Decode-and-Forward Cooperative Relay with Multi-User Detection in Uplink CDMA Networks

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***Abstract*—The use of multi-user detection (MUD) in a cooperative CDMA network is investigated for the uplink in synchronous CDMA systems. Suppose that, at any instant in time, part of the users serve as sources while the others serve as relays. The proposed MUD scheme decorrelates the sources' messages at the destination with the help of precoding at the relays. Three cooperation methods are considered: (1) transmit beamforming, (2) selective relaying and (3) distributed space-time coding. The optimal weighting factors of each method are determined by taking the quality of the source-to-relay and/or the relay-to-destination links into account. We show that significant improvements in terms of the spatial diversity and multiple-access interference (MAI) mitigation can be attained when precoding is employed at the relays to aid the decorrelation at the destination. The advantages are even more pronounced when selective relaying is combined with the other two schemes.**

I. Introduction

Consider the uplink of a cooperative CDMA system where users cooperate by relaying each other's messages to the base station. This is an application scenario of cooperative communications studied in [1]–[3]. Under such a context, some users serve as sources while others serve as relays that forward messages from sources to base-stations at each time instant. Quite a few relay-based cooperation methods have been proposed and studied in the past. Amplify-and-forward (AF) and decode-and-forward (DF) [2] have been among the most popular ones due to the simple and intuitive design. In a cooperative system, relaying users play an equivalent role of a distributed antenna array and provide diversity for sources without requiring multiple antennas on each device. Most work in the literature has focused on the performance of a single source and then extends the problem to multiple sources by assuming orthogonal channels among them [4]–[6].

In this work, we examine a cooperative CDMA system where the relays are allowed to jointly decode and forward the messages from more multiple sources using the sources' spreading waveforms. The spreading sequences are not assumed to be orthogonal and, thereby, the signal detection performance may degrade significantly due to the multiple-access interference (MAI). The MAI effect is especially severe when the target user is distant from the receiver, *i.e.,* the near-far effect. It is not obvious whether the advantages of cooperation still remain in the presence of MAI. Several multi-user detection (MUD) schemes [7] have been proposed to mitigate the MAI effect, including the maximal likelihood (ML) detector, the decorrelating detector, and the minimum mean square error (MMSE) linear detector. The main contribution of this work is to exploit the use of relay-assisted decorrelating MUD to mitigate MAI in a multi-user environment and demonstrate that cooperation still has advantages in such a context.

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MUD was considered for cooperative CDMA networks in [8], [9], where two users work as a cooperating pair and forward messages only for its cooperating partner. Then, MUD is used at the relay to decode messages from a single source. Here, we consider the case where each relay is allowed to cooperate with multiple users simultaneously and messages received from multiple sources are jointly processed at each relay. To address this problem, we apply precoding at the relays to facilitate the decorrelating operation at the destination. Moreover, by performing selection or optimal weighting at the relays, users that suffer from the near-far effect at certain relays may be suppressed while being enhanced at other relays if the near-far effect is less severe. Hence, cooperative diversity is used to combat fading as well as mitigate MAI.

We study MUD in three cooperative relaying schemes: (1) transmit beamforming, (2) selective relaying and (3) distributed space-time coding (DSTC). The precoding technique used at relays is optimized for each strategy. To design weighting factors for beamforming, error probabilities on source-to-relay links are considered to achieve diversity at the destination. Furthermore, by combining selective relaying with beamforming and DSTC, the diversity of the system can be significantly improved. Extensive computer simulation is conducted to corroborate our analysis.

II. System Model

Consider a cooperative network where users cooperate by relaying each other's messages to the destination. At a time instance, there are N source users and L relaying users that forward messages from sources to the destination as shown in Fig. 1. The cooperative transmission consists of two phases.

