Inter-Relay Interference Cancellation for AF MIMO Two-Path Relay Systems

Heesun Park* and Joohwan Chun†
*The Attached Institute of ETRI, Daejeon, Republic of Korea
†Dept. of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon, Republic of Korea
E-mail: hspark@ensec.re.kr; chun@ee.kaist.ac.kr

***Abstract*—This paper considers amplify-and-forward, multiple-input multiple-output, two-path relay systems in which the inter-relay interference (IRI) between two relay nodes leads to a degradation of performance. To solve this issue, we propose two IRI cancellation schemes that exploit the orthogonal projection methods using multiple antennas at the relay nodes; the proposed schemes effectively remove the IRI by projecting it onto the null space of the effective inter-relay channel. Simulation results show that the proposed IRI cancellation schemes achieve close-to-optimal performance in average rate.**

***Index Terms*—Amplify-and-forward, interference cancellation, MIMO, orthogonal projection, two-path relay.**

I. Introduction

Multiple-input multiple-output (MIMO) relay systems have been extensively considered due to the potential benefits of MIMO techniques such as spectral efficiency and link reliability [1], [2]. More specifically, amplify-and-forward (AF) MIMO relay systems, MIMO relay combined with AF relaying strategy, have attracted attention due to the virtue of simplicity on implementation [1]–[3]. Even though a half-duplex relay, which cannot transmit and receive a signal simultaneously, is in general preferable to full-duplex relay from an implementation aspect, the former results in a loss of spectral efficiency. To recover the spectral efficiency loss, two-path relaying protocol has been proposed in [4]–[6]; the delivery time of a message signal from the source to the destination, in this protocol, is halved by alternately exploiting two relay nodes between the source and destination nodes.

Despite the time efficiency of two-path relay systems, the inter-relay interference (IRI) resulting from the two-path relaying protocol itself decreases the signal-to-noise ratio (SNR) of the desired message signal at the destination node. To solve this issue, several IRI cancellation schemes have been proposed for decode-and-forward relaying in [7]–[9] and AF relaying in [10]–[13]. In [7], each relay node decodes the IRI and then subtracts it from the received signal before decoding the desired signal when the IRI is stronger than the desired signal. In [8], [9], the achievable rates of two-path relaying were studied by exploiting dirty-paper coding for IRI cancellation. To minimize the IRI, the transmit and receive beamforming schemes based on singular value decomposition (SVD) of the inter-relay channel were proposed in [10]. In addition, the IRI cancellation processes are conducted at the relay node [11] and at the destination node [12] by exploiting the previously received signals at the relay and destination nodes, respectively. Note, however, that the previous works in [7]–[12] consider only a deployment of single antenna at all the nodes except in [10] (multiple antennas are considered only at the relay nodes). The work in [13] proposed an AF two-path relaying scheme combined with MIMO techniques; however, the inter-relay channel was assumed to be absent for simplicity. While the IRI cancellation using multiple antennas was introduced in [14], the destination node subtracts an estimate of IRI (not the exact value of IRI) with the knowledge of channel state information of the inter-relay channel; thus, the IRI still remains to be removed. Our goal is therefore to remove the IRI using multiple antennas while not sacrificing the performance significantly.

In this paper, we propose two IRI cancellation schemes for AF MIMO two-path relay systems. To eliminate the IRI, we exploit orthogonal projection methods at the relay nodes; we derive the interference nulling matrix which projects the IRI onto the null space of the effective inter-relay channel. To provide the null space with an appropriate dimension, the effective inter-relay channel is obtained by combining the square matrix form of inter-relay channel with the SVD-based transmit or receive beamforming matrix. After the IRI cancellation process is complete, an optimal power allocation at the relay nodes is then performed to maximize the end-to-end data rate [15], [16]. Our analysis provides asymptotic performance of the proposed schemes; the proposed schemes achieve optimal performance in extreme cases. Simulation results show that the proposed schemes effectively eliminate the IRI with a very small loss in average rate performance.

Notation: For a matrix $\mathbf{A}$, $\mathbf{A}^H$, $\mathbf{A}^+$, $\mathrm{tr}(\mathbf{A})$, and $\mathbf{A}(i,j)$ denote the conjugate transpose, pseudo-inverse, trace, and (i,j)th element of $\mathbf{A}$. The term $\mathbb{C}^{a\times b}$ represents the $(a\times b)$-dimensional space with complex-valued elements. The term $E(\cdot)$ denotes the statistical expectation and $\mathcal{CN}(0,\sigma^2)$ denotes the complex Gaussian distribution with zero mean and variance of σ^2.

This paper is organized as follows: Section II introduces AF MIMO two-path relay systems. In Section III, we propose two IRI cancellation schemes. We analyze the asymptotic performance of the proposed schemes in Section IV. Simulation results are provided in Section V. Finally, Section VI concludes this paper with some remarks.

