**Title**

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# 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 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 (MF) and regularized zero-forcing (RZF) 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 channel and forward channel. The proposed beamforming designs are based on the QR decomposition (QRD) filter at the destination node which performs successive interference cancellation (SIC) 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**

MIMO relay, beamforming, successive interference cancellation, ergodic capacity.

# I. INTRODUCTION

Recently relay wireless networks have drawn considerable interest from both the academic and industrial communities. Due to 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, MIMO technique is well verified to provide significant improvement in the spectral efficiency and link reliability because of the 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. In order 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 single relay node. In [9], a linear relaying scheme fulfilling the target 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], [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 of 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 does not need any 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 and regularized zero-forcing beamforming designs implemented at multiple relay nodes while utilizing QRD of the effective channel matrix at the destination node. The destination can perform SIC to decode multiple data streams which have further enhancement effect on the channel capacity.

In this paper, boldface lowercase letter and boldface uppercase letter represent vectors and matrices, respectively. The notations $(\mathbf{A})_i$ and $(\mathbf{A})_{i,j}$ represent the $i$th row and $(i,j)$th entry of the matrix $\mathbf{A}$. Notations $\text{tr}(\cdot)$ and $(\cdot)^H$ denote 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 $\text{E}\{\cdot\}$.

## 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 non-regenerative relaying throughout this paper where it takes two non-overlapping time slots for the data to be transmitted from the source to the destination node via 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 destination. In this paper, the perfect CSIs 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 backward channels. The acquisition methods of FC's information would vary with two different duplex forms. If it is a FDD system, the destination should estimate the CSI of FC by using the relay-specific pilots first, and then feedback the CSI to each relay node. As for a TDD system, due to its intrinsic reciprocity, relay nodes can use the CSI of the link from destination to relay nodes to acquire the CSI of FC.

In the first time slot, the source node broadcasts the signal to all the relay nodes through BC. Let $M \times 1$ vector $\mathbf{s}$ be the transmit signal vector satisfying the power constraint $\text{E}\left\{\mathbf{s}\mathbf{s}^H\right\} = (P/M)\,\mathbf{I}_M$, where $P$ is defined as the total transmit power at the source node. Let $\mathbf{H}_k \in \mathbb{C}^{N \times M}$, $(k = 1, ..., K)$ stand for the BC MIMO channel matrix from the source node to the $k$th

relay node. All the relay nodes are supposed to be located in a cluster. Then all the backward channels $\mathbf{H}_1, \cdots, \mathbf{H}_K$ 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 $k$th 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 spatio-temporally white zero-mean complex additive Gaussian noise vector, independent across $k$, with the covariance matrix $\mathrm{E}\left\{\mathbf{n}_k\mathbf{n}_k^H\right\} = \sigma_1^2\mathbf{I}_N$. Therefore, noise variance $\sigma_1^2$ represents the noise power at each relay node.

In the second time slot, firstly 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 $k$th relay node is

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

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

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

After linear relay beamforming process, all the relay nodes forward their data simultaneously 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 $M \times N$ forward channel between the $k$th relay node and the destination. $\mathbf{n}_d \in \mathbb{C}^M$, satisfying $\mathrm{E}\left\{\mathbf{n}_d\mathbf{n}_d^H\right\} = \sigma_2^2\mathbf{I}_M$, denotes the zero-mean white circularly symmetric complex additive Gaussian noise at the destination node with the noise power $\sigma_2^2$.

## 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. And then we will propose two novel relay beamformer schemes based on the MF and RZF beamforming techniques.

## A. QR decomposition and SIC detection

Conventional receivers such as MF, zero-forcing (linear decorrelator) and linear minimum mean square error (L-MMSE) decoder have been well studied in the previous works. Matched filter receiver has bad performance in the high SNR region while ZF produces noise enhancement effect. MMSE equalizer which can be seen as a good tradeoff of the MF and ZF receivers, however, achieves the same order of diversity as ZF does. Hence 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 those conventional detectors and the performance of the QR detector is asymptotically equivalent to that of the maximum-likelihood detector (MLD). So we will utilize the QRD detector as the destination receiver $\mathbf{W}$ throughout this paper.

