Transmit Signal and Bandwidth Optimization in Multiple-Antenna Relay Channels

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Abstract—In a multiple-antenna relay channel, the full-duplex cut-set capacity upper bound and decode-and-forward rate are formulated as convex optimization problems. For half-duplex relaying, bandwidth allocation and transmit signals are optimized jointly. Moreover, achievable rates based on the compress-and-forward strategy are presented using rate-distortion and Wyner–Ziv compression schemes.

Index Terms—Bandwidth allocation, convex optimization, relay channel, transmit covariance matrix.

I. INTRODUCTION

In wireless communications, relaying has been proposed to improve system performance by allowing shortened transmission range, geographically distributed power sources, and cooperation with the source nodes to perform joint encoding of the transmit signals. In this letter, we investigate the optimization of transmit signals in a multiple-input multiple-output (MIMO) relay channel. In a point-to-point channel, using multiple transmit and receive antennas has been shown to provide substantial improvement in capacity [1], [2]. We evaluate the MIMO relay channel rates under different network geometry, and investigate the effectiveness of the corresponding relaying schemes.

In [3], a capacity upper bound and achievable coding strategies are presented for the relay channel, but the relay channel capacity remains an open problem. For Gaussian single-antenna relay channels, capacity bounds and power allocation are studied in [4]. Capacity bounds on half-duplex relaying are presented in [5], [6]. Bandwidth and power allocation are considered in [7], [8] for fading orthogonal relay channels, and in [9] for the amplify-and-forward scheme in Gaussian relay networks. Resource allocation in single-antenna relay channels is treated in [10], [11]. For relay channels with multiple-antenna terminals, bounds to the cut-set capacity upper bound and decode-and-forward rate are considered in [12]. In [13], [14], joint power optimization is considered for more general cooperative systems.

While the relay channel capacity bounds have been applied in single-antenna channels [15], evaluating the capacity bounds for MIMO relay channels requires the additional optimization of the source- and relay- antenna covariance matrices. We consider a multiple-antenna relay channel where the terminals have knowledge of the channel state information (CSI), and evaluate the MIMO cut-set capacity upper bound and the decode-and-forward achievable rate by formulating them as convex optimization problems. In the case of half-duplex relaying, the bandwidth allocation and the multiple-antenna transmit signals are optimized jointly. We also present achievable rates in MIMO relay channels using the compress-and-forward approach, under which the rate-distortion and Wyner-Ziv compression schemes are considered. Shortly before publication we learned of prior works [16], [17], which treated MIMO relay covariance optimization and time division duplex relaying. To contrast, in this letter, full-duplex decode-and-forward and compress-and-forward relaying are included. Furthermore, here, in the case of half-duplex cut-set bound and decode-and-forward relaying, joint optimization over bandwidth allocation and covariance matrices is considered: transmit power may be concentrated in sub-bands subject to average power constraints.

The remainder of this letter is organized as follows. Section II presents the system model. The cut-set bound and decode-and-forward rate optimization formulations are described in Section III. The compress-and-forward scheme is studied in Section IV. Numerical results are presented in Section V, followed by conclusions in Section VI.

II. SYSTEM MODEL

Consider a three-node wireless relay channel as illustrated in Fig. 1. The source node wishes to send a message to the destination; the relay node does not have its own message to send, but facilitates the transmission between the source and destination. Suppose the source has \( M_1 \) transmit antennas, and the destination has \( N_1 \) receive antennas. We assume the relay has \( M_2 \) transmit antennas and \( N_2 \) receive antennas (for instance, in full-duplex operation the relay may have different sets of transmit and receive antennas). We consider a discrete-time flat-fading channel model, which is described by

\[
y_1 = H_{11}x_1 + H_{12}x_2 + z_1, \quad y_2 = H_{21}x_1 + z_2
\]

where \( x_1 \in \mathbb{C}^{M_1}, x_2 \in \mathbb{C}^{M_2} \) are the respective transmit signals of the source and relay; \( y_1 \in \mathbb{C}^{N_1}, y_2 \in \mathbb{C}^{N_2} \) are the respective receive signals of the destination and relay; and \( z_1 \sim \mathcal{CN}(0, I_{N_1}) \in \mathbb{C}^{N_1}, z_2 \sim \mathcal{CN}(0, I_{N_2}) \in \mathbb{C}^{N_2} \) are independent zero-mean circularly symmetric complex Gaussian (ZMCSCG) noise at the destination and relay, respectively. The complex baseband channel from the source to destination is \( H_{11} \in \mathbb{C}^{N_1 \times M_1} \); from the source to relay is \( H_{21} \in \mathbb{C}^{N_2 \times M_1} \); and from the relay to destination is \( H_{12} \in \mathbb{C}^{N_1 \times M_2} \).