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

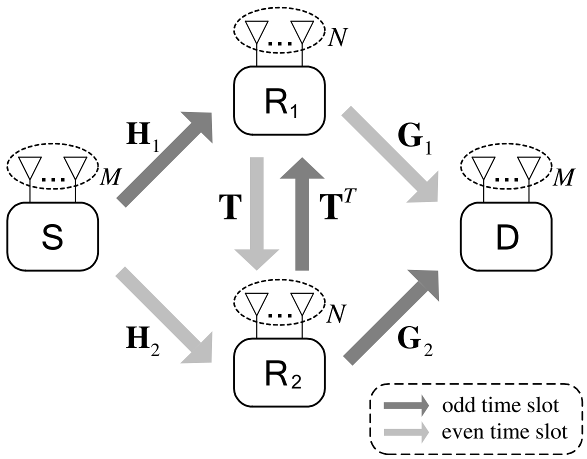

Fig. 1. AF MIMO two-path relay systems

II. System Model

Consider an AF MIMO two-path relay system in which the source node S and the destination node D have M antennas, and two relay nodes R_1 and R_2 have N antennas (see Fig. 1). All the nodes are assumed to operate in a half-duplex mode. There are two kinds of alternate transmission (AT) strategies at S:

- AT-indep: M independent data streams are transmitted to R_1 and R_2 in odd and even time slots, respectively.
- AT-split: $M/2$ independent data streams are transmitted to R_1 in odd time slot and the rest $M/2$ streams are transmitted to R_2 in even time slot.

Let L ($L = M$ for AT-indep and $L = M/2$ for AT-split) be the number of effective data streams for each transmission, and the condition of $N \geq L$ should be satisfied to support the transmission of L data streams. Two-path relaying protocol comprises two successive time slots, odd and even time slots. In odd time slot, S transmits a signal to R_1 while R_2 transmits the signal, received from S in the previous even time slot, to D. Conversely, R_2 receives a signal from S while R_1 transmits a signal to D in even time slot. By alternately exploiting R_1 and R_2, we can recover the loss of spectral efficiency; however, the IRI between R_1 and R_2 decreases the SNR of the desired signal at D. The direct link between S and D is assumed to be absent due to large path loss.

In each time slot, R_k receives the signal transmitted from S and the IRI from $\mathsf{R}_{\bar{k}}$ (i.e., $\bar{k} = 2$ for $k = 1$ and $\bar{k} = 1$ for $k = 2$) as follows:

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{s}_k + \mathbf{T}_{\bar{k}} \mathbf{x}_{\bar{k}} + \mathbf{n}_k \tag{1}$$

where $\mathbf{H}_k \in \mathbb{C}^{N\times M}$ denotes the channel matrix from S to R_k, $\mathbf{s}_k \in \mathbb{C}^{M\times 1}$ is the transmitted signal vector from S under the transmit power constraint of $\mathcal{P}_s$; that is, $\mathrm{tr}\{E(\mathbf{s}_k \mathbf{s}_k^H)\} = \mathcal{P}_s$, and $\mathbf{s}_k = \mathbf{P}_k \tilde{\mathbf{s}}_k$ is obtained by the source-precoder $\mathbf{P}_k \in \mathbb{C}^{M\times L}$ where $E(\tilde{\mathbf{s}}_k \tilde{\mathbf{s}}_k^H) = (\mathcal{P}_s/L)\mathbf{I}_L$. The term $\mathbf{T}_{\bar{k}} \in \mathbb{C}^{N\times N}$ denotes the inter-relay channel matrix between R_1 and R_2 ($\mathbf{T}_1 = \mathbf{T}$ and $\mathbf{T}_2 = \mathbf{T}^T$ in Fig. 1), $\mathbf{x}_{\bar{k}} \in \mathbb{C}^{N\times 1}$ is the transmitted signal vector from $\mathsf{R}_{\bar{k}}$, and $\mathbf{n}_k$ is the additive white Gaussian noise vector at R_k with $E(\mathbf{n}_k \mathbf{n}_k^H) = N_0 \mathbf{I}_N$. Without the IRI cancellation, D receives the signal transmitted from R_k as

$$\mathbf{y}_k = \mathbf{G}_k \mathbf{x}_k + \mathbf{z}_k \tag{2}$$

where $\mathbf{G}_k \in \mathbb{C}^{M\times N}$ denotes the channel matrix from R_k to D, $\mathbf{x}_k \in \mathbb{C}^{N\times 1}$ is the transmitted signal vector under the power constraint of $\mathrm{tr}\{E(\mathbf{x}_k \mathbf{x}_k^H)\} = \mathcal{P}_r$ at R_k, and $\mathbf{z}_k \in \mathbb{C}^{M\times 1}$ is the additive white Gaussian noise vector at D with $E(\mathbf{z}_k \mathbf{z}_k^H) = N_0 \mathbf{I}_M$.

III. Proposed Inter-Relay Interference Cancellation Schemes

To avoid the IRI component in the received signal at D, we propose two IRI cancellation schemes. The IRI cancellation processes, which are conducted at R_1 and R_2, exploit the orthogonal projection method [17] to construct the interference nulling matrix which projects the transmitted or received signal onto the null space of the effective inter-relay channel. We denote the IRI cancellation schemes with transmit nulling and receive nulling as ICT and ICR, respectively. Further performance improvements are provided by an optimal power allocation at the relay nodes [15], [16]. Note that the ICT and ICR schemes require the condition of $N \geq 2M$ and $N \geq M$ for AT-indep and AT-split strategies, respectively, allowing for a null space of inter-relay channel. We use the following notation for the SVD [18] of $\mathbf{H}_k$ and $\mathbf{G}_k$ for $k \in \{1, 2\}$:

$$\begin{aligned}
\mathbf{H}_k &= \bar{\mathbf{U}}_{hk} \bar{\mathbf{\Sigma}}_{hk} \bar{\mathbf{V}}_{hk}^H & \mathbf{G}_k &= \bar{\mathbf{U}}_{gk} \bar{\mathbf{\Sigma}}_{gk} \bar{\mathbf{V}}_{gk}^H \\
\mathbf{U}_{hk} &= \bar{\mathbf{U}}_{hk}(:, 1:L) & \mathbf{U}_{gk} &= \bar{\mathbf{U}}_{gk}(:, 1:L) \\
\mathbf{\Sigma}_{hk} &= \bar{\mathbf{\Sigma}}_{hk}(1:L, 1:L) & \mathbf{\Sigma}_{gk} &= \bar{\mathbf{\Sigma}}_{gk}(1:L, 1:L) \\
\mathbf{V}_{hk} &= \bar{\mathbf{V}}_{hk}(:, 1:L) & \mathbf{V}_{gk} &= \bar{\mathbf{V}}_{gk}(:, 1:L).
\end{aligned}$$

A. IRI cancellation at the Relay with Tx-nulling (ICT)

The ICT scheme exploits the orthogonal projection method to project the transmitted signal at R_k onto the null space of the inter-relay channel $\mathbf{T}_k$ for $k \in \{1, 2\}$. Note, however, that the null space of the inter-relay channel $\mathbf{T}_k$ does not exist because $\mathbf{T}_k$ is an $(N \times N)$-dimensional square matrix, and therefore, the nullity of $\mathbf{T}_k$ (with full rank) is zero.

To retain the diagonality of AF MIMO relay channels using SVD [15], [16], we have $\mathbf{s}_k = \mathbf{V}_{hk} \tilde{\mathbf{s}}_k$ for $k \in \{1, 2\}$ and combine the received signal at R_k as follows:

$$\tilde{\mathbf{r}}_k = \mathbf{U}_{hk}^H \mathbf{r}_k = \mathbf{\Sigma}_{hk} \tilde{\mathbf{s}}_k + \mathbf{U}_{hk}^H \mathbf{T}_{\bar{k}} \mathbf{x}_{\bar{k}} + \mathbf{U}_{hk}^H \mathbf{n}_k. \tag{3}$$

From (3), we now consider $\tilde{\mathbf{T}}_k = \mathbf{U}_{h\bar{k}}^H \mathbf{T}_k \in \mathbb{C}^{L\times N}$, with the $(N - L)$-dimension of null space, as the effective inter-relay channel from R_k to $\mathsf{R}_{\bar{k}}$. To project the transmitted signal onto the null space of $\tilde{\mathbf{T}}_k$, we construct the following interference nulling matrix

$$\mathbf{Q}_k = \mathbf{I}_N - \tilde{\mathbf{T}}_k^+ \tilde{\mathbf{T}}_k, \tag{4}$$

and the transmitted signal at R_k is then given by

$$\mathbf{x}_k = \Gamma_k \mathbf{Q}_k \tilde{\mathbf{V}}_{gk} \tilde{\mathbf{r}}_k \tag{5}$$

where Γ_k is the power coefficient at R_k and $\tilde{\mathbf{V}}_{gk} \in \mathbb{C}^{N\times L}$ is the L right singular vectors corresponding to the L largest singular values of $\tilde{\mathbf{G}}_k = \mathbf{G}_k\mathbf{Q}_k$. The power coefficient Γ_k is given by

$$\begin{aligned}\Gamma_k &= \sqrt{\frac{\mathcal{P}_r/N_0}{\rho_s \mathrm{tr}\left(\mathbf{Q}_k\tilde{\mathbf{V}}_{gk}\mathbf{\Sigma}_{hk}^2\tilde{\mathbf{V}}_{gk}^H\mathbf{Q}_k^H\right) + \mathrm{tr}\left(\mathbf{Q}_k\tilde{\mathbf{V}}_{gk}\tilde{\mathbf{V}}_{gk}^H\mathbf{Q}_k^H\right)}} \\ &= \sqrt{\frac{\mathcal{P}_r/N_0}{\rho_s \mathrm{tr}\left(\mathbf{\Sigma}_{hk}^2\right) + L}} \qquad (6)\end{aligned}$$

where $\rho_s = \mathcal{P}_s/(LN_0)$ and $\tilde{\mathbf{V}}_{gk}^H\mathbf{Q}_k^H\mathbf{Q}_k\tilde{\mathbf{V}}_{gk} = \mathbf{I}_L$ because $\tilde{\mathbf{V}}_{gk}$ belongs to the null space of $\tilde{\mathbf{T}}_k$. Premultiplying by $\mathbf{Q}_k$ to the transmitted signal at R_k, therefore, provides no IRI in the received signal at $\mathsf{R}_{\bar{k}}$, i.e., $\tilde{\mathbf{T}}_k\mathbf{x}_k = \mathbf{0}$. The received signal at D is subsequently combined as follows:

$$\tilde{\mathbf{y}}_k = \tilde{\mathbf{U}}_{gk}^H\mathbf{y}_k = \Gamma_k\tilde{\mathbf{\Sigma}}_{gk}\mathbf{\Sigma}_{hk}\tilde{\mathbf{s}}_k + \Gamma_k\tilde{\mathbf{\Sigma}}_{gk}\mathbf{U}_{hk}^H\mathbf{n}_k + \tilde{\mathbf{U}}_{gk}^H\mathbf{z}_k \quad (7)$$

where the SVD of $\tilde{\mathbf{G}}_k$ is given by $\tilde{\mathbf{G}}_k = \tilde{\mathbf{U}}_{gk}\tilde{\mathbf{\Sigma}}_{gk}\tilde{\mathbf{V}}_{gk}^H$.