From the above discussion, the final received signal at 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 equation (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 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 QR decomposition 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 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 be formulated mathematically as

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

$$s.t. \quad p\left(\mathbf{t}_k\right) \leq Q_k, \tag{9}$$

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

Note that the closed-form solution is difficult to obtain when trying to solve the optimization problem (8) directly. In order to get a specific form of the relay beamformers, we further assume that a power control factor $\rho_k$ is set with $\mathbf{F_k}$ in (2) to guarantee that each relay transmit power is equal to $Q_k$. Since $\mathbf{H}_1, \cdots, \mathbf{H}_K$ (and $\mathbf{G}_1, \cdots, \mathbf{G}_K$) 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 $\rho_k$ can be derived from equation (3) as

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

*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: a receive beamformer $\mathbf{H}_k^H$ and a transmit beamformer $\mathbf{G}_k^H$. The receive beamformer $\mathbf{H}_k^H$ is the optimal weight matrix that maximizes 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 $\rho_k$ is given by substituting (12) into equation (11). Performing 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 $r_{m,m}\,(m = 1, ..., M)$ of (17) are real positive numbers. With the destination node carrying out the SIC detection, the effective SNR for the $m$th data stream of MF relay beamforming scheme can be derived as

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

*C. MF-RZF beamforming*

In this subsection, we utilize the regularized zero-forcing (RZF) precoding [18] as the transmit beamformer for FC while MF is still kept as the receive beamformer matching with the BC condition. So 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 $\alpha_k$ is an adjustable parameter that controls the amount of interference among multiple data streams in the second hop. One possible metric for choosing $\alpha_k$ is to maximize the end-to-end effective SNR which will be given below. Hence the corresponding received signal at the destination is

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

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

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

where $\mathbf{A}_k = \mathbf{G}_k \mathbf{F}_k^{MF-RZF}$. Term $\tilde{r}_{m,m}$ is the $m$th diagonal entry of the right upper triangular matrix $\mathbf{R}_{\mathcal{SD}}^{MF-RZF}$ derived from QRD operation of $\mathbf{H}_{\mathcal{SD}}^{MF-RZF}$ like (14). And $\rho_k$ of the MF-RZF relay beamforming is given by substituting (19) into equation (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

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

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

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

*D. Computational complexity analysis and remarks*

In spite of no additional signal processing at the destination, referenced schemes in [14] implement QR decomposition of matrices at each relay node actually. More precisely, for QR-P-QR scheme in [14], each backward channel $\mathbf{H}_k$ and forward channel $\mathbf{G}_k^H$ should have a QRD operation. Each relay node has twice QRD operations of $N \times M$ complex matrix. Therefore, it costs $2K$ times of QRD ($N \times M$ complex matrix) for QR-P-QR scheme. For QR-P-ZF scheme, it still needs to implement $K$ times of QRD of the $N \times M$ matrix. When it comes to our schemes, for both MF and MF-RZF relay beamforming, the whole signal processing spend only once 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 from the antenna number $N$ and the relay number $K$. Obviously, the proposed schemes reduce the computational complexity sharply compared with the referenced methods in [14].

Additionally, in order to guarantee the effective channel matrix to take the right lower triangular form, the phase control and ordering matrix has to be used in the relay beamformers in [14]. This

results in a performance loss in terms of the network capacity. While the QRD of the compound effective channel at the destination proposed in this paper makes the relay beamformer design more flexible, because the effective channel matrix is not necessary to be a triangular form.

