Efficient Relay Beamforming Design With SIC Detection for Dual-Hop MIMO Relay Networks

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***Abstract*—In this paper, we consider a dual-hop multiple-input–multiple-output (MIMO) relay wireless network, in which a source–destination pair, which are both equipped with multiple antennas, communicates through a large number of half-duplex amplify-and-forward (AF) relay terminals. Two novel linear beamforming schemes based on the matched filter and regularized zero-forcing precoding techniques are proposed for the MIMO relay system. We focus on the linear process at the relay nodes and design the new relay beamformers by utilizing the channel-state information (CSI) of both backward and forward channels. The proposed beamforming designs are based on the QR decomposition filter at the destination node, which performs successive interference cancellation to achieve the maximum spatial-multiplexing gain. Simulation results demonstrate that the proposed beamformers that fulfil both the intranode array gain and distributed array gain outperform other relaying schemes under different system parameters in terms of the ergodic capacity.**

***Index Terms*—Beamforming, ergodic capacity, multiple-input–multiple-output (MIMO) relay, successive interference cancellation (SIC).**

I. Introduction

Recently, relay wireless networks have drawn considerable interest from both the academic and industrial communities. Due to the low complexity and low cost of the relay elements, the architectures of multiple fixed relay nodes implemented in cellular systems and many other kinds of networks are considered to be a promising technique for future wireless networks [1]. Meanwhile, the multiple-input–multiple-output (MIMO) technique is well verified to provide significant improvement in the spectral efficiency and link reliability because of its multiplexing and diversity gain [2], [3]. Combining the relaying and MIMO techniques can make use of both advantages to increase the data rate in the cellular edge and extend the network coverage.

The capacity of MIMO relay networks has been well investigated in several papers [4]–[6], in which [5] derives lower bounds on the capacity of a Gaussian MIMO relay channel under the condition of transmitting precoding. To improve the capacity of relay networks, various kinds of linear distributed MIMO relaying schemes have been investigated in [7]–[14]. In [7], the authors analyze the stream signal-to-interference ratio statistic and consider different relay beamforming based on the finite-rate feedback of the channel states. Assuming Tomlinson–Harashima precoding at the base station and linear processing at the relay, [8] proposes upper and lower bounds on the achievable sum rate for the multiuser MIMO system with a single relay node. In [9], a linear relaying scheme that fulfils the target signal-to-noise ratios (SNRs) on different substreams is proposed, and the power-efficient relaying strategy is derived in closed form. The optimal relay beamforming scheme and power control algorithms for a cooperative and cognitive radio system are presented in [12]. In [13] and [14], the authors design three relay beamforming schemes based on matrix triangularization, which have superiority over the conventional zero-forcing (ZF) and amplify-and-forward (AF) beamformers.

Inspired by these heuristic works, this paper proposes two novel relay beamformer designs for the dual-hop MIMO relay networks, which can achieve both the distributed array gain and intranode array gain. Intranode array gain is the gain obtained from the introduction of multiple antennas in each node of the dual-hop networks. Distributed array gain results from the implementation of multiple relay nodes and needs no cooperation among them. Assuming the same scenario given in [14], the new relay beamformers outperform the three schemes proposed in [14] under various network conditions. The innovation points of our relaying schemes are reflected in the matched filter (MF) and regularized zero-forcing (RZF) beamforming designs implemented at multiple relay nodes while utilizing QR decomposition (QRD) of the effective channel matrix at the destination node. The destination can perform successive interference cancellation (SIC) to decode multiple data streams, which have further enhancement effects on the channel capacity.

In this paper, boldface lowercase and uppercase letters represent vectors and matrices, respectively. The notations $(\mathbf{A})_i$ and $(\mathbf{A})_{i,j}$ represent the ith row and (i,j)th entry of the matrix $\mathbf{A}$. Notations $\mathrm{tr}(\cdot)$ and $(\cdot)^H$ denote the trace and conjugate transpose operation of a matrix. Term $\mathbf{I}_N$ is an $N \times N$ identity matrix, and $\|\mathbf{a}\|$ stands for the Euclidean norm of a vector $\mathbf{a}$. Finally, we denote the expectation operation by $\mathrm{E}\{\cdot\}$.

