Exchange-and-Forward Protocol for Half-Duplex Transmitter Cooperation

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Abstract—In a transmitter-cooperative network, the source nodes help each other and jointly encode their data, so as to maximize their mutual benefits. In this paper, we focus on a half-duplex four-node network, and study the feasible achievable rates. A transmission scheme, called exchange-and-forward, is proposed. In this scheme, the messages from the two source nodes are first exchanged, and then jointly encoded by using some coding techniques for MISO broadcast channel. The achievable rate region is compared with some existing schemes in literature.

Keywords: Cooperative diversity, transmitter cooperation, half-duplex, MIMO broadcast channel, zero-forcing precoding, dirty-paper coding.

I. INTRODUCTION

In a cooperative network, the users jointly process their data and achieve better data rates for all participating users. The resulting performance gain is sometime called cooperative diversity [1]–[3]. With transmitters’ cooperations, the transmitting nodes help each other by acting as relay nodes. Capacity bounds for full-duplex transmitter-cooperative networks are addressed in [4]. In this paper, we adopt a more practical half-duplex model, in which users cannot transmit and receive simultaneously.

Previous works on cooperative transmission with half-duplex transmitters include [5]–[11] and the references therein. The coding scheme in [5] is based on the compress-and-forward scheme for 3-node relay network. In [6], [7], coding schemes for single-antenna broadcast channel are used. In [6], [8], analog network coding is adopted in the cooperative transmission scheme. But the authors in [12] have shown that the precision errors in real and complex processing can increase the condition number of the network transform matrix, which can potentially reduce the achievable rates substantially. The authors in [9], [10] proposed cooperative transmission scheme where channel state information is unavailable. However, in slow fading channels, such information can be obtained by existing channel estimation schemes. Hence, in this paper, we consider how the transmitters cooperate based on the channel state information. In [11], the authors consider a special case that the two destination nodes are physically collocated.

We introduce two cooperative transmission coding techniques based on two different multiple-input-multiple-output (MIMO) broadcast channel codes. We call them exchange-and-forward schemes. Although the proposed transmission schemes are conceptually simple, a significant gain over other schemes can be obtained.

The system model for the transmitter-cooperative network is described in Section II. Based on some building blocks in Section III, we derive two cooperative transmission schemes in Section IV. The resulting rate regions are compared with some other transmission schemes in V.

II. SYSTEM MODEL AND NOTATION

We consider a network with two source-destination pairs: (1,3) and (2,4) (See Fig. 1). Both source nodes operate in half-duplex mode, i.e., they cannot transmit and receive at the same time. The link gain from node $i$ to node $j$ is denoted by $g_{ij}$. We assume that the channel remains constant over many symbol durations, and regard the link gains as fixed constants. The link gains are assumed to be estimated with no error and known to all nodes.

The whole transmission period is divided into three phases. In the first phase, node 1 transmits, and nodes 2, 3, 4 receive. In the second phase, node 2 transmits, and nodes 1, 3, 4 receive.
In the third phase, both nodes 1 and 2 transmit, and nodes 3 and 4 receive. For \( \phi = 1, 2, 3 \), let \( T_\phi \) be the set of time indices when the system is in phase \( \phi \). The fraction \( |T_\phi|/n \), where \( n \) is the block length and \( |T_\phi| \) is the number of time indices in \( T_\phi \), is called the time-sharing factor and denoted by \( \tau_\phi \).

For \( i = 1, 2 \), let the symbol transmitted by node \( i \) at time \( k \) be \( x_i[k] \), and for \( j = 1, 2, 3, 4 \), the symbol received at node \( j \) at time \( k \) be \( y_j[k] \). The channel symbols are modeled as complex numbers. In phase 1, the channel is described by

\[
y_j[k] = \hat{g}_{ij} x_i[k] + z_j[k]
\]

for \( j = 2, 3 \) and 4, where \( z_j[k] \) is a complex circular Gaussian random variable with mean zero and variance \( \sigma^2 \). In phase 2, we have

\[
y_j[k] = \hat{g}_{ij} x_2[k] + z_j[k]
\]

for \( j = 1, 3 \) and 4. In the third phase, the received symbols are

\[
y_3[k] = \hat{g}_{13} x_1[k] + \hat{g}_{23} x_2[k] + z_3[k] \tag{1}
y_4[k] = \hat{g}_{14} x_1[k] + \hat{g}_{24} x_2[k] + z_4[k]. \tag{2}
\]