In phase I, source nodes in set $\mathcal{S} = \{S_1, S_2, \cdots, S_N\}$ transmit their respective data symbols to relay nodes using spreading waveforms $s_i(t) = (1/\sqrt{M})\sum_{m=1}^{M} c_i(m)\varphi(t - mT_c)$, $i = 1, \cdots, N$, where $c_i(m)$ is the m-th element of the ± 1 spreading sequence assigned to node S_i, *i.e.,* the spreading

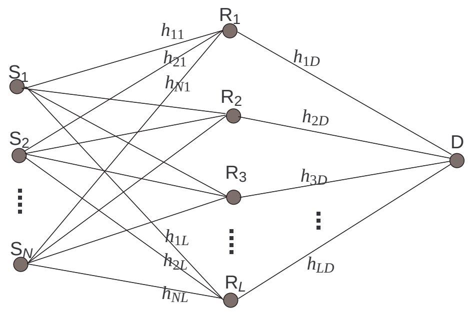

Fig. 1. The system model.

sequence of S_i is denoted by $\mathbf{c}_i = [c_i(1), \cdots, c_i(M)]^T$, and $\varphi(t)$ is the normalized chip waveform of duration $T_c = T/M$ such that $\int |\varphi(t)|^2 dt = 1$. The spreading sequences are assumed to be non-orthogonal, which may occur especially when the number of users is greater than the processing gain, *i.e.*, $N + L > M$. Thus, the signal transmitted by S_i is $u_i(t) = \sqrt{P_s} x_i s_i(t)$, $i = 1, 2, \cdots, N$, where P_s is the transmit power of the source and x_i is the BPSK data symbol with zero mean and $\mathbf{E}[x_i x_j] = \delta_{ij}$, where δ_{ij} is the Kronecker delta. Relay nodes R_1, R_2, $\cdots$, R_L decode data symbols $\mathbf{x} = [x_1, x_2, \cdots, x_N]^T$ using a linear MMSE multi-user detector [c.f. section III-A]. The decoded vector of symbols at R_k is denoted by $\hat{\mathbf{x}}_k = [\hat{x}_{k,1}, \cdots, \hat{x}_{k,N}]^T$.

In phase II, each relay node (*e.g.*, node R_k) precodes detected symbols $\hat{\mathbf{x}}_k$ into $\mathbf{t}_k = [t_{k,1}, t_{k,2}, \cdots, t_{k,N}]^T$ and retransmits the data using the set of spreading waveforms $\{s_i(t), 1 \leq i \leq N\}$, where $t_{k,i}$ is modulated with $s_i(t)$. The transmitted signal of relay node R_k is given by $\tilde{u}_k(t) = \sum_{i=1}^{N} t_{k,i} s_i(t)$.

III. MMSE Multi-User Detection

A. MMSE Detection at Relays

It is assumed that transmitted signals are synchronous so that messages arrive at relays at the same time and relays have the knowledge of all signature waveforms. In the first phase, relay node R_k passes the received signal through the matched filter bank (MFB) corresponding to spreading waveforms $s_1(t)$, $\cdots$, $s_N(t)$. The output of the filter bank can be written as

$$\mathbf{y}_k = \sqrt{P_s} \mathbf{R} \mathbf{H}_k \mathbf{x} + \eta_k, k = 1, 2, \cdots, L.$$

where $\mathbf{R}$ is the correlation matrix of spreading waveforms with $[\mathbf{R}]_{i,j} = \int_0^T s_i(t) s_j(t) dt$, $\mathbf{H}_k = \mathrm{diag}(h_{1k}, h_{2k}, \cdots, h_{Nk})$ with h_{ik} being the complex channel coefficient between source S_i and relay R_k, η_k is the additive Gaussian noise at R_k which is zero mean and has covariance $\mathbf{E}[\eta_k \eta_k^H] = \sigma^2 \mathbf{R}$. Let us assume that the correlation matrix $\mathbf{R}$ is non-singular. It is straightforward to find that the MMSE estimation of the data symbol at the k-th relay is

$$\begin{aligned} \mathbf{z}_k &= \mathbf{E}[\mathbf{x}\mathbf{y}_k^H] \mathbf{E}[\mathbf{y}_k \mathbf{y}_k^H]^{-1} \mathbf{y}_k \\ &= \sqrt{P_s} \mathbf{H}_k^H \mathbf{R} (P_s \mathbf{R} \mathbf{H}_k \mathbf{H}_k^H \mathbf{R} + \sigma^2 \mathbf{R})^{-1} \mathbf{y}_k. \end{aligned} \quad (1)$$