II. System Model

The considered MIMO relay network consists of a single source and destination node, both equipped with M antennas, and K N-antenna relay nodes distributed between the source–destination pair, as illustrated in Fig. 1. When the source node implements spatial multiplexing (SM), the requirement that $N \geq M$ must be satisfied if every relay node is supposed to support all the M independent data streams. We consider half-duplex nonregenerative relaying throughout this paper, where it takes two nonoverlapping time slots for the data to be transmitted from the source to the destination node through the backward channel (BC) and forward channel (FC). Due to deep large-scale fading effects produced by the long distance, we assume that there is no direct link between the source and the destination. In this paper, the perfect channel-station information (CSI) of BC and FC are assumed to be available at relay nodes. In a practical system, each relay uses the training sequences or pilot sent from the source node to acquire the CSI of all the BCs. The acquisition methods of the FC's information would vary with two different duplex forms. If it is a frequency-division duplexing (FDD) system, the destination should estimate the CSI of the FC by using the relay-specific pilots first and

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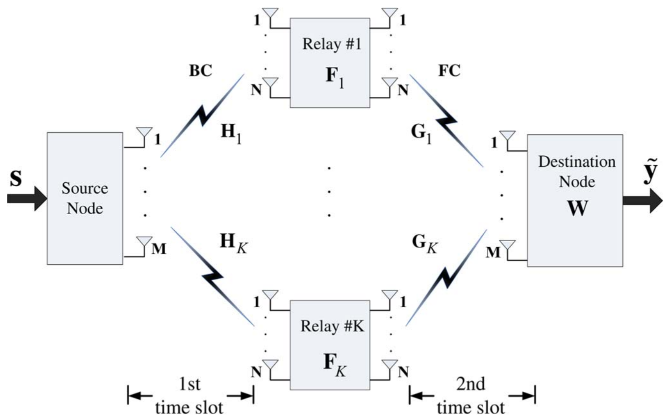

Fig. 1. System model of a dual-hop MIMO network with relay beamforming.

then feed the CSI back to each relay node. As for a time-division duplexing (TDD) system, due to its intrinsic reciprocity, relay nodes can use the CSI of the link from the destination to relay nodes to acquire the CSI of the FC. Due to the estimation error in CSI and the error in feedback channels, perfect CSI is not available in a practical system. It is very useful to consider the imperfect CSIs in the future work.

In the first time slot, the source node broadcasts the signal to all the relay nodes through the BC. Let an $M \times 1$ vector $\mathbf{s}$ be the transmit signal vector that satisfies the power constraint $\mathrm{E}\{\mathbf{s}\mathbf{s}^H\} = (P/M)\mathbf{I}_M$, where P is defined as the total transmit power at the source node. Let $\mathbf{H}_k \in \mathbb{C}^{N\times M}$, $(k = 1, \ldots, K)$ stand for the BC MIMO channel matrix from the source node to the kth relay node. All the relay nodes are supposed to be located in a cluster. Then, all the BCs $\mathbf{H}_1, \ldots, \mathbf{H}_K$ can be supposed to be independently and identically distributed (*i.i.d.*) and experience the same Rayleigh flat fading. Then, the corresponding received signal at the kth relay can be written as

$$\mathbf{r}_k = \mathbf{H}_k\mathbf{s} + \mathbf{n}_k \tag{1}$$

where the term $\mathbf{n}_k$ is the spatiotemporal white zero-mean complex additive Gaussian noise vector, independent across k, with the covariance matrix $\mathrm{E}\{\mathbf{n}_k\mathbf{n}_k^H\} = \sigma_1^2\mathbf{I}_N$. Therefore, noise variance σ_1^2 represents the noise power at each relay node.

In the second time slot, first, each relay node performs linear process by multiplying $\mathbf{r}_k$ with an $N \times N$ beamforming matrix $\mathbf{F}_k$. Consequently, the signal vector sent from the kth relay node is

$$\mathbf{t}_k = \mathbf{F}_k\mathbf{r}_k. \tag{2}$$

Based on a more practical consideration, we assume that each relay node has its own power constraint that satisfies $\mathrm{E}\{\mathbf{t}_k^H\mathbf{t}_k\} \le Q_k$, which is independent of power P. Hence, a power constraint condition of $\mathbf{t}_k$ can be derived as

$$p(\mathbf{t}_k) = \mathrm{tr}\left\{\mathbf{F}_k\left(\frac{P}{M}\mathbf{H}_k\mathbf{H}_k^H + \sigma_1^2\mathbf{I}_N\right)\mathbf{F}_k^H\right\} \le Q_k. \tag{3}$$