B. IRI cancellation at the Relay with Rx-nulling (ICR)

In the ICR scheme, the interference nulling matrix $\mathbf{Q}_k$ removes the IRI included in the received signal at R_k:

$$\mathbf{r}'_k = \mathbf{Q}_k\mathbf{r}_k = \mathbf{Q}_k\mathbf{H}_k\mathbf{s}_k + \mathbf{Q}_k\mathbf{T}_{\bar{k}}\mathbf{x}_{\bar{k}} + \mathbf{Q}_k\mathbf{n}_k \quad (8)$$

where $\tilde{\mathbf{H}}_k = \mathbf{Q}_k\mathbf{H}_k = \tilde{\mathbf{U}}_{hk}\tilde{\mathbf{\Sigma}}_{hk}\tilde{\mathbf{V}}_{hk}^H$, $\mathbf{s}_k = \tilde{\mathbf{V}}_{hk}\tilde{\mathbf{s}}_k$, and $\tilde{\mathbf{n}}_k = \mathbf{Q}_k\mathbf{n}_k$. The IRI component in (8) should be removed by $\mathbf{Q}_k$, i.e.,

$$\mathbf{Q}_k\mathbf{T}_{\bar{k}}\mathbf{x}_{\bar{k}} = \mathbf{0}. \quad (9)$$

The combined received signal at R_k is subsequently obtained as

$$\tilde{\mathbf{r}}_k = \tilde{\mathbf{U}}_{hk}^H\mathbf{r}'_k = \tilde{\mathbf{\Sigma}}_{hk}\tilde{\mathbf{s}}_k + \tilde{\mathbf{U}}_{hk}^H\tilde{\mathbf{n}}_k, \quad (10)$$

and the transmitted signal at R_k is represented as

$$\mathbf{x}_k = \Gamma_k\mathbf{V}_{gk}\tilde{\mathbf{r}}_k. \quad (11)$$

From (9) and (11), we consider $\tilde{\mathbf{T}}_{\bar{k}} = \mathbf{T}_{\bar{k}}\mathbf{V}_{g\bar{k}} \in \mathbb{C}^{N\times L}$ as the effective inter-relay channel from $\mathsf{R}_{\bar{k}}$ to R_k. To satisfy the condition of (9), $\mathbf{Q}_k$ becomes a form of orthogonal projection matrix which projects the received signal at R_k onto the left null space of $\tilde{\mathbf{T}}_{\bar{k}}$:

$$\mathbf{Q}_k = \mathbf{I}_N - \tilde{\mathbf{T}}_{\bar{k}}\tilde{\mathbf{T}}_{\bar{k}}^+. \quad (12)$$

The power coefficient Γ_k at R_k is given by

$$\begin{aligned}\Gamma_k &= \sqrt{\frac{\mathcal{P}_r/N_0}{\rho_s \mathrm{tr}\left(\mathbf{V}_{gk}\tilde{\mathbf{\Sigma}}_{hk}^2\mathbf{V}_{gk}^H\right) + \mathrm{tr}\left(\tilde{\mathbf{U}}_{hk}^H\mathbf{Q}_k\mathbf{Q}_k^H\tilde{\mathbf{U}}_{hk}\right)}} \\ &= \sqrt{\frac{\mathcal{P}_r/N_0}{\rho_s \mathrm{tr}\left(\tilde{\mathbf{\Sigma}}_{hk}^2\right) + L}} \qquad (13)\end{aligned}$$

where $\tilde{\mathbf{U}}_{hk}^H\mathbf{Q}_k\mathbf{Q}_k^H\tilde{\mathbf{U}}_{hk} = \mathbf{I}_L$ because $\tilde{\mathbf{U}}_{hk}$ belongs to the left null space of $\tilde{\mathbf{T}}_{\bar{k}}$. Consequently, we have the following combined received signal at D without the IRI:

$$\tilde{\mathbf{y}}_k = \mathbf{U}_{gk}^H\mathbf{y}_k = \Gamma_k\mathbf{\Sigma}_{gk}\tilde{\mathbf{\Sigma}}_{hk}\tilde{\mathbf{s}}_k + \Gamma_k\mathbf{\Sigma}_{gk}\tilde{\mathbf{U}}_{hk}^H\tilde{\mathbf{n}}_k + \mathbf{U}_{gk}^H\mathbf{z}_k. \quad (14)$$

Note that both the ICT and ICR schemes completely isolate the two alternate paths of relay channels, $\mathsf{S} \to \mathsf{R}_1 \to \mathsf{D}$ and $\mathsf{S} \to \mathsf{R}_2 \to \mathsf{D}$, by projecting the IRI onto the null space of the effective inter-relay channel. For each of the isolated relay channels, the optimal relay power allocation in [15], [16], therefore, can be used to maximize the end-to-end data rate. The ICT-2 and ICR-2 schemes perform optimal relay power allocations for the ICT and ICR schemes, respectively.