Then, the decoded vector $\hat{\mathbf{x}}_k$ can be obtained from the hard decision on $\mathbf{z}_k = [z_{k,1}, \cdots, z_{k,N}]^T$, where $\hat{x}_{k,i} = \chi_{\{\Re(z_{k,i})>0\}}$, and where $\chi_{\{\cdot\}}$ is the indicator function. The decoding error probability for symbol x_i at the k-th relay is given by

$$e_{k,i} = \Pr\{\hat{x}_{k,i} \neq x_i\} = Q\left(\sqrt{\frac{2[\mathbf{\Gamma}_k]_{i,i}}{1 - [\mathbf{\Gamma}_k]_{i,i}}}\right), \quad (2)$$

where

$$\mathbf{\Gamma}_k = \mathbf{E}[\mathbf{z}_k \mathbf{z}_k^H] = P_s \mathbf{H}_k^H (P_s \mathbf{H}_k \mathbf{H}_k^H + \sigma^2 \mathbf{R}^{-1})^{-1} \mathbf{H}_k$$

is the correlation matrix of the MMSE detection $\mathbf{z}_k$ and $Q(u) = \frac{1}{\sqrt{2\pi}} \int_u^\infty e^{-v^2/2} dv$. It is worthwhile to point out that, if two of the spreading waveforms are highly correlated, matrix $\mathbf{R}$ has an eigenvalue close to zero. Then, the error rate of messages transmitted with the corresponding spreading waveforms would be higher.

B. MMSE Detection at Destination

It is assumed that all channel coefficients and spreading waveforms are known at the destination. In the second phase, the received signal at the destination is passed through an MFB again and the resultant signal can be expressed as

$$\mathbf{y} = \sum_{k=1}^{L} h_{kD} \mathbf{R} \mathbf{t}_k + \mathbf{v},$$

where h_{kD} is the channel coefficient between R_k and the destination, and $\mathbf{v}$ is the additive Gaussian noise vector with zero mean and covariance $\mathbf{E}[\mathbf{v}\mathbf{v}^H] = \sigma_v^2 \mathbf{R}$. With knowledge of the spreading waveforms, we can choose $\mathbf{t}_k$ to be

$$\mathbf{t}_k = \mathbf{L}^{-H} \mathbf{W}_k \hat{\mathbf{x}}_k, \quad (3)$$

where $\mathbf{L}$ is the Cholesky factorization of matrix $\mathbf{R}$, *i.e.*, $\mathbf{R} = \mathbf{L}\mathbf{L}^H$, and $\mathbf{W}_k = \mathrm{diag}(w_{k,1}, \cdots, w_{k,N})$ whose diagonal terms depend on the cooperating strategy adopted by relays as discussed in Section IV.

The multiplication of $\mathbf{L}^{-H}$ at the relay can be viewed as the precoding that allows to decompose user's signals at the destination. Weighting factors $w_{k,i}$, $k = 1, \cdots, L$ and $i = 1, \cdots, N$, are chosen to optimize the detection performance at the destination subject to the constraint on the total transmit power of relays, *i.e.*,

$$\int_0^T \sum_{k=1}^{L} \mathbf{E}|\tilde{u}_k(t)|^2 dt = \sum_{k=1}^{L} \mathbf{E}[\mathbf{t}_k^H \mathbf{R} \mathbf{t}_k] = \sum_{k=1}^{L} \sum_{i=1}^{N} |w_{k,i}|^2 \leq P_R. \quad (4)$$

In this case, we have

$$\mathbf{y} = \sum_{k=1}^{L} h_{kD} \mathbf{L} \mathbf{W}_k \hat{\mathbf{x}}_k + \mathbf{v}. \quad (5)$$

By applying a whitening filter at the destination, the signal becomes

$$\bar{\mathbf{y}} = \mathbf{L}^{-1} \mathbf{y} = \sum_{k=1}^{L} h_{kD} \mathbf{W}_k \hat{\mathbf{x}}_k + \bar{\mathbf{v}}, \quad (6)$$

where the noise term is whitened, *i.e.*, $\bar{\mathbf{v}} \sim \mathcal{CN}(\mathbf{0}, \sigma_v^2 \mathbf{I})$. This is equivalent to having N orthogonal channels with independent noise on each channel. Each channel corresponds to a different user in the system. The MMSE estimate of symbol x_i ($i = 1, \cdots, N$) at the destination is given by

$$z_i = \frac{\mathbf{E}[x_i \bar{y}_i^*]}{\mathbf{E}[|\bar{y}_i|^2]} \bar{y}_i, \tag{7}$$