After linear relay beamforming, all the relay nodes simultaneously forward their data to the destination. Thus, the signal vector received by the destination can be expressed as

$$\mathbf{y} = \sum_{k=1}^{K}\mathbf{G}_k\mathbf{t}_k + \mathbf{n}_d = \sum_{k=1}^{K}\mathbf{G}_k\mathbf{F}_k\mathbf{H}_k\mathbf{s} + \sum_{k=1}^{K}\mathbf{G}_k\mathbf{F}_k\mathbf{n}_k + \mathbf{n}_d \tag{4}$$

where $\mathbf{G}_k$, under the same assumption as $\mathbf{H}_k$, is the $M \times N$ FC between the kth relay node and the destination. $\mathbf{n}_d \in \mathbb{C}^M$, which satisfies $\mathrm{E}\{\mathbf{n}_d\mathbf{n}_d^H\} = \sigma_2^2\mathbf{I}_M$, denotes the zero-mean white circularly symmetric complex additive Gaussian noise at the destination node with the noise power σ_2^2.

III. Relay Beamforming Design

In this section, the network ergodic capacity with the QR detector applied at the destination node for SIC detection is analyzed. Then, we will propose two novel relay beamformer schemes based on the MF and RZF beamforming techniques.

A. QRD and SIC Detection

Conventional receivers such as MF, ZF (linear decorrelator), and linear minimum mean square error (L-MMSE) decoder have been well studied in previous works. The MF receiver has bad performance in the high-SNR region, whereas the ZF produces a noise enhancement effect. The MMSE equalizer, which is shown as a good tradeoff of the MF and ZF receivers, however, achieves the same order of diversity as ZF does. Hence, a much larger intranode array gain also cannot be obtained from the MMSE receiver. As analyzed in [15], SIC detection based on the QRD has significant advantage over conventional detectors, and the performance of the QR detector is asymptotically equivalent to that of the maximum-likelihood detector (MLD). Therefore, we will utilize the QRD detector as the destination receiver $\mathbf{W}$ throughout this paper.

Based on the aforementioned discussion, the final received signal at the destination can be derived as follows. Let the term $\sum_{k=1}^{K}\mathbf{G}_k\mathbf{F}_k\mathbf{H}_k = \mathbf{H}_{\mathcal{SD}}$, and $\sum_{k=1}^{K}\mathbf{G}_k\mathbf{F}_k\mathbf{n}_k + \mathbf{n}_d = \mathbf{z}$. Then, (4) can be rewritten as

$$\mathbf{y} = \mathbf{H}_{\mathcal{SD}}\mathbf{s} + \mathbf{z} \tag{5}$$

where $\mathbf{H}_{\mathcal{SD}}$ represents the effective channel between the source and the destination node, and $\mathbf{z}$ is the effective noise vector cumulated from the noise $\mathbf{n_k}$ at each relay node and the noise vector $\mathbf{n}_d$ at the destination. Implement the QRD of the effective channel as

$$\mathbf{H}_{\mathcal{SD}} = \mathbf{Q}_{\mathcal{SD}}\mathbf{R}_{\mathcal{SD}} \tag{6}$$

where $\mathbf{Q}_{\mathcal{SD}}$ is an $M \times M$ unitary matrix, and $\mathbf{R}_{\mathcal{SD}}$ is an $M \times M$ right upper triangular matrix. Therefore, the QR detector at the destination node is chosen as $\mathbf{W} = \mathbf{Q}_{\mathcal{SD}}^H$, and the signal vector after detection becomes

$$\tilde{\mathbf{y}} = \mathbf{R}_{\mathcal{SD}}\mathbf{s} + \mathbf{Q}_{\mathcal{SD}}^H\mathbf{z}. \tag{7}$$

Finally, the optimal relay beamformer design problem can mathematically be formulated as

$$\hat{\mathbf{F}}_k = \arg\max_{\mathbf{F}_k} C(\mathbf{F}_k) \tag{8}$$

$$\text{s.t.} \quad p(\mathbf{t}_k) \le Q_k \tag{9}$$

where $C(\mathbf{F}_k)$ is the network ergodic capacity with various specific forms decided by the destination detector $\mathbf{W}$ and relay beamforming matrix $\mathbf{F}_k$ that will be discussed in detail in the following sections.