We consider a block-fading channel model: the channels realize independently according to their distribution at the beginning of each fading block, and they remain unchanged within the duration of the fading block. We assume the...
channel states can be estimated accurately and conveyed in a timely manner to all terminals, i.e., we assume channel state information (CSI) is available at all nodes. The source and the relay are under the respective transmit power constraints: $\mathbb{E}[x_i^H x_i] \leq P_i$, $i = 1, 2$, where the expectations are over repeated channel uses within every fading block. Power allocation across fading blocks is not permitted. The transmit signals have zero mean: $\mathbb{E}[x_1] = 0$, $\mathbb{E}[x_2] = 0$. It is convenient to write (1) in block-matrix form $y = Hx + z$, where

$$
y \triangleq \begin{bmatrix} y_1 \\
y_2 \end{bmatrix} \in \mathbb{C}^N, \quad H \triangleq \begin{bmatrix} H_{11} & H_{12} \\
H_{21} & 0 \end{bmatrix} \in \mathbb{C}^{N \times M} \quad (2)
$$

$$
x \triangleq \begin{bmatrix} x_1 \\
x_2 \end{bmatrix} \in \mathbb{C}^M, \quad z \triangleq \begin{bmatrix} z_1 \\
z_2 \end{bmatrix} \in \mathbb{C}^N \quad (3)
$$

with $M \triangleq M_1 + M_2$, and $N \triangleq N_1 + N_2$. Moreover, we denote the joint covariance matrix of the transmit signals of the source and relay as

$$
Q \triangleq \mathbb{E}[xz^H] \in \mathbb{H}_+^M \quad (4)
$$

where $\mathbb{H}_+^M$ denotes the set of $M \times M$ positive semidefinite Hermitian matrices. The conformally partitioned blocks (with respect to $x_1, x_2$) of $Q$ have dimensions

$$
Q_{11} \triangleq \mathbb{E}[x_1 x_1^H] \in \mathbb{H}_+^{M_1}, \quad Q_{22} \triangleq \mathbb{E}[x_2 x_2^H] \in \mathbb{H}_+^{M_2}
$$

$$
Q_{12} \triangleq \mathbb{E}[x_1 x_2^H] = Q_{21}^T \in \mathbb{C}^{M_1 \times M_2}. \quad (5)
$$

### III. MIMO RELAY CHANNEL CAPACITY BOUNDS

#### A. Full-Duplex Relaying

In this section, we present the optimization frameworks for evaluating the MIMO relay channel cut-set capacity upper bound and the decode-and-forward achievable rate. We first adopt the full-duplex assumption where the relay can transmit and receive in the same frequency band at the same time. The cut-set capacity upper bound [3] for the relay channel is given as an optimization in terms of the channel mutual information as follows:

$$
R_{CS} = \max_{p(x_1, x_2)} \min \{ I(x_1; y_1, y_2|x_2), I(x_1, x_2; y_1) \}. \quad (6)
$$

Gaussian signals are optimal in the cut-set bound and decode-and-forward rate [15, Proposition 2]. We denote the transmit signals by: $x \sim \mathcal{CN}(0, Q)$, where $Q \in \mathbb{H}_+^M$ is the covariance matrix of $x$. Then the mutual information expressions in (6) evaluate [2] to

$$
R_{CS} = \max_{p(x_1, x_2)} \min \left\{ \log \det( I_N + H_1 Q_{12} H_1^H ), \log \det( I_{N_1} + H_1 Q_{11} H_1^H ) \right\} \quad (7)
$$

where $H_1$ and $H_1$ are, respectively, the first block column and block row of $H$, i.e., $H_1 \triangleq [H_{11}^T H_{21}^T]^T \in \mathbb{C}^{N \times M_1}$, $H_1 \triangleq [H_{11} H_{12}] \in \mathbb{C}^{N_1 \times M}$; and the conditional covariance matrix $Q_{12} \triangleq \mathbb{E}[x_1 x_2^H|x_2]$ is given by the Schur complement of $Q_{22}$ in $Q$