We will use a superscript (\( \phi \)) to indicate that a variable is associated with phase \( \phi \). Suppose that node 1 transmits with power \( P_1^{(1)} \) in phase 1, node 2 transmits with power \( P_2^{(2)} \) in phase 2. For \( i = 1, 2 \), we have the following power constraint

\[
\frac{1}{|T_i|} \sum_{k \in T_i} |x_i[k]|^2 \leq P_i^{(i)} \tag{3}
\]

In phase 3, the power of nodes 1 and 2 are denoted by \( P_1^{(3)} \) and \( P_2^{(3)} \) respectively, and the power constraints are

\[
\frac{1}{|T_3|} \sum_{k \in T_3} |x_i[k]|^2 \leq P_i^{(3)} \tag{4}
\]

for \( i = 1, 2 \). The overall power constraints over the three phases are

\[
\tau_1 P_1^{(1)} + \tau_3 P_1^{(3)} \leq \hat{P}_1 \tag{5}
\]

\[
\tau_2 P_2^{(2)} + \tau_3 P_2^{(3)} \leq \hat{P}_2. \tag{6}
\]

Here \( \hat{P}_i \) denote the maximum power of node \( i \).

Let the data rate from node 1 to node 3 and from node 2 to node 4 be \( R_1 \) and \( R_2 \), respectively. A rate pair \( (R_1, R_2) \) is said to be achievable if for any \( \epsilon > 0 \), we can find an encoding scheme, satisfying power constraints (3) to (6), such that node 1 can send at a rate of \( R_1 \) bits per channel use to node 3, node 2 can send at a rate of \( R_2 \) bits per channel use to node 4, and the error probability is less than \( \epsilon \).

We normalize the link gains by \( \sigma \), and define \( g_{ij} := \hat{g}_{ij}/\sigma \). Let

\[
G := \begin{bmatrix} g_{13} & g_{23} \\ g_{14} & g_{24} \end{bmatrix} \tag{7}
\]

be the normalized link gain matrix in the third phase, and

\[
g_1 := [g_{13}, g_{23}] \quad \text{and} \quad g_2 := [g_{14}, g_{24}] \tag{8}
\]

be the first and second row of \( G \). Let

\[
\Gamma_{ij} := |g_{ij}|^2 \hat{P}_1/\sigma^2
\]

be the signal-to-noise ratio (SNR) for the link between nodes \( i \) and \( j \). We will also use the notation

\[
C(x) := \log_2(1 + x)
\]

for Shannon’s capacity formula, and \( I \) for the \( 2 \times 2 \) identity matrix. Given a constant \( k \) and a subset \( \mathcal{A} \) of \( \mathbb{R}^2 \), their product \( k\mathcal{A} \) is defined as \( \{ka : a \in \mathcal{A}\} \).

### III. Background on Coding Techniques

#### A. Multiplexed Coding

Multiplexed coding [4] is a useful building block for cooperative communication. Suppose that we have two messages, \( m_1 \) and \( m_2 \), with \( m_1 \in \{1, 2, \ldots, W_1\} \) and \( m_2 \in \{1, 2, \ldots, W_2\} \). We generate an array of complex Gaussian vectors, \( \mathbf{v}(m_1, m_2) \), of length \( n \). Each of them has unit energy. Given the messages \( m_1 \) and \( m_2 \), the vector \( \sqrt{\mathcal{P}} \mathbf{v}(m_1, m_2) \) is sent from the source. Suppose that a user wants to decode both messages \( m_1 \) and \( m_2 \), and the link gain between the source and this user is \( a_1 \). According to Shannon’s coding theorem, the decoding error can be made arbitrarily small, by increasing the block length, provided that \( \log_2(W_1 W_2)/n \leq C(a_1^2 \mathcal{P}) \). Now suppose that another user knows \( m_2 \) and wants to get the message \( m_1 \). There are only \( W_1 \) possible candidate codewords, \( \mathbf{v}(m_1, m_2) \), for \( m_1 = 1, 2, \ldots, W_1 \). If the link gain is \( a_2 \), \( m_1 \) can be decoded reliably if \( \log_2(W_1)/n \leq C(a_2^2 \mathcal{P}) \).