Note that the closed-form solution is difficult to obtain when trying to directly solve the optimization problem (8). To get a specific form of the relay beamformers, we further assume that a power control factor ρ_k is set with $\mathbf{F}_k$ in (2) to guarantee that each relay transmit power is equal to Q_k. Because $\mathbf{H}_1, \ldots, \mathbf{H}_K$ (and $\mathbf{G}_1, \ldots, \mathbf{G}_K$) are *i.i.d.* distributed and experience the same Rayleigh fading, all the relay beamformers can have a uniform design type. Hence, the transmit signal from each relay node after linear beamforming and power control becomes

$$\mathbf{t}_k = \rho_k \mathbf{F}_k \mathbf{r}_k \tag{10}$$

where the power control parameter ρ_k can be derived from (3) as

$$\rho_k = \left(Q_k \Big/ \mathrm{tr}\left\{ \mathbf{F}_k \left(\frac{P}{M} \mathbf{H}_k \mathbf{H}_k^H + \sigma_1^2 \mathbf{I}_N \right) \mathbf{F}_k^H \right\} \right)^{\frac{1}{2}}. \tag{11}$$

B. MF Beamforming

According to the principles of maximum ratio transmission (MRT) [16] and maximum ratio combining (MRC) [17], we choose the MF as the beamformer for each relay node. Therefore, we get the beamforming matrix as

$$\mathbf{F}_k^{MF} = \mathbf{G}_k^H \mathbf{H}_k^H \tag{12}$$

where each relay beamformer can be divided into two parts: 1) a receive beamformer $\mathbf{H}_k^H$ and 2) a transmit beamformer $\mathbf{G}_k^H$. The receive beamformer $\mathbf{H}_k^H$ is the optimal weight matrix that maximizes the received SNR at the relay. Consequently, the received signal at the destination can be rewritten from (10) and (12) as

$$\mathbf{y} = \underbrace{\sum_{k=1}^{K} \rho_k \mathbf{G}_k \mathbf{G}_k^H \mathbf{H}_k^H \mathbf{H}_k}_{\mathbf{H}_{\mathcal{SD}}^{MF}} \mathbf{s} + \underbrace{\sum_{k=1}^{K} \rho_k \mathbf{G}_k \mathbf{G}_k^H \mathbf{H}_k^H \mathbf{n}_k + \mathbf{n}_d}_{\mathbf{z}^{MF}} \tag{13}$$

where ρ_k is given by substituting (12) into (11). Perform the QRD of the $\mathbf{H}_{\mathcal{SD}}^{MF}$ as

$$\mathbf{H}_{\mathcal{SD}}^{MF} = \mathbf{Q}_{\mathcal{SD}}^{MF} \mathbf{R}_{\mathcal{SD}}^{MF}. \tag{14}$$

Then, we get the destination receiver as

$$\mathbf{W}^{MF} = \left(\mathbf{Q}_{\mathcal{SD}}^{MF} \right)^H. \tag{15}$$

Hence, the signal vector after QR detection becomes

$$\tilde{\mathbf{y}}^{MF} = \mathbf{R}_{\mathcal{SD}}^{MF} \mathbf{s} + \left(\mathbf{Q}_{\mathcal{SD}}^{MF} \right)^H \mathbf{z}^{MF}. \tag{16}$$

Note that the matrix $\mathbf{R}_{\mathcal{SD}}^{MF}$ has the right upper triangular form as

$$\mathbf{R}_{\mathcal{SD}}^{MF} = \begin{pmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,M} \\ & r_{2,2} & & \vdots \\ & & \ddots & \\ \mathbf{0} & & & r_{M,M} \end{pmatrix} \tag{17}$$

where the diagonal entries $r_{m,m}\,(m = 1, \ldots, M)$ of (17) are real positive numbers. With the destination node carrying out the SIC detection, the effective SNR for the mth data stream of the MF relay beamforming scheme can be derived as

$$\mathrm{SNR}_m^{MF} = \frac{(P/M) r_{m,m}^2}{\left(\sum_{k=1}^{K} \left\| \left(\rho_k (\mathbf{Q}_{\mathcal{SD}}^{MF})^H \mathbf{G}_k \mathbf{G}_k^H \mathbf{H}_k^H \right)_m \right\|^2 \right) \sigma_1^2 + \sigma_2^2}. \tag{18}$$