IV. Asymptotic Performance Analysis

To investigate the average rate performance of the proposed IRI cancellation schemes, we represent the average rate of the lth data stream of the path $\mathsf{S} \to \mathsf{R}_k \to \mathsf{D}$ for $k = \{1, 2\}$ as follows:

$$\mathcal{R}_{o,l} = \log_2(1 + f_{o,l}) = \log_2\left(1 + \rho_s\frac{h_l g_l x_o}{1 + g_l x_o}\right) \quad (15)$$

$$\mathcal{R}_{t,l} = \log_2(1 + f_{t,l}) = \log_2\left(1 + \rho_s\frac{h_l \tilde{g}_l x_t}{1 + \tilde{g}_l x_t}\right) \quad (16)$$

$$\mathcal{R}_{r,l} = \log_2(1 + f_{r,l}) = \log_2\left(1 + \rho_s\frac{\tilde{h}_l g_l x_r}{1 + g_l x_r}\right) \quad (17)$$

$$\mathcal{R}_{d,l} = \log_2(1 + f_{d,l}) = \log_2\left(1 + \rho_s\frac{h_l g_l x_d}{1 + (1+\phi_l) g_l x_d}\right) \quad (18)$$

where $\mathcal{R}_{o,l}$, $\mathcal{R}_{t,l}$, $\mathcal{R}_{r,l}$, and $\mathcal{R}_{d,l}$ denote the data rates of no IRI case, ICT, ICR, and ICD[1] schemes, respectively. Note that the pre-log factor $1/2$ is omitted here. The parameters given in (15)-(18) are represented as

$$\begin{cases} x_t = x_o = \frac{\mathcal{P}_r/N_0}{\rho_s\sum_{i=1}^{L} h_i + L} \\ x_r = \frac{\mathcal{P}_r/N_0}{\rho_s\sum_{i=1}^{L} \tilde{h}_i + L} \\ x_d = \frac{\mathcal{P}_r/N_0}{\rho_s\sum_{i=1}^{L} h_i + L + \alpha} \\ \phi_l = \|\mathbf{\Phi}_k(l,:)\|^2;\;\; \mathbf{\Phi}_k = \mathbf{U}_{hk}^H\mathbf{T}_{\bar{k}}\mathbf{G}_{\bar{k}}^+ \\ h_l = \lambda_l\left(\mathbf{H}_k^H\mathbf{H}_k\right) > \tilde{h}_l = \lambda_l\left(\tilde{\mathbf{H}}_k^H\tilde{\mathbf{H}}_k\right) \\ g_l = \lambda_l\left(\mathbf{G}_k\mathbf{G}_k^H\right) > \tilde{g}_l = \lambda_l\left(\tilde{\mathbf{G}}_k\tilde{\mathbf{G}}_k^H\right) \end{cases} \quad (19)$$

where $\lambda_l(\cdot)$ denotes the lth eigenvalue of $(\cdot)$. The terms α and ϕ_l are positive values; α is a positive value to meet the relay power constraint $\mathcal{P}_r$ and ϕ_l results from the IRI estimation error in [14]. The eigenvalues in (19) have the following properties as N increases [19]:

$$h_l = N\sigma_H^2; \qquad g_l = N\sigma_G^2 \quad (20)$$

$$\tilde{h}_l = (N-L)\sigma_H^2; \qquad \tilde{g}_l = (N-L)\sigma_G^2. \quad (21)$$

A. $N \to \infty$ for a fixed L

In this case, we have $h_l = \tilde{h}_l$ and $g_l = \tilde{g}_l$ from (20) and (21), and therefore, $f_{t,l} = f_{r,l} = f_{o,l} > f_{d,l}$ because $\alpha > 0$ and $\phi_l > 0$. Both the ICT and ICR schemes provide optimal performance; both achieves the same performance with respect to the case of imposing no IRI [13]. The performance loss in average rate is, therefore, expected to be greatly reduced as N increases.

[1]We denote the IRI cancellation scheme in [14] that subtracts an estimate of IRI at D as ICD.

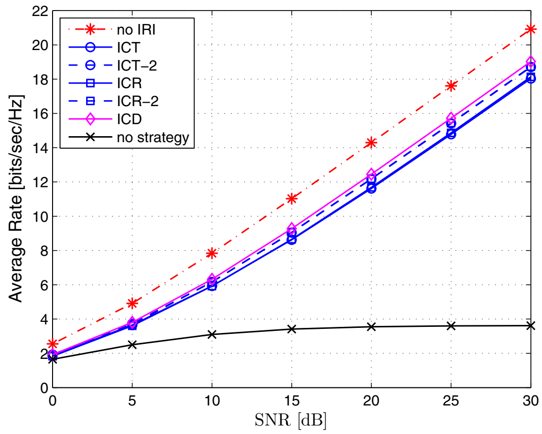

Fig. 2. Average rate versus SNR for AT-indep if $M = 2$, $N = 4$, and $\text{SNR} = \text{SNR}_{sr} = \text{SNR}_{rd} = \text{SNR}_{rr}$

