Joint Source-Relay Precoding with MMSE-based Interference Suppression in two-way MIMO Amplify and Forward Relays

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***Abstract*—In this paper, we consider a two-way multiple input multiple output (MIMO) Amplify-and-Forward (AF) relay system, where interference is observed at the relay node during the multiple access (MAC) phase. For such a scenario, two new joint source-relay precoding algorithms with interference suppression are proposed and their performance analyzed through simulation results. These linear minimum mean-squared error (MMSE) based receiver algorithms provide acceptable error rate performance even in the presence of strong interference. Additionally, the effect of number of relay antennas and the number of interference streams on the overall diversity of the system is also investigated. We show that it is possible to handle interference at the relay node at the cost of losing some of the diversity gain offered by the extra antennas available at the relay.**

***Index Terms*—Two-way MIMO relay, Amplify-and-Forward, MMSE Interference Suppression, Joint Source-Relay Precoding**

I. Introduction

The use of relays in future wireless networks as a means to extend coverage as well as to improve the overall spectral efficiency has been gaining considerable attention recently. The principle of two-way relaying makes the use of relays spectrally efficient in spite of the additional hop, thus making it suitable for mass deployment in future wireless networks, where improving overall spectral efficiency is one of the goals.

While it is as yet not clear how relays will fit into the overall scheme of things in upcoming wireless networks, what can be inferred to a certain degree of confidence is that relays will mostly be operational in interference limited environments. One such plausible interference limited scenario is when a base-station (BS) acts as a relay between a user-pair and also receives information on the uplink from some other user, as illustrated in Fig. 1. To the user pair A, B (also referred to as sources) using the BS as a relay, the signal received by the BS from a different user C appears as interference. This is an example of interference affecting the performance of a relay during the MAC phase. A situation where interference is observed during the broadcast phase is shown in Fig. 2, where the user B sees interference from a neighboring BS serving its user D. It is important to observe from Fig. 1 and Fig. 2 that the cause of interference in the MAC and broadcast phases are different. Hence, MAC phase interference has an entirely different characteristics when compared to broadcast phase interference. Thus, the two kinds of interference are independent and therefore the two problems can be studied separately.

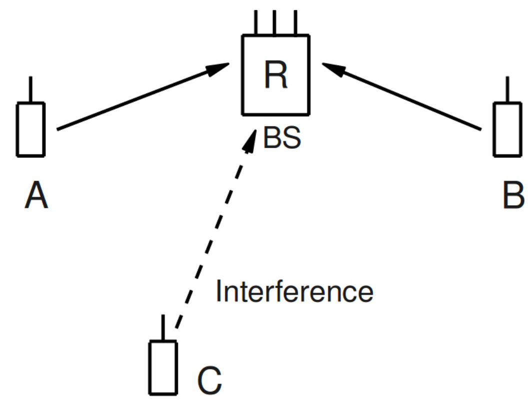

Fig. 1. Interference during MAC phase

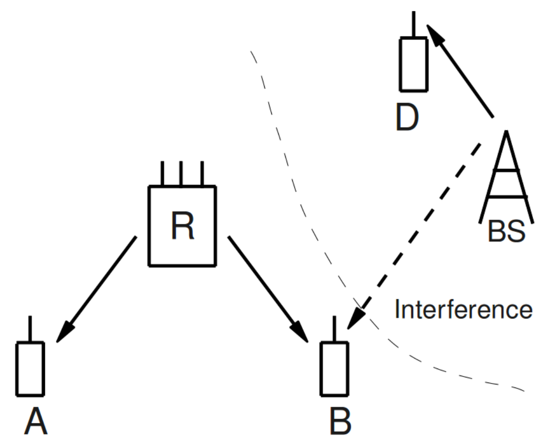

Fig. 2. Interference during broadcast phase

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In this paper, we focus on the case where the performance of a two-way AF relay performance is hampered by interference during the MAC phase (Fig. 1). For such a situation, we are interested in devising an effective method to suppress the detrimental impact of interference. Furthermore, if all nodes have multiple antennas, additional gains can be achieved by means of MIMO precoding at both source and relay. Thus, in this work, we focus on the problem of joint source-relay precoding with interference suppression.