C. MF–RZF Beamforming

In this section, we utilize the RZF precoding [18] as the transmit beamformer for FC, whereas the MF is still kept as the receive beamformer matching with the BC condition. Therefore, the MF–RZF beamformer is constructed as

$$\mathbf{F}_k^{MF-RZF} = \mathbf{G}_k^H \left(\mathbf{G}_k \mathbf{G}_k^H + \alpha_k \mathbf{I}_M \right)^{-1} \mathbf{H}_k^H \tag{19}$$

where α_k is an adjustable parameter that controls the amount of interference among multiple data streams in the second hop. One possible metric for choosing α_k is to maximize the end-to-end effective SNR, which will be given as follows. Hence, the corresponding received signal at the destination is

$$\begin{aligned} \mathbf{y} &= \sum_{k=1}^{K} \mathbf{G}_k \mathbf{F}_k \mathbf{H}_k \mathbf{s} + \sum_{k=1}^{K} \mathbf{G}_k \mathbf{F}_k \mathbf{n}_k + \mathbf{n}_d \\ &= \sum_{k=1}^{K} \rho_k \mathbf{G}_k \mathbf{G}_k^H \left(\mathbf{G}_k \mathbf{G}_k^H + \alpha_k \mathbf{I}_M \right)^{-1} \mathbf{H}_k^H \mathbf{H}_k \mathbf{s} \\ &\quad + \sum_{k=1}^{K} \rho_k \mathbf{G}_k \mathbf{G}_k^H \left(\mathbf{G}_k \mathbf{G}_k^H + \alpha_k \mathbf{I}_M \right)^{-1} \mathbf{H}_k^H \mathbf{n}_k + \mathbf{n}_d. \end{aligned} \tag{20}$$

The effective channel matrix between the source and the destination is derived from (20) as

$$\mathbf{H}_{\mathcal{SD}}^{MF-RZF} = \sum_{k=1}^{K} \rho_k \mathbf{G}_k \mathbf{G}_k^H \left(\mathbf{G}_k \mathbf{G}_k^H + \alpha_k \mathbf{I}_M \right)^{-1} \mathbf{H}_k^H \mathbf{H}_k. \tag{21}$$

Similarly, after the QRD of $\mathbf{H}_{\mathcal{SD}}^{MF-RZF}$ and the SIC detection at the destination node, the effective SNR for the mth data stream of the MF–RZF relay beamforming is obtained as

$$\mathrm{SNR}_m^{MF-RZF} = \frac{(P/M)\tilde{r}_{m,m}^2}{\left(\sum_{k=1}^{K} \left\| \left(\rho_k \left(\mathbf{Q}_{SD}^{MF-RZF} \right)^H \mathbf{A}_k \right)_m \right\|^2 \right) \sigma_1^2 + \sigma_2^2} \tag{22}$$

where $\mathbf{A}_k = \mathbf{G}_k \mathbf{F}_k^{MF-RZF}$. The term $\tilde{r}_{m,m}$ is the mth diagonal entry of the right upper triangular matrix $\mathbf{R}_{\mathcal{SD}}^{MF-RZF}$ derived from the QRD operation of $\mathbf{H}_{\mathcal{SD}}^{MF-RZF}$ such as (14). In addition, ρ_k of the MF–RZF relay beamforming is given by substituting (19) into (11).

Finally, the ergodic capacity of a dual-hop MIMO relay network with relay beamforming can be derived by summing up the data rate of all the streams as

$$C = E_{\{\mathbf{H}_k, \mathbf{G}_k\}_{k=1}^K} \left\{ \frac{1}{2} \sum_{m=1}^{M} \log_2 (1 + \mathrm{SNR}_m) \right\} \tag{23}$$

where SNR_m refers to the effective SNR in (18) or (22). According to the cut-set theorem in the network information theory [6], the upper bound capacity of the MIMO relay networks is

$$C_{upper} = \mathrm{E}_{\{\mathbf{H}_k\}_{k=1}^K} \left\{ \frac{1}{2} \log\det \left(\mathbf{I}_M + \frac{P}{M\sigma_1^2} \sum_{k=1}^{K} \mathbf{H}_k^H \mathbf{H}_k \right) \right\}. \tag{24}$$

D. Computational Complexity Analysis and Remarks

Despite the fact that there is no additional signal processing at the destination, the referenced schemes in [14] implement the QRD of matrices at each relay node. More precisely, for the QR–P–QR scheme in [14], each BC $\mathbf{H}_k$ and FC $\mathbf{G}_k^H$ should have a QRD operation. Each relay node has twice the QRD operations of the $N \times M$ complex matrix. Therefore, it costs $2K$ times of QRD ($N \times M$ complex matrix) for the QR–P–QR scheme. For the QR–P–ZF scheme, it still needs to implement K times of the QRD of the $N \times M$ matrix. When it comes to our schemes, for both MF and MF–RZF relay beamforming, the whole signal process spends only one QRD at the destination node. Moreover, in our design, the QRD is operated on the effective channel matrix $\mathbf{H}_{\mathcal{SD}}$ between the source and the destination. The dimension of the complex matrix for QRD is $M \times M$, which is free of the antenna number N and the relay number K. Obviously, the proposed schemes sharply reduce the computational complexity compared with the referenced methods in [14].