#### B. Coding Schemes for MISO Gaussian Broadcast Channel

In the third phase, the two transmitting nodes jointly encode the data bits and can be viewed as a combined “super-node” equipped with two transmitting antennas. The third phase can be treated as a multiple-input-single-output (MISO) broadcast channel with two receiving nodes, with each receiving node equipped with one antenna. The MISO broadcast channel is described by a \( 2 \times 2 \) link gain matrix \( \mathbf{G} \). The two received symbols at the destinations, \( y_1 \) and \( y_2 \), are related to the transmitted \( 2 \times 1 \) vectors, \( \mathbf{x} \), by

\[
\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{G} \mathbf{x} + \mathbf{z}, \tag{9}
\]

where \( \mathbf{z} \) is the noise vector. The source “super-node” has two messages \( M_1 \) and \( M_2 \), and want to send \( M_i \) to the \( i \)th receiving node, for \( i = 1, 2 \).

Unlike the usual MISO Gaussian broadcast channel considered in the literature, in which total power constraint is imposed across all transmitting antennas, in this paper, it is required that each transmitting antenna is subject to an individual power constraint. It is because the two transmitting antennas are from two separated nodes, whose energy sources cannot be shared. We thus have to consider per-antenna power constraints in the MISO broadcast channel for our application. The two power constraints for the two transmitting antennas are denoted by \( P_{1\max} \) and \( P_{2\max} \).

We list two existing coding schemes for the MISO Gaussian broadcast channel.
1) Zero-forcing Pre-coding: With zero-forcing pre-coding, the MISO broadcast channel is decoupled into two orthogonal virtual channels (see e.g. [13], [14]). The decoupling is accomplished by pre-multiplying the transmitted symbols by a $2 \times 2$ matrix $T$ and make a change of variable $x = Tu$, where $u$ is a $2 \times 1$ information vector that with covariance matrix $E[uu^H] = I_2$. The pre-coding matrix $T$ is chosen such that $GT$ is a diagonal matrix $\text{diag}(h_1, h_2)$. The channel is then transformed to two orthogonal channels, with virtual channel gains $h_1$ and $h_2$.

\[
\begin{bmatrix}
y_1 \\
y_2
\end{bmatrix} = \begin{bmatrix} h_1 & 0 \\
0 & h_2 \end{bmatrix} \begin{bmatrix} u \\
z \end{bmatrix}.
\]

With the per-antenna power requirement, the precoding matrix $T$ must satisfy the following constraints

\[
|t_{11}|^2 + |t_{12}|^2 \leq P_{1\text{max}} \\
|t_{21}|^2 + |t_{22}|^2 \leq P_{2\text{max}}.
\]

By employing point-to-point coding scheme for each orthogonal channel, data can be sent to receiving node $i$ at a rate of $C(h_i^2/\sigma^2)$, for $i = 1, 2$. We will denote the set of all achievable rate pairs by zero-forcing per-coding by $C_{ZF}(P_{1\text{max}}, P_{2\text{max}}, G)$.

2) Dirty-paper Coding: We first consider a point-to-point channel, where the received signal $y[t] = x[t] + s[t] + z[t]$ is composed of data-carrying signal $x[t]$, interfering signal $s[t]$ and additive white Gaussian noise $z[t]$. The power of $x[t]$, $s[t]$ and $z[t]$ are denoted by $P$, $Q$ and $N$ respectively. If the interfering signal $s[t]$ is non-causally known to the encoder, we can apply dirty-paper coding [15] and achieve a data rate of $\log_2(1 + P/N)$, which is the same as the data rate as if the interference is absent.

Dirty-paper coding is applied to the MISO Gaussian broadcast channel in the following way [16]. It is proved in [17] that dirty-paper coding can achieve the capacity region of multiple-input multiple-output (MIMO) broadcast channel in general. We first specify an encoding order. For example, we encode the message to receiver 1 first, and then encode the message to receiver 2. After the signal to receiver 1 is generated, we treat it as interference $s[t]$. The condition that the interference is perfectly known non-causally to the transmitter is thus satisfied. The signal to the second user, $x[t]$, is dirty-paper coded on top of $s[t]$. At the receiver of the first user, $x[t]$ and $z[t]$ are treated as interference and noise, and the rate for the first user is $\log(1 + Q/(P + N))$. The second user can decode at a rate as if the signal $s[t]$ is absent, and achieve a data rate of $\log(1 + P/N)$.