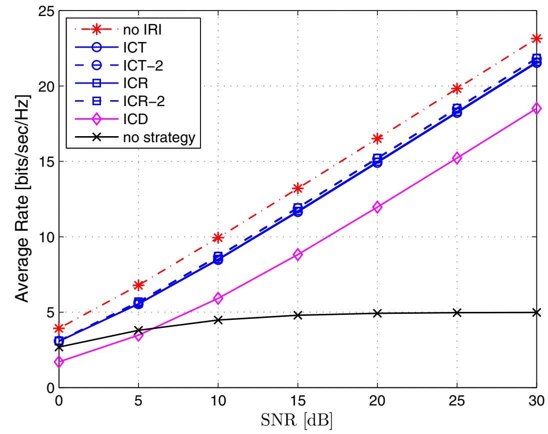

Fig. 3. Average rate versus SNR for AT-split if $M = 4$, $N = 4$, and $\text{SNR} = \text{SNR}_{sr} = \text{SNR}_{rd} = \text{SNR}_{rr}$

B. $\mathcal{P}_r \gg \mathcal{P}_s$ for a fixed $\mathcal{P}_s$

If $\mathcal{P}_r$ increases for a fixed $\mathcal{P}_s$, i.e., $\mathcal{P}_r/\mathcal{P}_s \to \infty$, the log functions in (16)-(18) become

$$\begin{aligned} f_{t,l} &= \rho_s \frac{h_l}{1+\frac{1}{\tilde{g}_l x_t}} = \rho_s \frac{h_l}{1+\frac{\frac{\mathcal{P}_s}{\mathcal{P}_r}\frac{1}{LN_0}\sum_i h_i + \frac{L}{\mathcal{P}_r}}{\tilde{g}_l/N_0}} \\ &\simeq \rho_s h_l = f_{\text{bound}} \end{aligned} \tag{22}$$

$$\begin{aligned} f_{r,l} &= \rho_s \frac{\tilde{h}_l}{1+\frac{1}{\tilde{g}_l x_r}} = \rho_s \frac{\tilde{h}_l}{1+\frac{\frac{\mathcal{P}_s}{\mathcal{P}_r}\frac{1}{LN_0}\sum_i \tilde{h}_i + \frac{L}{\mathcal{P}_r}}{g_l/N_0}} \\ &\simeq \rho_s \tilde{h}_l < f_{\text{bound}} \end{aligned} \tag{23}$$

$$\begin{aligned} f_{d,l} &= \rho_s \frac{h_l}{1+\phi_l+\frac{1}{g_l x_d}} = \rho_s \frac{h_l}{1+\phi_l+\frac{\frac{\mathcal{P}_s}{\mathcal{P}_r}\frac{1}{LN_0}\sum_i h_i + \frac{L}{\mathcal{P}_r} + \frac{\alpha}{\mathcal{P}_r}}{g_l/N_0}} \\ &\simeq \rho_s \frac{h_l}{1+\phi_l+\frac{\alpha/\mathcal{P}_r}{g_l/N_0}} < f_{\text{bound}} \end{aligned} \tag{24}$$

where $f_{\text{bound}} = \rho_s h_l$ is the information-theoretic upper bound [13]. Only the ICT scheme, therefore, achieves the theoretic upper bound in this case.

V. Simulation Results

We consider a Rayleigh flat fading channel for $\mathbf{H}_k$, $\mathbf{G}_k$, and $\mathbf{T}_k$ with $k \in \{1, 2\}$; that is, $\mathbf{H}_k(i,j) \sim \mathcal{CN}(0, \sigma_H^2)$, $\mathbf{G}_k(i,j) \sim \mathcal{CN}(0, \sigma_G^2)$, and $\mathbf{T}_k \sim \mathcal{CN}(0, \sigma_T^2)$. All the transmission nodes S, R_1, and R_2 are assumed to have the same transmit power constraint of $\mathcal{P}$, i.e., $\mathcal{P}_s = \mathcal{P}_r = \mathcal{P}$ except in the simulation corresponding to Fig. 6. The receive SNRs are defined as $\text{SNR}_{sr} = \rho_s \sigma_H^2$ for the link $\mathsf{S} \to \mathsf{R}_k$, $\text{SNR}_{rd} = \rho_r \sigma_G^2$ for the link $\mathsf{R}_k \to \mathsf{D}$, and $\text{SNR}_{rr} = \rho_r \sigma_T^2$ for the link $\mathsf{R}_k \to \mathsf{R}_{\bar{k}}$ where $\rho_r = \mathcal{P}_r/(LN_0)$.

In Fig. 2, we show the average rate performance of the IRI cancellation schemes for AT-indep if $M = 2$, $N = 4$, and $\text{SNR} = \text{SNR}_{sr} = \text{SNR}_{rd} = \text{SNR}_{rr}$. As SNR increases, the proposed schemes provide significant improvements in average rate over the scheme without any IRI cancellation (denoted by 'no strategy' in the figure). In addition, the proposed schemes retain a small gap as compared to the ideal case, in which no IRI exists between R_1 and R_2, with optimal relay power allocation [13] (denoted by 'no IRI' in the figure) for the entire range of SNR. Further improvements are provided by relay power allocation for the ICT-2 and ICR-2 schemes at high SNR regime, and those achieve almost the same performance with respect to the ICD scheme.[2]