$$
Q_{12} = Q_{11} - Q_{12} Q_{22}^{-1} Q_{21} \quad (8)
$$

where we assume $Q_{22} > 0$. The zero-mean Gaussian signal $x$ is fully characterized by its covariance; therefore, in (7), the sole optimization variable is the joint covariance matrix $Q$. The cut-set bound maximization in (7) can be formulated as follows:

maximize $R_{CS}$

over $R_{CS} \in \mathbb{R}_+$, $Q \in \mathbb{H}_+^M$, $Q_{12} \in \mathbb{H}_-^{M_1}$

subject to

$$
R_{CS} \leq \log \det( I_N + H_1 Q_{12} H_1^H ) \quad (11)
$$

$$
R_{CS} \leq \log \det( I_{N_1} + H_1 Q_{11} H_1^H ) \quad (12)
$$

$$
\text{tr}(C_1^T Q_{11} C_1) \leq P_1, \quad \text{tr}(C_2^T Q_{12} C_2) \leq P_2 \quad (13)
$$

$$
Q - C_1 Q_{12} C_2^T \succeq 0 \quad (14)
$$

where $C_1, C_2$ are constant matrices defined as

$$
C_1 \triangleq \begin{bmatrix} I_{M_1} \\
0 \end{bmatrix} \in \mathbb{C}^{M \times M_1}, \quad C_2 \triangleq \begin{bmatrix} 0 \\
I_{M_2} \end{bmatrix} \in \mathbb{C}^{M \times M_2}. \quad (15)
$$

In the optimization, (11), (12) follow from the two terms inside the min expression in (7); and (13) represents the per-node transmit power constraints at the source and relay, respectively. The constraint (14) results from relaxing the equality constraint in (8)

$$
Q_{12} = Q_{11} - Q_{12} Q_{22}^{-1} Q_{21} \quad \implies \quad Q_{12} \preceq Q_{11} - Q_{12} Q_{22}^{-1} Q_{21}. \quad (16)
$$

By the semidefiniteness property of Schur complements [18], we have the following identity on the right-hand side of (16):

$$
(Q_{11} - Q_{12} Q_{22}^{-1} Q_{21}) \succeq 0 \quad \implies \quad \begin{bmatrix} (Q_{11} - Q_{12}) & Q_{12} \\
Q_{12} & Q_{22} \end{bmatrix} \succeq 0 \quad (17)
$$

where the right-hand side of (17) is equivalent to $Q - C_1 Q_{12} C_2^T \succeq 0$ when written in the block-matrix form as defined in (4). Finally, we show the relaxation in (16) does not increase the optimal value in (9). Suppose given a set of fixed $Q_{11}, Q_{12}, Q_{21}, Q_{22}$, we consider all $X \in \mathbb{H}_+^{M_1}$ such that $X \preceq Q_{11} - Q_{12} Q_{22}^{-1} Q_{21}$. Recalling that the determinant is matrix increasing [19] on the set of positive semidefinite matrices, we get

$$
\log \det( I_N + H_1 X H_1^H ) \leq \log \det( I_N + H_1 (Q_{11} - Q_{12} Q_{22}^{-1} Q_{21}) H_1^H ) \quad (18)
$$

which only limits the feasible set in (11).

1 In the interior-point optimization method, $Q$ may be arbitrarily close to being singular but remains positive definite.
The maximization in (9)–(14) is a convex optimization problem; in particular, the log-determinant function is concave on positive definite matrices [19]. The solution of (9) can be efficiently computed using standard convex optimization numerical techniques, for instance, by the interior-point method [19]–[21]. The above optimization can also be solved by the CVX [22] software package, which uses a successive approximation approach to model the log-determinant inequalities. All optimization formulations presented in this letter are convex problems, unless otherwise noted.