For the MISO broadcast channel (9) with per-antenna constraint $P_{1\text{max}}$ and $P_{2\text{max}}$, if we encode the message of user 1 first and user 2 next, the achievable rates of the two users by dirty-paper coding is

\[
C \left( \frac{g_1 \Sigma_1 g_1^H}{1 + g_1 \Sigma_2 g_1^H} , \frac{g_2 \Sigma_2 g_2^H}{1 + g_2 \Sigma_1 g_2^H} \right).
\]

where $\Sigma_1$ and $\Sigma_2$ are covariance matrices satisfying

\[
\text{tr} \left( \begin{bmatrix} 1 & 0 \\
0 & 0 \end{bmatrix} (\Sigma_1 + \Sigma_2) \right) \leq P_{1\text{max}} \tag{10}
\]

\[
\text{tr} \left( \begin{bmatrix} 0 & 0 \\
0 & 1 \end{bmatrix} (\Sigma_1 + \Sigma_2) \right) \leq P_{2\text{max}}. \tag{11}
\]

In words, the power constraints in (10) and (11) require that the upper left and lower right entry of $\Sigma_1 + \Sigma_2$ are less than $P_{1\text{max}}$ and $P_{2\text{max}}$, respectively.

If the encoding order is reversed, we have the following achievable rate pair

\[
\left( C(g_1 \Sigma_1 g_1^H), C \left( \frac{g_2 \Sigma_2 g_2^H}{1 + g_2 \Sigma_1 g_2^H} \right) \right).
\]

The capacity region of the MISO broadcast channel is the convex hull of the union of all such rate pairs over all covariance matrices $\Sigma_1$ and $\Sigma_2$ satisfying (10) and (11), and over the two encoding orders. Given the two power constraints $P_{1\text{max}}$ and $P_{2\text{max}}$ for the two transmitting antennas, the capacity region of MISO broadcast channel is denoted by $C_{DP}(P_{1\text{max}}, P_{2\text{max}}, G)$. Details on transmitter optimization for dirty-paper coding with per-antenna power constraint can be found in [18] for instance.

IV. EXCHANGE-AND-FORWARD SCHEME

The transmission schemes are based on the decode-and-forward method. The two source nodes first exchange their messages during phase 1 and phase 2, and then jointly encode the two messages in phase 3. We call this approach exchange-and-forward. In phase 3, there are two options. One can use the zero-forcing pre-coding scheme or the dirty-paper coding schemes. The transmission scheme with zero-forcing pre-coding scheme is called EF-ZF, the transmission scheme with dirty-paper coding is called EF-DP. We describe the transmission scheme in details below.

For $i = 1, 2$, the message for node $i$ is divided into two parts, $m_{ir}$ and $m_{id}$, the first one consists of $nR_{ir}$ bits and the second $nR_{id}$ bits. The two data rates $R_{ir}$ and $R_{id}$ are chosen such that $R_i = R_{ir} + R_{id}$. The subscript “d” indicates that the data is transmitted directly from the source to the intended destination, while the subscript “r” indicates that the data is delayed via the opposite source node. We pick two real numbers $\alpha, \beta$ such that $0 \leq \alpha, \beta \leq 1$.

Let $n$ be the block length. Phase 1 consists of the first $\tau_1 n$ symbols. The message $(m_{1r}, m_{1d})$ is encoded into a codeword $x_1(m_{1r}, m_{1d})$ of length $\tau_1 n$, with energy equals $\alpha P_1 \tau_1 n$. At the end of phase 2, node 2 decodes both $m_{1r}$ and $m_{1d}$. Node 3 buffers the received signal for later processing.

Phase 2 consists of the next $\tau_2 n$ symbols. Node 2 encodes $(m_{2r}, m_{2d})$ into a codeword $x_2(m_{2r}, m_{2d})$ of length $\tau_2 n$, with energy $\beta P_2 \tau_2 n$. Upon receiving $x_2(m_{2r}, m_{2d})$, node 1 decodes both $m_{2r}$ and $m_{2d}$, and node 3 stores the received signal.

Phase 3 occupies the remaining $\tau_3 n$ symbols. The messages $m_{1r}$ and $m_{2r}$ are now known to both node 1 and node 2.
and are jointly encoded using zero-forcing pre-coding or dirty-paper coding. At the end of phase 3, node 3 decodes \( m_{1r} \) and node 4 decodes \( m_{2r} \). Then, after node 3 has decoded \( m_{1r} \), the message \( m_{1d} \) can be recovered from \( x_1(m_{1r}, m_{1d}) \) by multiplexing coding. Similarly, having decoded \( m_{2r} \), node 4 decodes \( m_{2d} \) by multiplexing coding at the end of the transmission.