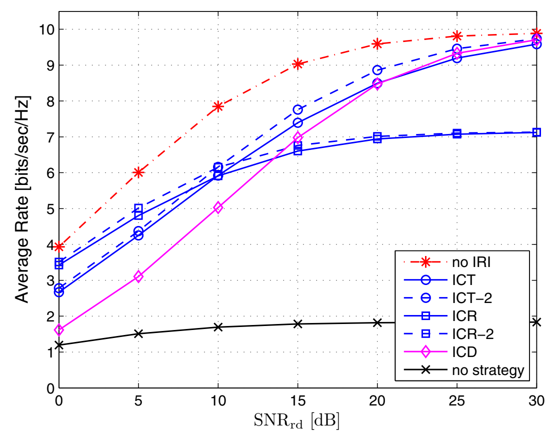

Fig. 4. Average rate versus SNR_{rd} for AT-indep if $M = 2$, $N = 4$, $\text{SNR}_{sr} = 10\text{dB}$, and $\text{SNR}_{rr} = 15\text{dB}$

Fig. 3 shows the average rate performance versus SNR for AT-split if $M = 4$, $N = 4$, and $\text{SNR} = \text{SNR}_{sr} = \text{SNR}_{rd} = \text{SNR}_{rr}$. The proposed ICT and ICR (also the ICT-2 and ICR-2) schemes show close-to-optimal performance with a loss of about 2.5dB as compared to the optimal result (no IRI). In contrast, the ICD scheme performs worse than the other proposed schemes because a square matrix inversion with $M = N$ in [14] yields large errors in the IRI estimation.

Fig. 4 presents the average rate versus SNR_{rd} for AT-indep if $M = 2$, $N = 4$, $\text{SNR}_{sr} = 10\text{dB}$, and $\text{SNR}_{rr} = 15\text{dB}$. In the low SNR_{rd} regime, the ICR and ICR-2 schemes outper-

[2] From (15)-(18), the ICD scheme can perform better than the proposed schemes under specific conditions. For example, decreasing σ_T^2 (thus, decreasing ϕ_l in (19)) increases $\mathcal{R}_{d,l}$ in (18). As provided in Section IV, the ICD scheme requiring the channel state information of the inter-relay channel at D, however, does not achieve optimal performance even in extreme cases.

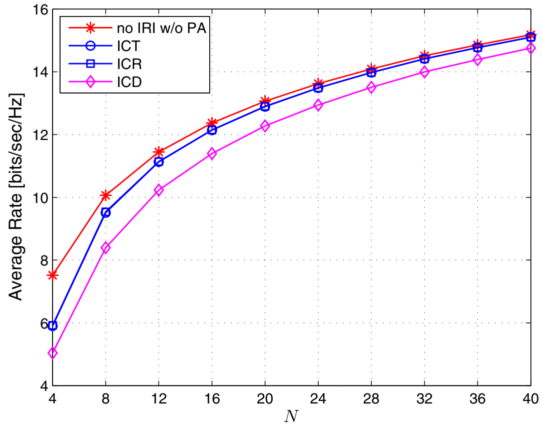

Fig. 5. Average rate versus N for AT-indep if $M = 2$, $\mathrm{SNR}_{sr} = 10$dB, $\mathrm{SNR}_{rd} = 10$dB, and $\mathrm{SNR}_{rr} = 15$dB

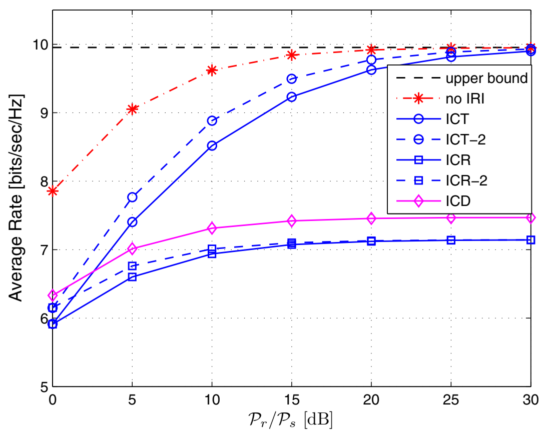

Fig. 6. Average rate versus $\mathcal{P}_r/\mathcal{P}_s$ for AT-indep if $M = 2$, $N = 4$, and $\mathrm{SNR}_{sr} = 10$dB

forms the rest and are close to the no IRI case. In contrast, the ICT and ICT-2 schemes show near-optimal performance in the high SNR_{rd} regime. These observations indicate that the IRI cancellation with rx-nulling, which yields a reduction of magnitudes of elements in $\tilde{\mathbf{\Sigma}}_{hk}(\leq \mathbf{\Sigma}_{hk})$ while preserving the values of $\mathbf{\Sigma}_{gk}$ for $k \in \{1, 2\}$, is effective in the regime of low SNR_{rd}. The tx-nulling with $\mathbf{\Sigma}_{hk}$ and $\tilde{\mathbf{\Sigma}}_{gk}(\leq \mathbf{\Sigma}_{gk})$ is effective in the regime of high SNR_{rd} for the same reason.

Fig. 5 shows the average rate versus N for AT-indep if $M = 2$, $\mathrm{SNR}_{sr} = 10$dB, $\mathrm{SNR}_{rd} = 10$dB, and $\mathrm{SNR}_{rr} = 15$dB. As expected from the analysis in Section IV.A, the ICT and ICR schemes achieve almost the same performance with respect to the no IRI case without the relay power allocation as N increases, whereas the ICD scheme does not. Even when used with the relay power allocation, we obtain similar results.