A. Prior Art

The joint design of source and relay precoders, along with source decoders is considered in [1] for a noise-limited system where only one stream of data is sent between the two communicating nodes utilizing the multi-antenna relay. However, with multi-antenna source and relay nodes, we would also like to transmit more than one stream of data from the sources. The problem of transmitting multiple streams has been studied in [2], where the source and relay precoders and decoders have been jointly optimized according to the AMSE (Arithmetic sum of Mean-Squared Error) as well as the ABER (Arithmetic sum of Bit-Error Rate) criteria for a purely noise-limited system without considering co-channel interference during the MAC phase. To the best of our knowledge, interference management in two-way MIMO relays has not been well-explored. Interference in MIMO relays has been handled in [3] in the limited context of separating the signal streams of multiple user pairs which are simultaneously using the same relay. In this work, we use a more generic model of interference and make an attempt to extend the framework proposed in [2] to cover the case where interference is also present in the system by. The key conclusion of this paper is that the joint source-relay precoding scheme designed for noise-limited systems in [2] can be used even in the presence of co-channel interference during the MAC phase as long as the relay performs MMSE-based interference suppression, for which only the knowledge of second-order statistics of interference is required.

B. Notation

Throughout this work, bold upper-case letters denote matrices (e.g., $\mathbf{X}, \mathbf{Y}$) while bold lower-case letters denote vectors (e.g., $\mathbf{x}$, $\mathbf{y}$). $(.)^T$, $(.)^H$ and $(.)^{-1}$ denote the transpose, hermitian (complex conjugate-transpose) and inverse of a matrix while $Tr\{.\}$ and $\mathbb{E}\{.\}$ represent the trace of a matrix and the expectation operator, respectively. CWGN stands for Circular White Gaussian Noise and $\mathcal{CN} \sim (\mu, K)$ represents a complex Gaussian random vector with mean μ and covariance matrix K.

This paper is divided into five sections. Section II details the signal model used, following which the joint source-relay MIMO precoding framework is presented in Section III. We back our hypothesis with simulation results presented in Section IV, and finally, Section V concludes the paper.

II. Signal Model

We interest ourselves in the problem where two multi-antenna transceiver nodes, A and B communicate with each other via an intermediate relay R. Let M_A, M_B and M_R denote the number of antennas at A, B and R, respectively. Such a configuration shall henceforth be referred to as a $M_A - M_R - M_B$ system. Let $\mathbf{H_A} \in \mathbb{C}^{M_R \times M_A}$ and $\mathbf{H_B} \in \mathbb{C}^{M_R \times M_B}$ represent the channels $A \longrightarrow R$ and $B \longrightarrow R$, respectively. Channel reciprocity is assumed to hold, whereby the channels $R \longrightarrow A$ and $R \longrightarrow B$ are represented by $\mathbf{H_A}^T$ and $\mathbf{H_B}^T$, respectively. A and B transmit L_A and L_B streams of data, respectively, where $L_A \leq \min(M_R, \min(M_A, M_B))$ and $L_B \leq \min(M_R, \min(M_B, M_A))$. The vectors $\mathbf{s_A} \in \mathbb{C}^{L_A \times 1}$ and $\mathbf{s_B} \in \mathbb{C}^{L_B \times 1}$ denote the symbols transmitted by A and B, respectively, and are assumed to contain independent, unit-energy symbols. The MIMO nature of the links can be exploited by performing precoding at A and B. Let $\mathbf{F_A} \in \mathbb{C}^{M_A \times L_A}$ and $\mathbf{F_B} \in \mathbb{C}^{M_B \times L_B}$ be the precoders used by A and B, respectively. Therefore, the signal at R seen after the first phase (MAC phase) is given by

$$\mathbf{y_R} = \mathbf{H_A F_A s_A} + \mathbf{H_B F_B s_B} + \mathbf{z} + \eta_R \tag{1}$$

where $\mathbf{z}$ denotes the interference seen at the relay and $\eta_R \sim \mathcal{CN}(0, \sigma_R^2 \mathbf{I}_{M_R})$ is the CWGN at the relay. We model the interference as streams of data transmitted by nodes other than A or B, i.e.,