In addition, to guarantee the effective channel matrix to take the right lower triangular form, the phase control and ordering matrix have to be used in the relay beamformers in [14]. This approach results in a performance loss in terms of the network capacity. The QRD of the compound effective channel at the destination proposed in this paper makes the relay beamformer design more flexible, because it is not necessary for the effective channel matrix to be a triangular form.

IV. Simulation Results

In this section, numerical simulations are carried out to verify the performance superiority of the proposed relay beamforming strategies. We compare the ergodic capacities of MF and MF–RZF relay beamformers with the QR–P–QR and QR–P–ZF proposed in [14] and the conventional AF relaying scheme in the dual-hop MIMO relay networks. The capacity upper bound is also taken into account as a baseline. All the schemes are compared under the condition of various system parameters, including the total number of relay nodes and power constraints at the source and relay nodes, i.e., different PNRs and QNRs. Here, $PNR = P/\sigma_1^2$, which is the SNR of BC; $QNR = Q_k/\sigma_2^2$, which is the SNR of FC. For simplicity, the entries of $\mathbf{H}_k$ and $\mathbf{G}_k$ are assumed to be *i.i.d.* complex Gaussian with zero mean and unit variance. All the relay nodes are supposed to have the same power constraint $Q_k = Q\,(k = 1, \ldots, K)$, and $\alpha_k = 1\,(k = 1, \ldots, K)$, which, within a limited range, has no significant impact on the ergodic capacity of the MF–RZF relay beamforming.

A. Capacity Versus Total Number of Relay Nodes

Similar to [13] and [14], the capacity comparisons are given with the increase of the total number of relay nodes. To illustrate how the SNRs of BC and FC have an impact on the ergodic capacity with various relay beamforming schemes, three different PNRs and QNRs are taken into account. Fig. 2 shows the capacities change with K when $N = M = 4$, PNR $=$ QNR $= 10$ dB. Apparently, the proposed MF and MF–RZF relay beamformers outperform the QR–P–ZF and QR–P–QR relaying schemes in [14] for $K > 1$. For this moderate PNR and QNR, the MF–RZF beamformer has the best ergodic capacity performance among the five relaying schemes and approaches the capacity upper bound. This result can be explained as a result that the MF receive beamformer can maximize receive SNRs at each relay node, whereas the RZF transmit beamformer precancel interstream interference before transmitting the signal to the destination node.

The relative capacity gains that change with the PNR and QNR is demonstrated in Figs. 3 and 4. It is shown in Fig. 3 that MF and MF–RZF keep the superiority over other relaying schemes when the network has low SNR in BC (PNR $= 5$ dB) and high SNR in FC (QNR $= 20$ dB). This result is because the MF is used as the receive beamformer for the first-hop channel, showing the advantage

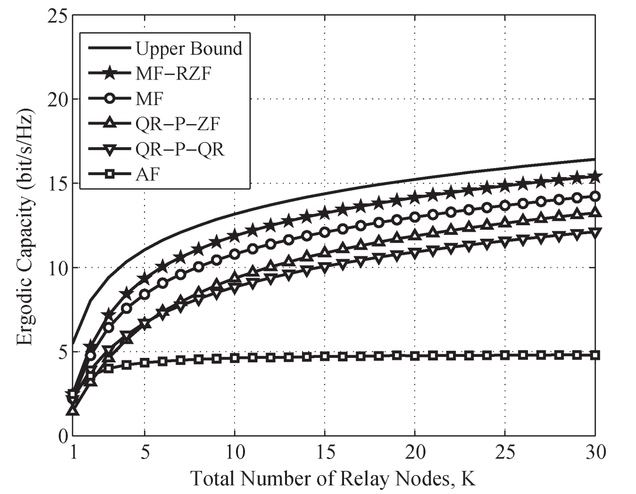

Fig. 2. Ergodic capacity comparisons versus K $(N = M = 4, \text{PNR} = \text{QNR} = 10\text{ dB})$.