where $\bar{y}_i$ is the i-th element of $\bar{\mathbf{y}}$. The detection of symbol x_i is given by

$$\begin{aligned} \hat{x}_i &= \text{sign}(\Re\{z_i\}) = \text{sign}\left(\Re\{\mathbf{E}[x_i \bar{y}_i^*] \cdot \bar{y}_i\}\right) \\ &= \text{sign}\left(\sum_{k=1}^{L} (1-2e_{k,i}) \Re\{h_{kD}^* w_{k,i}^* \bar{y}_i\}\right). \end{aligned} \tag{8}$$

As shown in Eq. (6), it appears that the correlation matrix of spreading waveforms does not have a direct influence on signal detection at the destination. However, a higher correlation among spreading waveforms does result in a higher decoding error rate at relays and, consequently, more errors at the destination. The overall performance can be significantly improved by choosing weighting factors carefully as discussed in the following section.

IV. Cooperative Transmission Strategies

Based on the channel status information (CSI), we can apply different cooperative transmission schemes at relays. The following three schemes are considered in this section: (a) transmit beamforming; (b) selective relaying (at the relay or the destination); and (c) distributed space-time coding.

A. Transmit Beamforming

As shown in Eq. (6), L relays form a virtual antenna array that forwards messages from N sources using orthogonal channels. When the CSI is known at all relays, the transmit beamforming technique can be used to maximize the strength of the received signal. Here, we compare two beamforming methods depending on whether decoding errors at relays are considered or not.

(1) **Beamforming with Perfect Relay Detection (BF-P):**

If the detection at the relay is perfect, *i.e.*, without any error, symbols to be transmitted at relays will be identical and the transmission will be identical to that of a source with L co-located antennas. The weighting factors are then given by

$$w_{k,i} = \beta_{\text{BFP}} h_{kD}^*, \tag{9}$$

where β_{BFP} is a positive constant used to satisfy the constraint on the total transmit power in Eq. (4).

(2) **Beamforming with Detection Errors (BF-E):**

Although precoding allows us to decorrelate each user's messages from relays to the destination, symbol decoding at relays may have errors, which depend on the channel status and the correlation properties of spreading waveforms. Thus, for each relay, one should adjust the weighting factors by taking decoding reliability into account. By minimizing the mean square error of z_i ($i = 1, \cdots, N$), we can obtain the optimal weighting factors corresponding to source S_i. That is, the optimal weighting factors in $\mathbf{w}_i = [w_{1,i}, \cdots, w_{L,i}]^T$ are given by

$$\begin{aligned} \mathbf{w}_i &= \arg\min_{\mathbf{w_i}} \{\min_{c_i} |c_i z_i - x_i|^2\} \\ &= \beta_{i,BFE} (\mathbf{\Phi}_i + \frac{\sigma_v^2}{P_i} \mathbf{I})^{-1} \mathbf{p}_i, \end{aligned} \tag{10}$$

where $\mathbf{p}_i = [h_{1D}(1-2e_{1,i}), \cdots, h_{LD}(1-2e_{L,i})]^H$, and $\mathbf{\Phi}_i$ is an $L \times L$ matrix with elements

$$[\mathbf{\Phi}_i]_{k,m} = \begin{cases} |h_{kD}|^2 & m = k \\ h_{kD}^* h_{mD} (1-2e_{k,i})(1-2e_{m,i}) & m \neq k \end{cases}.$$

Constant $\beta_{i,BFE}$ in Eq. (10) is set to meet the individual power constraint $\|\mathbf{w}_i\|^2 = P_i$, where $\sum_{i=1}^{N} P_i = P_R$. For simplicity, we choose $P_i = P_R/N$ here. It is however possible to apply power allocation among sources to optimize the overall detecting performance furthermore.

B. Selective Relaying

If only the local CSI is available at the relay, we consider two selective relaying strategies, which are conducted at local relay nodes and the destination, respectively.