$$\mathbf{z} = \sum_{i=1}^{k} \mathbf{H_i s_i} \tag{2}$$

where we assume the presence of k streams of interference ($k \geq 1$), and $\mathbf{H_i} \in \mathbb{C}^{M_R \times 1}$ and $\mathbf{s_i} \in \mathbb{C}$ respectively denote the channel from the k^{th} interference stream to R, and the symbol transmitted by the k^{th} interference stream. Additionally, $\mathbf{F_A}$ and $\mathbf{F_B}$ satisfy the following constraints

$$Tr\{\mathbf{F_A F_A}^H\} \leq P_A \tag{3}$$

$$Tr\{\mathbf{F_B F_B}^H\} \leq P_B \tag{4}$$

where P_A and P_B represent the maximum average transmit powers at A and B, respectively. The signal $\mathbf{y_R}$ in (1) is amplified at R using the relay amplification matrix $\mathbf{G}$.

$$\tilde{\mathbf{y}}_\mathbf{R} = \mathbf{G y_R} \tag{5}$$

This signal $\tilde{\mathbf{y}}_\mathbf{R}$ satisfies the following power constraint

$$Tr(\mathbb{E}\{\tilde{\mathbf{y}}_\mathbf{R} \tilde{\mathbf{y}}_\mathbf{R}^H\}) \leq P_R, \tag{6}$$

where P_R is the maximum power available at R.

In the second phase (broadcast phase), the relay signal $\tilde{\mathbf{y}}_R$ is transmitted to both A and B. The signals received at A and

B are as follows

$$\begin{aligned}\mathbf{y_A} &= \mathbf{H_A}^T\tilde{\mathbf{y}}_\mathbf{R} + \eta_A \\ &= \underbrace{\mathbf{H_A}^T\mathbf{G}\mathbf{H_A}\mathbf{F_A}\mathbf{s_A}} + \mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B}\mathbf{s_B} + \mathbf{H_A}^T\mathbf{G}\mathbf{z} \\ &\quad + \mathbf{H_A}^T\mathbf{G}\eta_R + \eta_A \end{aligned} \tag{7}$$

$$\begin{aligned}\mathbf{y_B} &= \mathbf{H_B}^T\tilde{\mathbf{y}}_\mathbf{R} + \eta_B \\ &= \mathbf{H_B}^T\mathbf{G}\mathbf{H_A}\mathbf{F_A}\mathbf{s_A} + \underbrace{\mathbf{H_B}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B}\mathbf{s_B}} + \mathbf{H_B}^T\mathbf{G}\mathbf{z} \\ &\quad + \mathbf{H_B}^T\mathbf{G}\eta_R + \eta_B \end{aligned} \tag{8}$$

Here, $\eta_A \sim \mathcal{CN}(0, \sigma_A^2\mathbf{I}_{M_A})$ and $\eta_B \sim \mathcal{CN}(0, \sigma_B^2\mathbf{I}_{M_B})$ denote CWGN at A and B, respectively, while the highlighted terms in (7) and (8) represent the self-interference seen at A and B, respectively. If $\mathbf{G}$ and $\mathbf{H_A}$ are known at A, then the self-interference seen by A can be subtracted, and similarly an equivalent condition holds at B too. We assume A, B and R to have perfect CSI of $\mathbf{H_A}$ and $\mathbf{H_B}$. Under such an assumption, it shall be seen that $\mathbf{G}$ can be computed in a decentralized manner at all the 3 nodes. The signals of interest therefore at A and B, after cancelling the back-propagating self-interference are as follows

$$\tilde{\mathbf{y}}_\mathbf{A} = \mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B}\mathbf{s_B} + \mathbf{H_A}^T\mathbf{G}\mathbf{z} + \mathbf{H_A}^T\mathbf{G}\eta_R + \eta_A \tag{9}$$

$$\tilde{\mathbf{y}}_\mathbf{B} = \mathbf{H_B}^T\mathbf{G}\mathbf{H_A}\mathbf{F_A}\mathbf{s_A} + \mathbf{H_B}^T\mathbf{G}\mathbf{z} + \mathbf{H_B}^T\mathbf{G}\eta_R + \eta_B \tag{10}$$

A and B employ linear receivers $\mathbf{D_A}$ and $\mathbf{D_B}$ to get their respective estimates of $\mathbf{s_B}$ and $\mathbf{s_A}$.