## IV. SIMULATION RESULTS

In this section, numerical simulations are carried out in order to verify the performance superiority of the proposed relay beamforming strategies. We compare the ergodic capacities of MF and MF-RZF relay beamformers with QR-P-QR, 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 total number of relay nodes and power constraints at source and relay nodes, i.e., different PNR ($P/\sigma_1^2$, the SNR of BC), and different QNR ($Q_k/\sigma_2^2$, the SNR of FC). For simplicity, the exntries 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 $Q_k = Q\,(k = 1, ..., K)$, and $\alpha_k = 1\,(k = 1, ..., K)$, 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

Like in [13], [14], the capacity comparisons are given with the increase of the total number of relay nodes. In order to illustrate how the SNRs of BC and FC have impact on the ergodic capacity with various relay beamforming schemes, three different PNR and QNR are taken into account. Fig. 2 shows the capacities change with $K$ when $N = M = 4, \mathrm{PNR} = \mathrm{QNR} = 10\mathrm{dB}$. 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 to the capacity upper bound. This can be explained as a result that the MF receive beamformer can maximize receive SNRs at each relay node while the RZF transmit beamformer pre-cancel inter-stream interference before transmitting the signal to the destination node.

The relative capacity gains changing with the PNR and QNR is demonstrated in Fig. 3 and Fig. 4. It can be seen from Fig. 3 that MF and MF-RZF keep the superiority over other relaying schemes when the network has low SNR in BC (PNR= 5dB) and high SNR in FC (QNR=

20dB). This is because that the MF is used as the receive beamformer for the first hop channel, showing the advantage of MF against the low SNR condition. Furthermore, Fig. 3 shows that the capacity gains of MF-RZF scheme over other beamformers become larger, while the performance superiority of MF decreases when compared to the scenario in Fig. 2. This is because that the MF performance becomes worse with the increase of SNR, while the RZF in FC turns to be better. A larger gap between 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 RZF in high SNR regions, the fact illustrated in Fig. 4 that ergodic capacity of MF-RZF becomes a little bit smaller than MF in low QNR environment is reasonable.

Finally, in all the three environments considered above, the conventional AF relaying keeps as a bad relaying strategy. It can be seen that AF can not obtain the distributed array gain since 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 does not utilize any 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. From Fig. 2 to Fig. 4, it can be seen that AF relaying is no longer the worst one 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 (PNR= 5dB)and high QNR (QNR= 10dB). MF-RZF's capacity has about 0.1bps loss than QR-P-ZF beamforming while MF has 0.03bps gain over QR-P-QR scheme. However, if the dual-hop network has moderate PNR and QNR (see Fig. 2) or high QNR (see Fig. 4), the MF and MF-RZF still outperform the schemes proposed in [14]. For example, when $K = 1, \text{PNR} = \text{QNR} = 10\text{dB}$, the ergodic capacity of MF-RZF beamforming achieves 0.3bps and 1.01bps gains over QR-P-QR and QR-P-ZF schemes respectively. As for the MF beamformer, these gains become 0.05bps and 0.77bps. From the above 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. It should be noticed that simplest AF relaying has desirable capacity performance in this case. Therefore, the AF scheme might be regarded as an alternative solution, especially 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 to measure the performance of the proposed schemes. The performances of MF and MF-RZF linear relaying schemes are shown in Fig. 5 and Fig. 6. We set QNR=PNR in Fig. 5, which is the same as done in [14]. The ergodic capacities of both MF-RZF and MF relaying strategies grow approximately 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 QNR= 10dB. 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 AF scheme can even outperform the QR-P-ZF beamforming in the high PNR region in this case. And capacity upper bound keeps growing linearly with PNR since it is determined only by the BC conditions as can be verified in equation (24). The result in Fig. 6 illustrates that if the SNR of FC keeps 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 MF and RZF techniques have been derived for a dual-hop MIMO relay network with Amplify-and-Forward (AF) relaying protocol. The proposed MF and MF-RZF beamformers are constructed jointly with the QR decomposition 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 gain 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 $\alpha_k$ values of the MF-RZF beamformer are still challenging problems that need further research effort.