(1) **Selection by Relays (SEL-R):**

In this case, each relay has only the knowledge of local CSI between sources and itself. By estimating the error probability for each user, the relay node only forwards messages from users that are decoded reliably. That is, for the k-th relay, we set $w_{k,i} = \beta_{SR} > 0$ if the decoding error rate $e_{k,i}$ is less than a certain threshold and $w_{k,i} = 0$ if $e_{i,k}$ is larger than the threshold. The positive constant β_{SR} is set to meet the total power constraint as given in Eq. (4). This strategy can be combined with strategy BF-P by setting $w_{k,i} = \beta_{SR} h_{k,D}^*$ if $e_{k,i}$ exceeds the desired threshold.

(2) **Selection by Destination (SEL-D):**

In this case, the destination has the knowledge of global CSI and chooses a single relay path for each source in the system. The decision is then fed back to relays. Specifically, we set $w_{i,k} = \sqrt{P_R/N}$ for

$$k = \arg\max_{m=1,\cdots,L} \min\{(P_s/\sigma^2)|h_{im}|^2, (P_R/N\sigma_v^2)|h_{mD}|^2\}$$

and $w_{i,k} = 0$, otherwise. The strategy can be carried out in a distributed manner by the use of opportunistic carrier sensing as proposed in [10].

C. Distributed Space-Time Coding (DSTC)

To exploit the spatial diversity without the CSI knowledge at relays, distributed space-time coding (DSTC) can be applied. Here, we adopt DSTC proposed in [11], where the coding matrix is randomly chosen by each relay.

Specifically, at each relay, DSTC is applied over T_s successive symbol periods. That is, we encode the data in the time domain and retransmit them using a set of spreading waveforms $\{s_i(t)\}_{i=1}^{N}$. Let $\hat{\mathbf{X}}_k$ be the $N \times T_s$ matrix whose i-th row contains the i-th user's symbols of length T_s decoded by the k-th relay. The length of the space-time code T_s should be equal or larger than the number of relays, L, to achieve full diversity at high SNR [11]. Let $\mathbf{T}_k$ be an $N \times T_s$ matrix whose n-th column contains symbols transmitted by the k-th relay with spreading waveforms in the n-th symbol period of the second phase. Matrix $\mathbf{T}_k$ is given by

$$\mathbf{T}_k = \mathbf{L}^{-H}\mathbf{W}_k\hat{\mathbf{X}}_k\mathbf{A}_k,$$

where $\mathbf{A}_k$ is a $T_s \times T_s$ unitary and isotropically random matrix that is used to encode each row of decoded symbols in $\hat{\mathbf{X}}_k$. In this case, diagonal matrix $\mathbf{W}_k$ is set to satisfy the power constraints at the k-th relay. The diagonal terms of $\mathbf{W}_k$ can be set to the same value or combined with the selective strategies such that only relays that have sufficiently reliable detection are allowed to forward messages.

At the destination, received symbols obtained at the output of the MFB followed by a whitening filter within T_s successive symbol-period is given by

$$\bar{\mathbf{Y}} = \sum_{k=1}^{L} h_{kD}\mathbf{W}_k\hat{\mathbf{X}}_k\mathbf{A}_k + \bar{\mathbf{V}},$$

where $\bar{\mathbf{V}}$ is an $N \times T_s$ additive white noise matrix whose elements are *i.i.d.* Gaussian distributed with variance σ_v^2. Since rows in matrix $\bar{\mathbf{Y}}$ are uncorrelated, transmitted symbols of each row can be decoded separately. Let $\mathbf{X}(i)$ be the i-th row of true symbol matrix $\mathbf{X}$ (*i.e.*, the packet transmitted by the i-th source) and $\bar{\mathbf{Y}}(i)$ be the i-th row of symbol matrix $\bar{\mathbf{Y}}$. The detection of $\mathbf{X}(i)$ can be obtained by the maximum-likelihood (ML) decoding, *i.e.*,

$$\hat{\mathbf{X}}(i) = \arg\min_{\mathbf{b}_n \in \{\pm 1\}^{1\times N}} \left\| \bar{\mathbf{Y}}(i) - \mathbf{b}_n \sum_{k=1}^{L} h_{kD} w_{k,i} \mathbf{A}_k \right\|^2.$$