The achievable rate regions are given below.

**Theorem 1:** A rate pair \((R_1, R_2)\) is achievable by EF-ZF if it satisfies

\[
R_1 = R_{1r} + R_{1d} \leq \tau_1 C(\alpha \Gamma_{12}/\tau_1) \tag{12}
\]

\[
R_2 = R_{2r} + R_{2d} \leq \tau_2 C(\beta \Gamma_{21}/\tau_2) \tag{13}
\]

\[
0 \leq R_{1d} \leq \tau_1 C(\alpha \Gamma_{13}/\tau_1) \tag{14}
\]

\[
0 \leq R_{2d} \leq \tau_2 C(\beta \Gamma_{24}/\tau_2) \tag{15}
\]

\[
(R_{1r}, R_{2r}) \in \mathcal{C}_{ZF} \left( \frac{\alpha P_1}{\tau_3}, \frac{\beta P_2}{\tau_3}, G \right) \tag{16}
\]

for some time-sharing factors \( \tau_1, \tau_2 \) and \( \tau_3 \), power-sharing factors \( \alpha, \bar{\alpha}, \beta, \bar{\beta} \) such that

\[
\alpha + \bar{\alpha} = \beta + \bar{\beta} = \tau_1 + \tau_2 + \tau_3 = 1
\]

\[
\alpha, \bar{\alpha}, \beta, \bar{\beta}, \tau_1, \tau_2, \tau_3 \geq 0.
\]

A rate pair \((R_1, R_2)\) is achievable by EF-DP if it satisfies (12) to (18), with \( \mathcal{C}_{ZF} \) in (16) replaced by \( \mathcal{C}_{DP} \).

**Proof:** We prove the achievability for EF-ZF. The analogous result for EF-DP is the same and omitted. Suppose \( \alpha, \beta, \bar{\alpha}, \bar{\beta}, \tau_1, \tau_2, \tau_3 \) are given numbers satisfying (17) and (18). The total amount of energy available to node 1 in \( n \) symbol times is \( nP_1 \). Node 1 divides the total available energy into two parts, \( \alpha nP_1 \) for the transmissions in phase 1 and 3 respectively. The resulting powers in phase 1 and phase 3 are respectively

\[
\alpha nP_1/(\tau_1 n) = \alpha P_1/\tau_1 \text{ and } \bar{\alpha} nP_1/(\tau_3 n) = \bar{\alpha} P_1/\tau_3.
\]

Similar, node 2 splits its total available energy to phase 2 and phase 3, such that the powers of node 2 in phase 2 and phase 3 are respectively \( \beta P_2/\tau_2 \) and \( \bar{\beta} P_2/\tau_3 \).

At the end of phase 1, node 2 is required to decode the message from node 1 correctly. This can be done if the rate constraint (12) is satisfied. On the other hand, node 1 is required to decode the message from node 2 correctly after phase 2. This induces the rate constraint (13). Since \( R_{1r} \) and \( R_{2r} \) satisfy (16), \( m_{1r} \) and \( m_{2r} \) can be decoded successfully. Finally, for the multiplexing coding, we need the rate requirements in (14) and (15).

**V. COMPARISON WITH OTHER SCHEMES**

We compare the performance of the exchange-and-forward scheme with some existing schemes.

1) Non-cooperative scheme: Both users transmit simultaneously and treat the signal from the other as noise. Optimal point-to-point Gaussian signaling scheme is employed. The achievable rate region is a rectangle described by the following inequalities:

\[
0 \leq R_1 \leq C(\Gamma_{13}/(\Gamma_{24} + 1))
\]

\[
0 \leq R_2 \leq C(\Gamma_{24}/(\Gamma_{13} + 1)).
\]

2) TDMA scheme: In this scheme, the source nodes cooperate by making an agreement on the transmission schedule. The total transmission time is divided into two phases; node 1 transmits in the first phase and node 2 transmits in the second phase. Let \( \tau_1 \) and \( \tau_2 \) be the time-sharing factors. A rate pair \((R_1, R_2)\) is achievable by the TDMA scheme if

\[
0 \leq R_1 \leq \tau_1 C(\Gamma_{13}/\tau_1)
\]

\[
0 \leq R_2 \leq \tau_2 C(\Gamma_{24}/\tau_2)
\]

for some \( \tau_1 \) and \( \tau_2 \) such that \( \tau_1 + \tau_2 = 1 \).