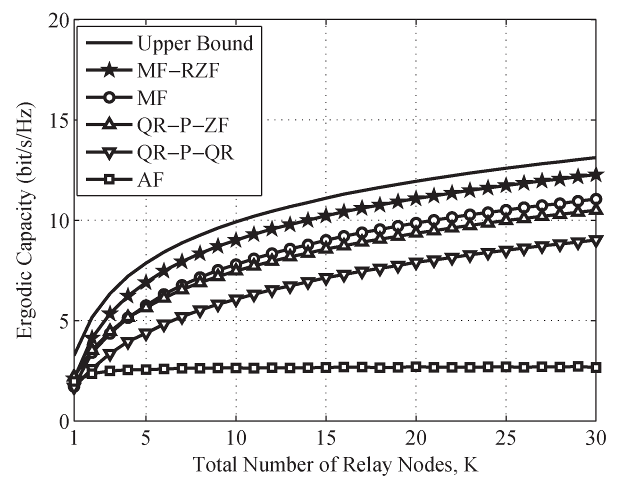

Fig. 3. Ergodic capacity comparisons versus K $(N = M = 4, \text{PNR} = 5\text{ dB}, \text{QNR} = 20\text{ dB})$.

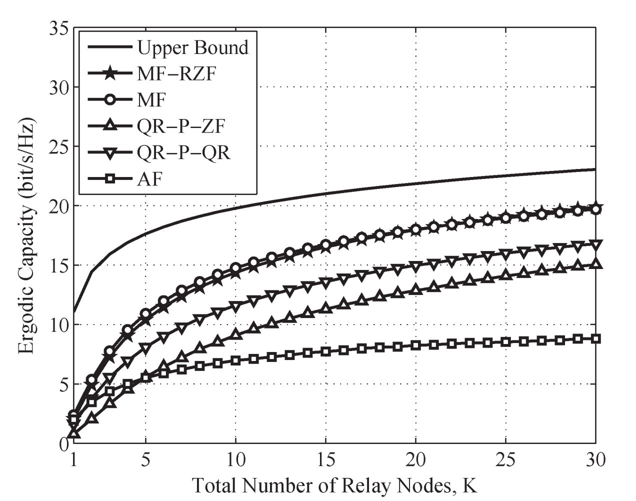

Fig. 4. Ergodic capacity comparisons versus K $(N = M = 4, \text{PNR} = 20\text{ dB}, \text{QNR} = 5\text{ dB})$.

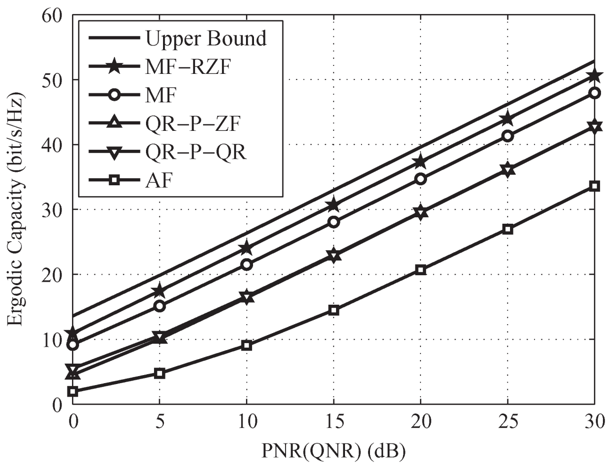

Fig. 5. Ergodic capacity comparisons versus PNR (QNR) $(N = M = 8, K = 10)$.

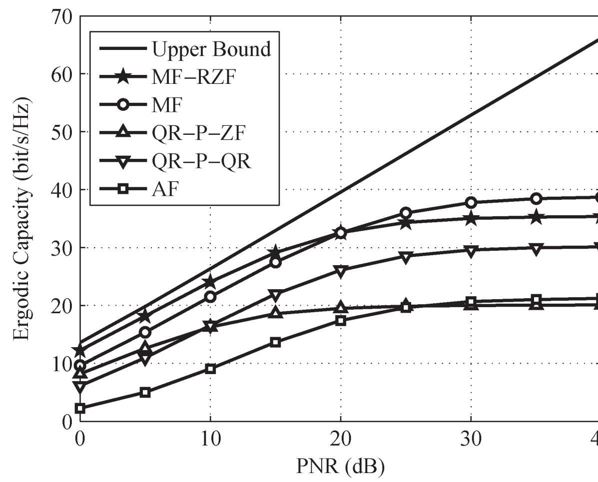

Fig. 6. Ergodic capacity comparisons versus PNR $(N = M = 8, \mathrm{QNR} = 10\ \mathrm{dB}, K = 10)$.

of MF against the low-SNR condition. Furthermore, Fig. 3 shows that the capacity gains of the MF–RZF scheme over other beamformers become larger, whereas the performance superiority of MF decreases to the scenario in Fig. 2, because the MF performance becomes worse with the increase of SNR, whereas the RZF in FC turns out to be better. A larger gap between the QR–P–ZF and QR–P–QR beamforming schemes also confirms the advantage of ZF being the transmit beamformer in the high-SNR region. With the knowledge of the performance characteristics of MF in low-SNR regions and the RZF in high-SNR regions, the fact illustrated in Fig. 4 that the ergodic capacity of MF–RZF becomes a little bit smaller than MF in a low-QNR environment is reasonable.