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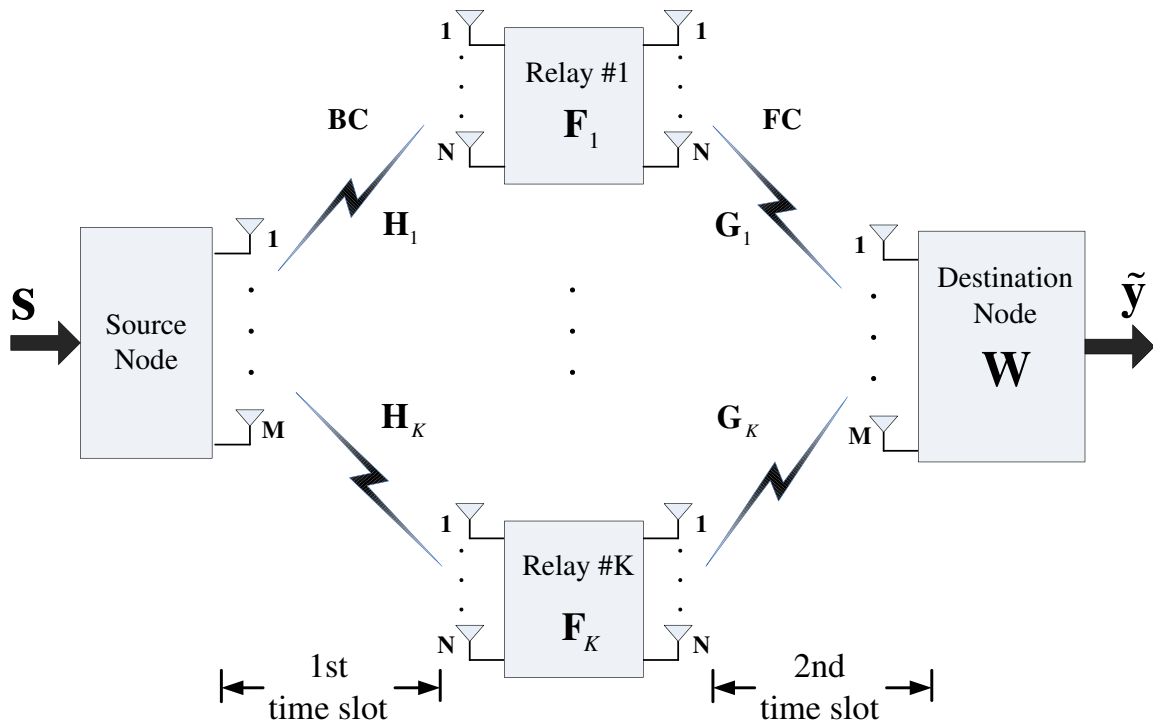
Fig. 1.   System model of a dual-hop MIMO network with relay beamforming.