3) Optimal coding scheme for interference channel with strong interference: In this scheme, both sources always transmit simultaneously and joint encoding is employed. The channel is reduced to a Gaussian interference channel (IC). Determining the capacity region for Gaussian interference channel in general is currently an open problem. However, when the interference is strong, meaning that \( |g_{13}| \leq |g_{14}| \) and \( |g_{24}| \leq |g_{23}| \), the capacity region is known [19]:

\[
0 \leq R_1 \leq C(\Gamma_{13})
\]

\[
0 \leq R_2 \leq C(\Gamma_{24})
\]

\[
R_1 + R_2 \leq C(\Gamma_{14} + \Gamma_{24})
\]

\[
R_1 + R_2 \leq C(\Gamma_{13} + \Gamma_{23}).
\]

4) Cooperative Broadcast (CB): This scheme was first studied in [7] for parallel channels. The two source nodes cooperate in the network-layer level, and transmit alternately. The third phase is not utilized. As in EF-ZF and EF-DP, data from each source node is divided into two data streams. In each phase, we employ the optimal coding scheme for the single-antenna Gaussian broadcast channel with three receivers, and denote the associated capacity region by \( \mathcal{C}_{BC} \). A rate pair \((R_1, R_2)\) is achievable under the CB scheme if

\[
(R_{1d}, R_{2d}, R_{1r}) \in \tau_1 \mathcal{C}_{BC}(\bar{P}_1/\tau_1, g_{13}, g_{14}, g_{12})
\]

\[
(R_{2d}, R_{1r}, R_{2r}) \in \tau_2 \mathcal{C}_{BC}(\bar{P}_2/\tau_2, g_{24}, g_{23}, g_{21})
\]

for some time sharing factors \( \tau_1 \) and \( \tau_2 \) such that \( \tau_1 + \tau_2 = 1 \).

Comparison of the achievable rate regions of the aforementioned schemes is shown in Fig. 2 and 3. Points on the boundaries of the rate regions are obtained by maximizing \( R_2 \) for fixed values of \( R_1 \), or vice versa. The computations are done with the help of CVX, a package for solving convex programs [20].

Since transmitter cooperation is effective only when the link gain between the two source nodes is high enough, we consider a scenario in which the inter-source link gain is the strongest. In Fig. 2, the link gains are set as follows: \( g_{12}^2 = g_{21}^2 = 36, g_{14}^2 = g_{23}^2 = 2.25, g_{13}^2 = g_{24}^2 = 1 \). The argument of the complex link gains are
We study and propose two transmission schemes for a four-node transmitter-cooperative network. Both of them leverage on coding schemes designed for the Gaussian MIMO broadcast channel. The first scheme is based on zero-forcing pre-coding and the second one is based on the dirty paper coding. Numerical example shows that the zero-forcing scheme is very efficient, with performance very close to the high-complexity dirty-paper scheme.

VI. Conclusion

Fig. 2. Achievable Rate Regions for Strong Inter-Source Links

Fig. 3. Achievable Rate Regions for Large Cross Link Gain and Low SNR

arbitrarily chosen. We set the per-antenna power constraints to $P_1 = P_2 = 10$ and all noise powers to 1. We can see that the rate regions of EF-ZF and EF-DP dominate the rate regions of the others, including the optimal coding scheme for IC in the strong interference regime. In Fig. 3, we plot the rate region in a low-SNR case and reduce the power constraints on both antenna to 1. The cross link gain are chosen to be largest among others. We set $|g_{13}|^2 = |g_{24}|^2 = 1$, $|g_{21}|^2 = 4$, $|g_{12}|^2 = 9$, and $|g_{14}|^2 = |g_{23}|^2 = 16$. Again the argument of the link gains are arbitrarily chosen and the noise powers are set to 1. As in the previous figure, the curves for EF-DP and EF-ZP dominates the other schemes. In Fig. 2 and 3, the boundaries of their rate regions are very close in a region near the maximal sum rate point. In both cases, the maximal sum rates of EF-DP and EF-ZF differ by less than one percent. As zero-forcing pre-coding can be implemented more easily than dirty paper coding, EF-ZF is a low-complexity solution with slight performance degradation for the four-node transmitter-cooperative network.

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