Fig. 6 plots the average rate versus $\mathcal{P}_r/\mathcal{P}_s$ for AT-indep if $M = 2$, $N = 4$, and $\mathrm{SNR}_{sr} = 10$dB. As the ratio of $\mathcal{P}_r/\mathcal{P}_s$ increases, only the IRI cancellations with tx-nulling, ICT and ICT-2, achieve the optimality in rate performance while the ICR, ICR-2, and ICD schemes converge to constant values which are considerably lower than the information-theoretic upper bound (denoted by 'upper bound' in the figure) [13]. This demonstrates the validity of Section IV.B.

VI. Conclusion

In this paper, we propose two IRI cancellation schemes for AF MIMO two-path relay systems. By exploiting orthogonal projection methods, the proposed ICT and ICR schemes separate two relaying paths, and therefore, remove the IRI. In addition, the proposed schemes can be further simplified by relaxing the constraint on the number of antennas, such as R_k has $N_k = L$ antennas and $\mathsf{R}_{\bar{k}}$ has $N_{\bar{k}} \geq 2L$ antennas (asymmetric antenna configuration at the relay nodes). Simulation results demonstrate that the proposed schemes effectively eliminate the IRI with a small loss in average rate performance.

References

[1] H. Bölcskei, R. U. Nabar, Ö. Oyman, and A. J. Paulraj, "Capacity scaling laws in MIMO relay networks," *IEEE Trans. Wireless Commun.*, vol. 5, no. 6, pp. 1433–1444, June 2006.

[2] Y. Fan and J. Thompson, "MIMO configurations for relay channels: Theory and practice," *IEEE Trans. Wireless Commun.*, vol. 6, no. 5, pp. 1774–1786, May 2007.

[3] S. Berger, M. Kuhn, A. Wittneben, T. Unger, and A. Klein, "Recent advances in amplify-and-forward two-hop relaying," *IEEE Commun. Mag.*, vol. 47, no. 7, pp. 50–56, July 2009.

[4] T. J. Oechtering and A. Sezgin, "A new cooperative transmission scheme using the space-time delay code," in *Proc. ITG Workshop on Smart Antennas*, Munich, Germany, Mar. 2004, pp. 41–48.

[5] A. Ribeiro, X. Cai, and G. B. Giannakis, "Opportunistic multipath for bandwidth-efficient cooperative multiple access," *IEEE Trans. Wireless Commun.*, vol. 5, no. 9, pp. 2321–2327, Sept. 2006.

[6] B. Rankov and A. Wittneben, "Spectral efficient protocols for half-duplex fading relay channels," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 379–389, Feb. 2007.

[7] Y. Fan, C. Wang, J. Thompson, and H. V. Poor, "Recovering multiplexing loss through successive relaying using repetition coding," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4484–4493, Dec. 2007.

[8] W. Chang, S.-Y. Chung, and Y. H. Lee, "Capacity bounds for alternating two-path relay channels," in *Proc. 45th Annu. Allerton Conf. Commun. Control, Comput.*, Allerton House, IL, Sept. 2007, pp. 1149–1155.

[9] R. Zhang, "On achievable rates of two-path successive relaying," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 2914–2917, Oct. 2009.

[10] W. H. Chin, C. K. Ho, and S. H. Ting, "Beamforming and interference cancellation for half duplex relaying," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Barcelon, Spain, Apr. 2009, pp. 1–5.

[11] H. Wicaksana, S. H. Ting, C. K, Ho, W. H. Chin, and Y. L. Guan, "AF two-path half duplex relaying with inter-relay self interference cancellation: Diversity analysis and its improvement," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4720–4729, Sept. 2009.

[12] C. Luo, Y. Gong, and F. Zheng, "Full interference cancellation for two-path relay cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 343–347, Jan. 2011.

[13] H. Park and J. Chun, "Alternate transmission relaying schemes for MIMO wireless networks," in *Proc. IEEE Wireless Commun. Network. Conf. (WCNC)*, Las Vegas, NV, Mar./Apr. 2008, pp. 1073–1078.

[14] H. Park and J. Chun, "An interference estimation algorithm using multi-element array sensors," in *Proc. Asia-Pacific Int. Conf. Synthetic Aperture Radar (APSAR)*, Seoul, Korea, Sept. 2011, pp. 1–3.

[15] X. Tang and Y. Hua, "Optimal design of non-regenerative MIMO wireless relays," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1398–1407, Apr. 2007.

[16] O. Muñoz-Medina, J. Vidal, and A. Agustín, "Linear transceiver design in nonregenerative relays with channel state information," *IEEE Trans. Signal Process.*, vol. 55, no. 6, pp. 2593–2604, June 2007.

[17] G. Strang, *Linear Algebra and Its Applications*. 3rd ed., Thompson Learning, Inc., 1988.

[18] G. H. Golub and C. F. Van Loan, *Matrix Computations*. 3rd ed. Baltimore, MD: Johns Hopkins Univ. Press, 1996.

[19] B. M. Hochwald, T. L. Marzetta, and V. Tarokh, "Multiple-antenna channel hardening and its implications for rate feedback and scheduling," *IEEE Trans. Inf. Theory*, vol. 50, no. 9, pp. 1893–1909, Sept. 2004.