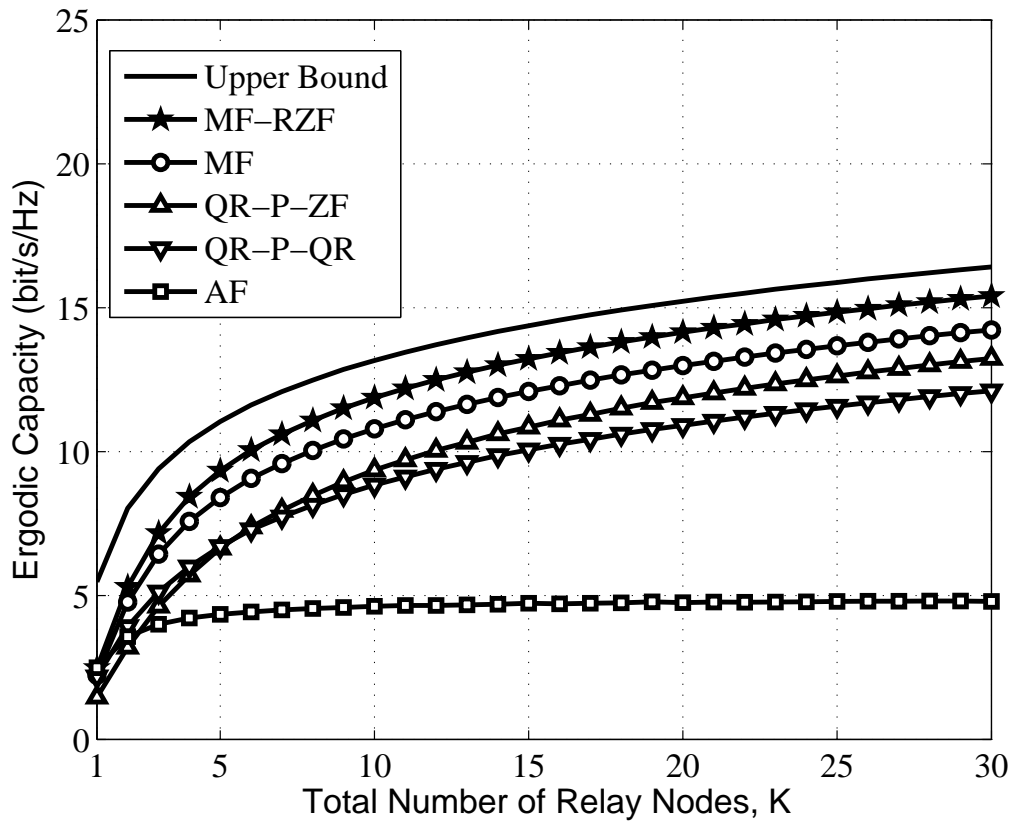
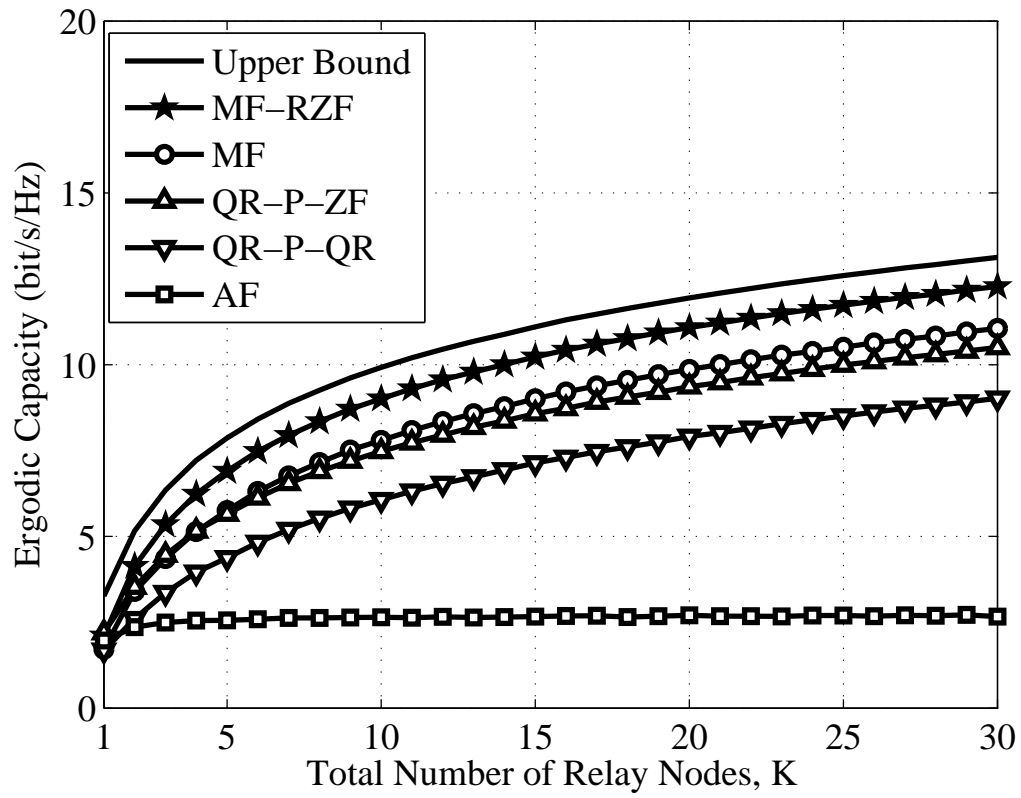Fig. 2. Ergodic capacity comparisons versus $K$ ($N = M = 4, PNR = QNR = 10dB$).