V. Simulation Results and Discussion

The performance of various methods discussed above are studied by numerical simulation in this section. Consider the case of $N = 3$ and spreading codes $\mathbf{c}_i$, $i = 1, 2, 3$, are generated randomly with spreading gain $M = 8$ subject to $\det(\mathbf{R}) > 0$. Suppose that h_{ik} and h_{kD}, for all i and k, are *i.i.d.* circularly symmetric Gaussian with unit variance. The additive noise at relays and destination are circularly symmetric Gaussian with $\sigma^2 = \sigma_v^2 = 1$. Let P be the total transmit power in both phases, *i.e.*, $P_s = P/N$ and $P_R = P$. The threshold for SEL-R is set to the average of decoding error probabilities over all sources and relays. For comparison, we consider the case with no cooperation where each source transmits directly to the base station with power $P_s = 2P/N$, and h_{iD}, $\forall i$, are *i.i.d.* circularly symmetric Gaussian with variance $1/2^{\alpha}$, where α is the path loss factor which is set to 2 in the simulation.

The BER curvers averaged over three sources for cases employing transmit beamforming at relays are shown in Fig. 2. Strategies of BF-P (dashed line), BF-P combined with SEL-R (solid line), and BF-E (dash-dot line) for $L = 3, 5$ are compared. We see that diversity is not well achieved if decoding errors at relays are not considered even though signals from all relays are coherently combined at the destination (*i.e.*, the case of BF-P). However, to increase the number of relays improves the BER performance by 3.5dB. Diversity can be well achieved by combining BF-P with SEL-R since relays that are likely to make an error will not be selected. With the knowledge of global CSI, BF-E provides astonishing performance gains as compared with the direct transmission scheme.

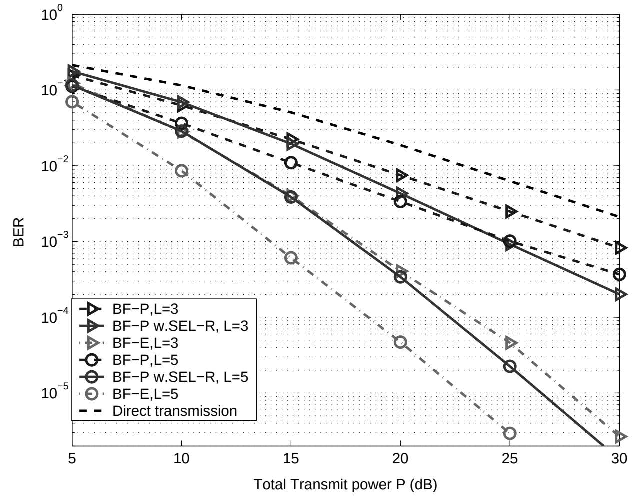

Fig. 2. The average BER as a function of total transmit power P for transmit beamforming.

We compare SEL-R, SEL-D and the the equal gain scheme that applies equal weighting factors to all users in Fig. 3. For the equal gain scheme and SEL-R, to increase the relay number is not beneficial since they cannot suppress random interference from different relays at the destination. However, by discarding symbols with a higher error probability at each relay, SEL-R outperforms the equal gain scheme by 2dB. With the selection rule based on the global CSI, SEL-D attains a much higher diversity gain since only one relay is used for each user and no random interference occurs at the destination. But this requires a feedback message from the destination.

We show the BER curves for selective relaying combined with DSTC in Fig. 4. The block length of DSTC is equal to the number of relays, *i.e.*, $T_s = L$. DSTC achieves better diversity even with an equal gain scheme. The performance gain is more obvious when DSTC is combined with SEL-R, since symbols with smaller SINR at relays are discarded and MAI is mitigated effectively at the destination. The cooperative strategy combining SEL-R and DSTC seems attractive since only the local CSI at each relay is needed. By comparing Figs. 3 and 4, we see that SEL-D with and without DSTC have similar performance. Since symbols forwarded by each relay node are different and these symbols are de-correlated at the destination, DSTC is not useful when the best selection strategy is utilized.