The decode-and-forward [3, Thm. 1] relay channel achievable rate is given by

\[
R_{\text{DF}} = \max_{p(x_1, x_2)} \min \{I(x_1; y_2|x_2), I(x_1, x_2; y_1)\}
\]

\[
= \max_Q \log \det \left( I_{N_2} + H_2 Q_{1|2} H_2^H \right)
\]

where \( Q_{1|2} \) is as given in (8). Note that (20) closely parallels (7); hence the decode-and-forward rate can be computed by a similar optimization formulation as in (9)–(14), except the aggregate channel \( H_1 \) in (11) is replaced with the source-relay channel \( H_{21} \).

\[\text{subject to}
\]

B. Half-Duplex Relaying

For the case when the relay cannot transmit and receive at the same time over the same frequency band, we consider half-duplex relaying. We normalize the channel to have unit bandwidth with bandwidth \( w_1 \) and another orthogonal sub-channel Band 2 with bandwidth \( w_2 \), with \( w_1 + w_2 \leq 1 \). The relay can only receive in Band 1 and can it only transmit in Band 2. Hence the channel is described by:

\[
y_1^{(1)} = H_{11} x_1^{(1)} + z_1^{(1)}; y_2^{(1)} = H_{12} x_1^{(1)} + z_2^{(1)}; y_1^{(2)} = H_{21} x_1^{(2)} + z_1^{(2)} \]

where the superscripts designate the corresponding bands. The noise powers in the sub-channels are given by:

\[E[|z_i^{(1)}|^2], E[|z_i^{(2)}|^2] = w_i I_N, \quad w_i \in \mathbb{R}_+ \]

Furthermore, let \( Q_1^{(1)}, Q_2^{(2)} \) denote the transmit signal covariance matrices in the two bands:

\[Q_1^{(1)} = E[x_1^{(1)} (x_1^{(1)})^H] \in \mathbb{H}_M^+; Q_2^{(2)} = E[x_2^{(2)} (x_2^{(2)})^H] \in \mathbb{H}_M^+ \]

To evaluate the half-duplex cut-set bound, let \( R_1, R_2 \) respectively, denote the ingress information rate out of the source in Band 1 and Band 2 as illustrated in Fig. 2(a). On the other hand, let \( R_d, R_c \) be the ingress information rate into the destination in Band 1 and Band 2, respectively, as shown in Fig. 2(b). We then maximize over the transmit signals and the bandwidth allocation:

\[
\text{maximize } R_{\text{hCS}} \quad \text{over } R_{\text{hCS}}, R_1, R_2, R_d, R_c,
\]

\[
\text{subject to}
\]

\[R_{\text{hCS}} \leq \min \{R_1 + R_2, R_d + R_c\} \]

\[R_1 \leq w_1 \log \det \left( I_{N_1} + \frac{1}{w_1} H_{11} Q_1^{(1)} H_{11}^H \right) \]

\[R_2 \leq w_2 \log \det \left( I_{N_1} + \frac{1}{w_2} H_{11} Q_2^{(2)} C_1 H_{11}^H \right) \]

\[R_d \leq w_1 \log \det \left( I_{N_1} + \frac{1}{w_1} H_{11} Q_{1|2} H_{11}^H \right) \]

\[R_c \leq w_2 \log \det \left( I_{N_1} + \frac{1}{w_2} H_{11} Q_{1|2} H_{11}^H \right) \]

where \( C_1, C_2 \) are as defined in (15). By continuity we define:

\[w \log \det(I + X/w) \big|_{w=0} = 0 \quad \text{for all } X > 0 \]

Next, Fig. 3 depicts the operation of decode-and-forward in the half-duplex mode. In Band 1, the source sends to the relay at rate \( R_r \), of which \( R_d \) is decodable at the destination. The relay fully decodes the message from the source, and in Band 2 the source and relay cooperatively send to the destination additional information at rate \( R_c \). The half-duplex decode-and-forward optimization is given as follows:

\[
\text{maximize } R_{\text{hDF}} \quad \text{over } R_{\text{hDF}}, R_r, R_d, R_c,
\]

\[w_1, w_2 \in \mathbb{R}_+, Q_1^{(1)} \in \mathbb{H}_M^+, Q_2^{(2)} \in \mathbb{H}_M^+ \]

subject to

\[R_{\text{hDF}} \leq \min \{R_r + R_d + R_c\} \]

\[R_r \leq w_1 \log \det \left( I_{N_1} + \frac{1}{w_1} H_{21} Q_1^{(1)} H_{21}^H \right) \]

\[R_d \leq w_2 \log \det \left( I_{N_1} + \frac{1}{w_2} H_{21} Q_{1|2} H_{21}^H \right) \]

\[R_c \leq w_2 \log \det \left( I_{N_1} + \frac{1}{w_2} H_{21} Q_{1|2} H_{21}^H \right) \]