Finally, in all the three environments considered, the conventional AF relaying is kept as a bad relaying strategy. It is shown that AF cannot obtain the distributed array gain, because its ergodic capacity does not increase with the total number of relay nodes. The reason is that, as for the AF relaying, each relay node uses the identity matrix as the beamformer, which utilizes none of the CSI of both BC and FC. It is also very important to investigate the behaviors of all the relay beamforming schemes when distributed array gain is unavailable, i.e., when there is only a single relay node in the network. In Figs. 2–4, it is shown that AF relaying is no longer the worst scheme and becomes acceptable when $K = 1$. Meanwhile, the performance advantages of the proposed methods over other conventional schemes vary from case to case. Look at the ergodic capacities of all the schemes at the point of $K = 1$ in Fig. 3. At this time, the single relay system has low PNR $(\mathrm{PNR} = 5\ \mathrm{dB})$ and high QNR $(\mathrm{QNR} = 10\ \mathrm{dB})$. MF–RZF's capacity has about a 0.1-b/s loss compared with QR–P–ZF beamforming, whereas MF has a 0.03-b/s gain over the QR–P–QR scheme. However, if the dual-hop network has moderate PNR and QNR (see Fig. 2) or high QNR (see Fig. 4), MF and MF–RZF still outperform the schemes proposed in [14]. For example, when $K = 1$, $\mathrm{PNR} = \mathrm{QNR} = 10\ \mathrm{dB}$, the ergodic capacity of MF–RZF beamforming achieves 0.3- and 1.01-b/s gains over the QR–P–QR and QR–P–ZF schemes, respectively. As for the MF beamformer, these gains become 0.05 b/s and 0.77 b/s. Based on the aforementioned discussion, it can be concluded that our proposed relaying schemes are still efficient when the relay network has no distributed array condition, and only intranode array gain is available. Note that the simplest AF relaying has desirable capacity performance in this case. Therefore, the AF scheme might be regarded as an alternative solution, particularly when the network has only one relay node and moderate SNRs of two-hop channels.

B. Capacity Versus PNR

The ergodic capacity versus the PNR and QNR is another important aspect for measuring the performance of the proposed schemes. The performances of the MF and MF–RZF linear relaying schemes are shown in Figs. 5 and 6. We set $\mathrm{QNR} = \mathrm{PNR}$ in Fig. 5, which is the same as in [14]. The ergodic capacities of both the MF–RZF and MF relaying strategies approximately grow linearly with the PNR (and QNR) like the upper bound and outperform other schemes.

In Fig. 6, we evaluate how the capacities change with the PNR by keeping $\mathrm{QNR} = 10\ \mathrm{dB}$. The two proposed relay beamformers can still achieve much better performance than the conventional schemes. However, the ergodic capacities of all the relay beamforming schemes become saturated as the PNR increases. Note that the AF scheme can even outperform the QR–P–ZF beamforming in the high-PNR region in this case. In addition, the capacity upper bound keeps growing linearly with PNR, because it is determined only by the BC conditions, as can be verified in (24). The result in Fig. 6 illustrates that, if the SNR of FC is kept under certain values, simply increasing the source transmit power has limited impact on the network capacity.

V. Conclusion and Future Work

In this paper, two novel relay beamformer design schemes based on the MF and RZF techniques have been derived for a dual-hop MIMO relay network with the AF relaying protocol. The proposed MF and MF–RZF beamformers are jointly constructed with the QRD filer at the destination node, which transforms the effective compound channel into a right upper triangular form. Consequently, multiple data streams can be decoded with the destination SIC detector. Simulation results demonstrate that our proposed schemes outperform the conventional relay beamforming strategies in the sense of the ergodic capacity under various network parameters. Furthermore, the two proposed relay beamforming schemes still have desirable performance when the distributed array gain is unavailable in the network.

Although the proposed relay beamforming strategies have performance gains over the conventional schemes, the original optimization problem (8) and (9), the imperfect CSIs of BC and FC, the overhead of the feedback traffic, and the optimal α_k values of the MF–RZF beamformer are still challenging problems that need further research effort.

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