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

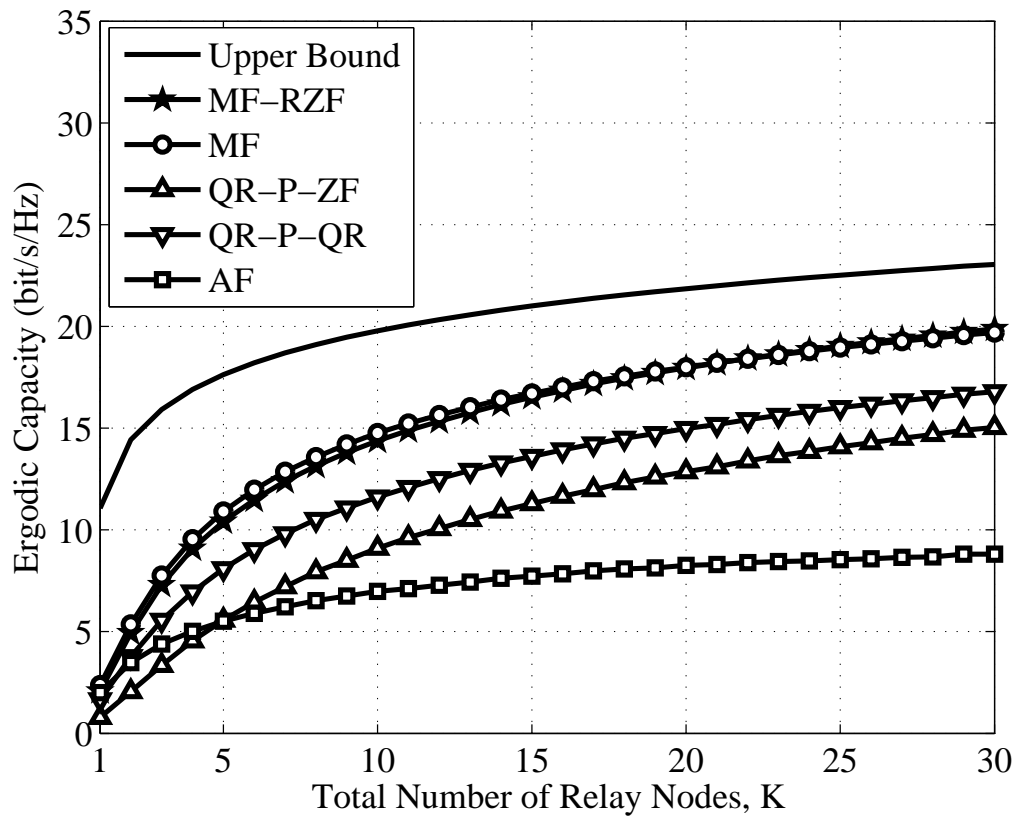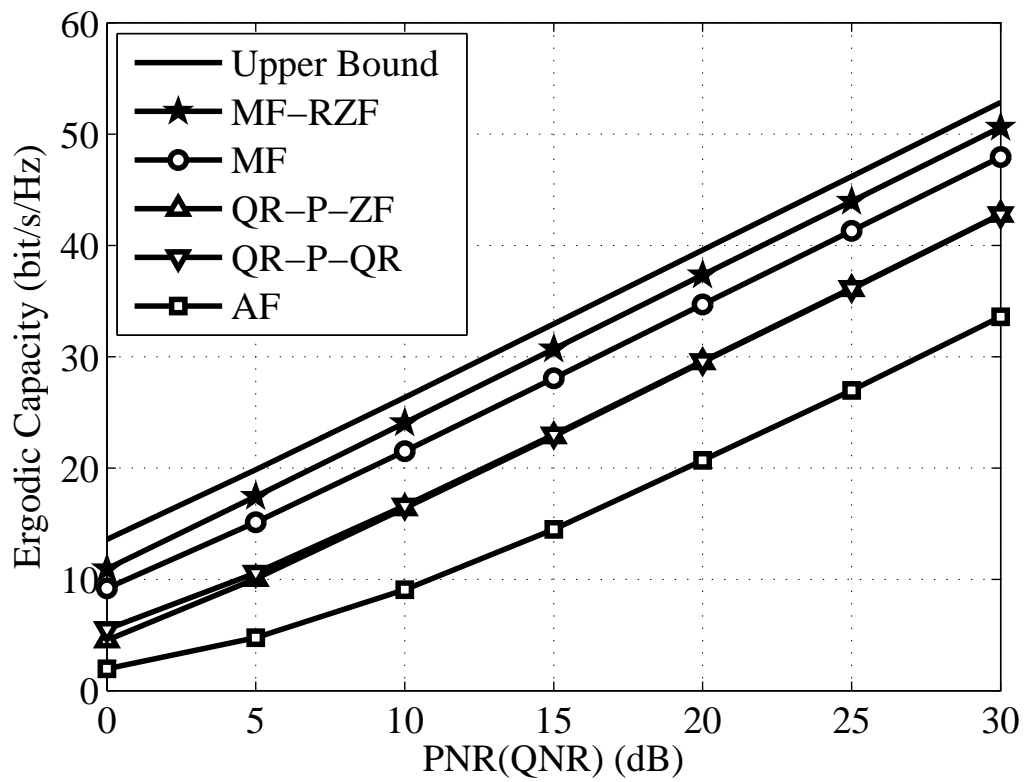Fig. 4.  Ergodic capacity comparisons versus $K$ ($N = M = 4, PNR = 20dB, QNR = 5dB$).