Numerical results of the full- and half-duplex cut-set bounds and decode-and-forward rates are presented in Section V.
is a constant scaling matrix, and the letter can be modeled by the capacity-achieving location and compression schemes. We assume the source and the relay use Gaussian signals. Using the capacity-achieving formulations, however, the transmit signal design and bandwidth allocation under compress-and-forward do not appear to be convex problems. In this section, we consider achievable compress-and-forward transmission schemes. We focus on full-duplex transmission; under fixed bandwidth allocation, the compression-and-forward operation readily extends to half-duplex relaying.

We first describe the general compress-and-forward strategy. The optimal joint design of the transmit signals and compression rate appears to be intractable; in the following we present suboptimal approaches to consider specific power allocation and compression schemes. We assume the source and the relay use Gaussian signals. Using the capacity-achieving strategy as in a multiple-access channel [23], suppose the destination performs successive interference cancellation: it first decodes the relay’s message so transmission from the source is interference-free. The source optimizes its own transmit signal covariance $Q_{11}$ according to

$$R_{11} = \max_{Q_{11}} \log \det(I + H_{11} Q_{11} H_{11}^H)$$

where the solution is given by the waterfilling procedure. Let $Q_{11}^{\ast}$ denote the covariance matrix that maximizes (38). Next, the relay optimizes its transmit signal against the interference from the source’s transmit

$$R_{12} = \max_{Q_{22}} \log \det(I + \hat{H}_{12} Q_{22} \hat{H}_{12}^H)$$

where $\hat{H}_{12}$ is the effective channel from the relay to destination treating interference from the source as noise, i.e.,

$$\hat{H}_{12} \triangleq (I + H_{11} Q_{11}^{\ast} H_{11}^H)^{-\eta/2} H_{12}. $$

Similarly, the solution in (39) is given by waterfilling against the effective channel $\hat{H}_{12}$.

In the compress-and-forward approach, the relay sends $\hat{y}_2 \in \mathbb{C}^{N_2}$ to the destination, which is a compressed version of the relay’s receive signal $y_2$, with compression rate $R_{12}$ as given in (39). The compression schemes considered in this letter can be modeled by $\hat{y}_2 = A y_2 + \tilde{z}$, where $A \in \mathbb{C}^{N_2 \times N_2}$ is a constant scaling matrix, and $\tilde{z} \sim \mathcal{CN}(0, Z) \in \mathbb{C}^{N_2}$ is independent additive Gaussian compression noise, with $Z \in \mathbb{H}_1^{N_2}$. Upon receiving $\hat{y}_2$ at the destination, the relay network is equivalent to an $M_1 \times (N_1 + N_2)$ MIMO channel, except that $N_2$ of its receive antennas are scaled by $A$ and corrupted by compression noise $\tilde{z}$.

$$\begin{bmatrix} y_1 \\ \hat{y}_2 \end{bmatrix} = \begin{bmatrix} H_{11} \\ A H_{21} \end{bmatrix} x_1 + \begin{bmatrix} z_1 \\ A z_2 + \tilde{z} \end{bmatrix}. $$

The corresponding channel capacity is given by $R_{CF} = \log \det(I + \hat{H}_{11} Q_{11}^{\ast} H_{11}^H)$, where $\hat{H}_{11}$ is the effective source-to-destination-and-relay MIMO channel, incorporating the degradation introduced by the compression scheme as given in (40)

$$\hat{H}_{11} = \left( (Z + AA^H)^{-1/2} A H_{21} \right) \in \mathbb{C}^{N \times M_1}. $$