Figure 5 shows the BER of all strategies described above for a network with five relays. The strategies with the equal gain, SEL-R and SEL-D are marked by triangles, circles and squares, respectively. Solid and dash-dot lines indicate cases

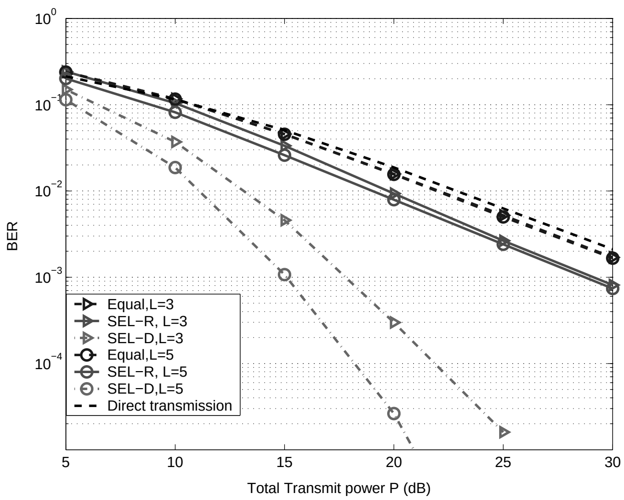

Fig. 3. The average BER as a function of total transmit power P for selective relaying.

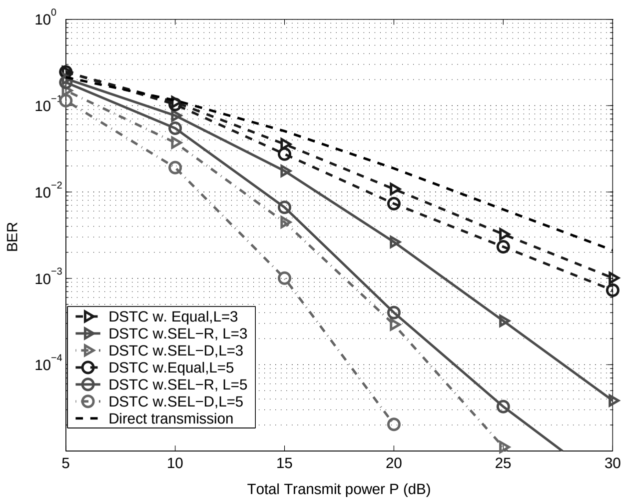

Fig. 4. The average BER curves as a function of total transmit power P for selective relaying with DSTC.

with DSTC and beamforming, respectively. We see from the figure that strategies using one of DSTC, SEL-R or the BF-P do not increase the diversity order, although they provide 5–8 dB gain over the direct transmission. In contrast, by combining either BF-P or DSTC with SEL-R, we can get an improved diversity gain. SEL-D is comparable with BF-E and even outperforms it at high SNR. Thus, by sharing local CSI with a reasonable amount of overhead, the selective strategy that selects the best relay path for each user offers a good design in a multiuser cooperative network.

VI. Conclusion and Future Work

The use of cooperative relaying in a multi-user cooperative CDMA network was studied. The MUD technique is applied at relays with precoding on messages from multiple users in order to decorrelate them at the destination and mitigate MAI. MUD is used in association with three cooperation methods; namely, beamforming, selective relaying and distributed space-time coding. It was shown that diversity can be achieved for beamforming only when we take the detection performance at the relay into account in the determination of weighting factors. With MUD at relays, cooperation provides spatial diversity as well as mitigate MAI for the uplink transmission. By combining selective relaying with beamforming and DSTC, the MAI and the near-far effects can be further reduced. Studies as reported in this work are however preliminary. Systematic design of cooperative DF networks and their performance analysis are under our current investigation.

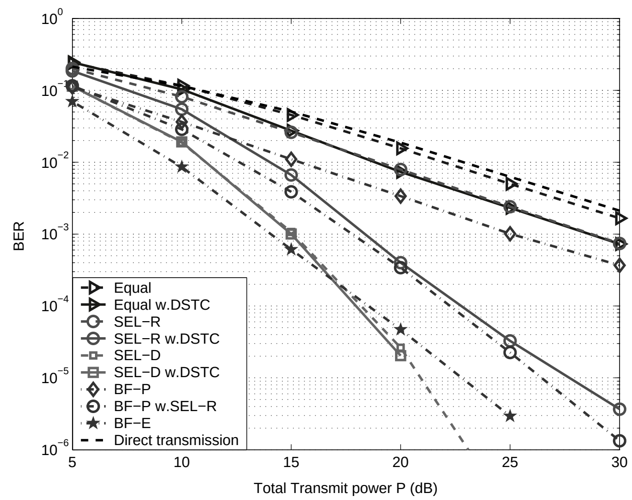

Fig. 5. The average BER curves as a function of total transmit power P for a network with 5 relays.

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