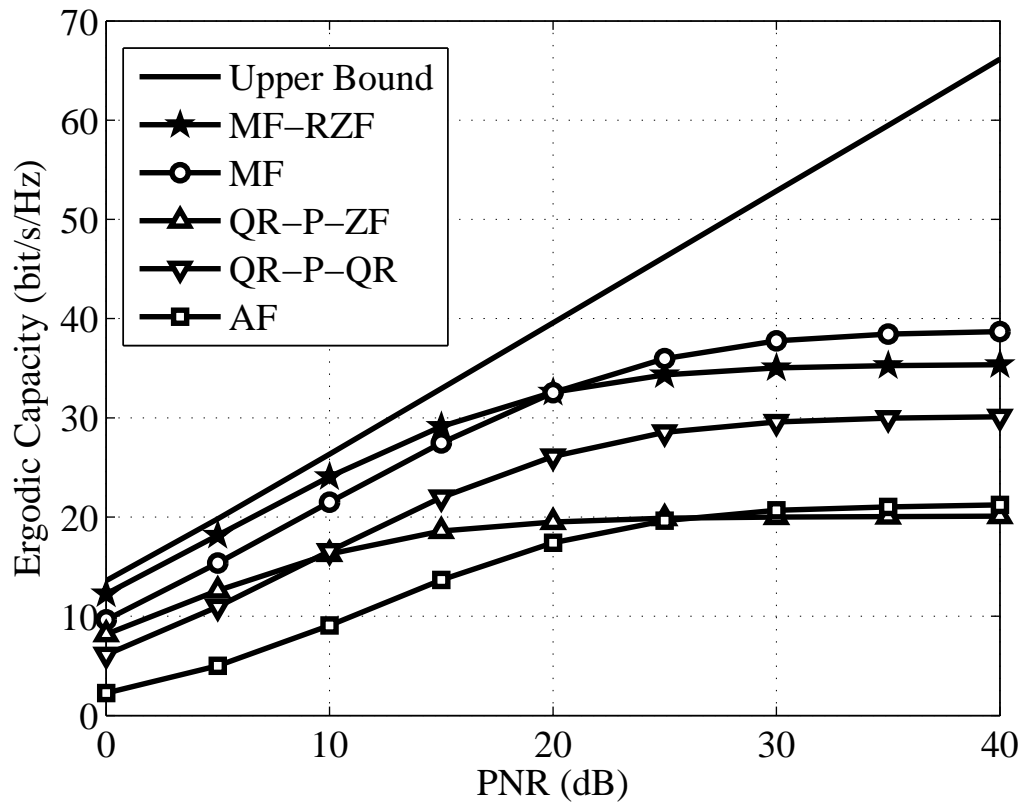Fig. 5.   Ergodic capacity comparisons versus PNR (QNR) ($N = M = 8, K = 10$).

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