The different compression schemes considered in this letter differ in their respective achieved values of $A$ and $Z$. Under rate–distortion compression,

$$A_{RD} = (I_{N_2} - Z_{RD} S_{22}^{-1/2})$$

$$S_{22} \triangleq \mathbb{E}[y_2 y_2^H] = I_{N_2} + H_{21} Q_{11}^H H_{21}^H \in \mathbb{H}_1^{N_2}$$

where $Z_{RD}$ is computed by the reverse waterfilling [23] procedure along the eigenmodes of $S_{22}$, and the subscripts in $A_{RD}, S_{RD}$ are used to designate the compression scheme under consideration. Wyner–Ziv compression [24] exploits the correlation between $y_1$ and $y_2$ as side information at the decoder, and the corresponding parameters are

$$A_{WZ} = (I_{N_2} - Z_{WZ} S_{22}^{-1/2})$$

$$S_{22} \triangleq \mathbb{E}[y_2 y_2^H | y_1] = S_{22} - S_{21} S_{11}^{-1} S_{21}^H \in \mathbb{H}_1^{N_2}$$

$$S_{11} \triangleq \mathbb{E}[y_1 y_1^H | x_2] = I_{N_1} + H_{11} Q_{11}^H H_{11}^H \in \mathbb{H}_1^{N_1}$$

$$S_{21} \triangleq \mathbb{E}[y_2 y_1^H | x_2] = H_{21} Q_{11}^H H_{11}^H \in \mathbb{C}^{N_2 \times N_1}$$

where $Z_{WZ}$ is computed from reverse waterfilling against $S_{22}$.

V. NUMERICAL RESULTS

We consider the following two-dimensional network: the source is located at coordinates $(0, 0)$, the destination is at $(1, 0)$, and the relay is at $(d_x, d_y)$. We use a distance-based path-loss power attenuation exponent $\eta = 4$, combined with independent and identically distributed (i.i.d.) Rayleigh fading for each channel matrix entry. For the numerical experiments presented in this letter, 50 random instances of the channel realizations are generated. Then under each channel realization, the corresponding optimization problems are solved to evaluate the relay channel capacity bounds and achievable rates. The convex optimization problems are solved using the barrier interior-point algorithm described in [19, Section 11.3].

The empirical cumulative distribution functions (CDFs) of the full-duplex cut-set (CS) bound and decode-and-forward (DF) rate of a MIMO relay channel, where the relay is located at $(d_x, d_y) = (1/3, 1/2)$, are shown in Fig. 4. Also shown are their half-duplex counterparts (hCS, hDF), and the orthogonal two-hop relaying (2hop) rate (with optimal bandwidth allocation). In orthogonal two-hop relaying, there is no direct link from the source to the destination: the source transmits to the relay in Band 1; the relay decodes the message, and re-encodes it to transmit to the destination in...
Band 2. The decode-and-forward achievable rates considerably outperform the direct channel capacity and are quite close to the cut-set capacity upper bound, while the two-hop relaying scheme achieves only a marginally higher rate than when the relay is not available. For comparison, the upper and lower bounds from [12, Thms. 3.1 and 3.2] are plotted and labeled (a) and (b), respectively. It is observed that the capacity upper and lower bounds can be tightened when the transmit signals of the source and relay are optimized.

Next, we investigate the relay channel capacity bounds and achievable rates as a function of the relay position. We fix \( d_y = \frac{1}{10} \), and vary \( d_x \) from \( \frac{1}{2} \) to \( \frac{1}{1/2} \); therefore, the relay ranges from being closer to the source, to being closer to the destination. The average rates for the different full- and half-duplex relaying schemes are plotted in Fig. 5. Consistent with the single-antenna relay channel results [15], over a wide range when the relay is near the source, the decode-and-forward rates are close to their respective cut-set capacity upper bounds. For the full-duplex compress-and-forward rates, Wyner–Ziv (WZ) outperforms rate–distortion (RD), since WZ exploits side information in the compression of the relay’s observations. Overall, the compress-and-forward rates do not perform as well as the decode-and-forward rates, except when the relay is far from the source and near the destination.

VI. CONCLUSIONS

We considered the optimization of transmit signals and bandwidth allocation for MIMO relay channels. We assumed that all terminals have channel state information, and we evaluated the cut-set capacity upper bounds and the decode-and-forward rates by formulating them as convex optimization problems. We also presented achievable relaying rates based on the compress-and-forward strategy, where the relay forwards a compressed version of its observations to the destination using the rate–distortion and Wyner–Ziv compression schemes. When the relay is close to the source, the decode-and-forward coding strategy is almost optimal. On the other hand, when the relay is close to the destination, decode-and-forward underperforms direct transmission as the source-relay link becomes a bottleneck. In this regime good performance is achieved by the compress-and-forward schemes, which always achieve rates that are equal to or better than the direct transmission rate.

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