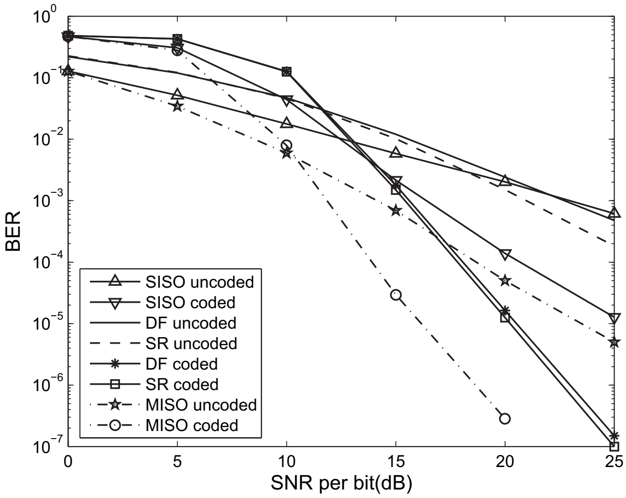

Fig. 6. USTM with $R = 1$ bits/s, $N = 2$.

and ISR achieve full diversity gain in a four-user system, as predicted by our analysis. Another important observation is that the impact of error propagation from relays to destination on the error performance of DF protocol is much more severe in larger systems: the gap between DF and SR protocols is insignificant in a two-user system, but exceeds 7dB at an SER of 10^{-3} in a four-user system. Therefore, in large user cooperative systems, the benefits of using SR will far outweigh the costs of implementing CRC.

C. Comparison with Existing Schemes

A user cooperative scheme called decode-and-remodulate (DR), based on differential BPSK, was developed in [9]. This scheme uses non-coherent reception, but requires that the destination knows the average received SNR. In Fig. 5, we compare the error performance of this DR protocol with that of the DUSTM-based user cooperative schemes using DF and SR protocols. The transmission rate of DR is set to $1/2$ bits/s and the rate of the DUSTM-based schemes is set to $2/3$ bits/s. We observe that DR relaying achieves a lower BER than DF, but is outperformed by the SR protocol, which supports a higher transmission rate.

D. Effects of Channel Coding

Finally, we investigate the effects of error control coding (ECC) on performance of various schemes using a convolutional code of rate 2/3. We assume that convolutional decoding is only performed at the destination. The transmission rate of the coded systems has been adjusted so that their effective information rate is $R = 1$ bits/s, the same as that of uncoded systems. Therefore, for the coded system we have $R = (2/3)R_{bc}$, where $R_{bc} = 3/2$ bits/s is the bit rate used before coding. From Fig. 6, we observe that the diversity gain is doubled with ECC, as the minimum free distance of the convolutional code we use is 2. The performance gain of user cooperative schemes, relative to the SISO benchmark, is even larger in coded systems.

VII. Conclusions

We have developed several non-coherent distributed space-time processing schemes based on non-coherent USTM and DUSTM modulations and TDD relaying protocols for a general N-user cooperative system. At the relays, we have considered DF, SR, IDF, and ISR protocols. Simulations demonstrate that these cooperative schemes achieve significant performance gain. We have shown that carefully designed non-coherent cooperative schemes outperform existing alternatives and achieve full diversity gain, with or without error control coding. [3]

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