$$\hat{\mathbf{s}}_\mathbf{B} = \mathbf{D_A}\tilde{\mathbf{y}}_\mathbf{A} \tag{11}$$

$$\hat{\mathbf{s}}_\mathbf{A} = \mathbf{D_B}\tilde{\mathbf{y}}_\mathbf{B} \tag{12}$$

III. Joint Source-Relay MIMO Precoding

From (9) and (11), the expression for the MSE matrix at A is given by

$$\begin{aligned} MSE_A &= \mathbb{E}\{(\mathbf{s_B} - \hat{\mathbf{s}}_\mathbf{B})(\mathbf{s_B} - \hat{\mathbf{s}}_\mathbf{B})^H\} \\ &= \mathbf{I} + \mathbf{D_A}\mathbb{E}\{\tilde{\mathbf{y}}_\mathbf{A}\tilde{\mathbf{y}}_\mathbf{A}^H\}\mathbf{D_A}^H - \mathbf{D_A}\mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B} \\ &\quad - (\mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B})^H\mathbf{D_A}^H \end{aligned} \tag{13}$$

where $\tilde{\mathbf{y}}_\mathbf{A}$ is as given in (9). For the rest of this section, we consider node A while presenting our analysis. The results for B can be obtained quite easily by the symmetry of the problem. For fixed $\mathbf{G}$, $\mathbf{F_A}$ and $\mathbf{F_B}$, the optimal linear receiver $\mathbf{D_A}$ in terms of minimizing the MSE can be obtained by evaluating $\nabla_{\mathbf{D_A}}(MSE_A) = 0$, which yields the familiar Wiener-filter solution.

$$\begin{aligned} \mathbf{D_A} &= (\mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B})^H\mathbb{E}\{\tilde{\mathbf{y}}_\mathbf{A}\tilde{\mathbf{y}}_\mathbf{A}^H\}^{-1} \\ &= (\mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B})^H[(\mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B})(\mathbf{H_A}^T\mathbf{G}\mathbf{H_B}\mathbf{F_B})^H \\ &\quad + (\mathbf{H_A}^T\mathbf{G})\mathbf{R_{i+n}}(\mathbf{H_A}^T\mathbf{G})^H + \sigma_a^2\mathbf{I}_{M_A}]^{-1} \end{aligned} \tag{14}$$

where $\mathbf{R_{i+n}} = \mathbb{E}\{\mathbf{z}\mathbf{z}^H\} + \sigma_R^2\mathbf{I}_{M_R}$ is the covariance matrix of the interference plus noise, at the relay. It is demonstrated in [4] that the BER is a convex increasing function of the MSE for small values of the argument (for BER less than 2×10^{-2} as a thumb rule). Thus, we are justified in our choice of a linear MMSE receiver as it is not only easy to implement but also ensures good BER performance for most practical cases.

Substituting (14) in (13) and using the matrix inversion lemma, the following expression is obtained for the MSE matrix at A

$$MSE_A = (\mathbf{I} + \mathbf{F_B}^H\mathbf{R_B}\mathbf{F_B})^{-1} \tag{15}$$

where $\mathbf{R_B} = (\mathbf{H_A}^T\mathbf{G}\mathbf{H_B})^H[(\mathbf{H_A}^T\mathbf{G})\mathbf{R_{i+n}}(\mathbf{H_A}^T\mathbf{G})^H + \sigma_A^2\mathbf{I}_{M_A}]^{-1}(\mathbf{H_A}^T\mathbf{G}\mathbf{H_B})$ We now focus our attention to the design of $\mathbf{F_A}$, $\mathbf{F_B}$ and $\mathbf{G}$ according to the AMSE and ABER optimization criteria, as specified in [2].

The AMSE and ABER objective functions have the following form:

(i) AMSE

$$f_{AMSE} = Tr\{MSE_A\} + Tr\{MSE_B\} \tag{16}$$

(ii) ABER

$$\begin{aligned} f_{ABER} &= \sum_{i=1}^{L_B} BER_{A_i} + \sum_{j=1}^{L_A} BER_{B_j} \\ &= \sum_{i=1}^{L_B} Q(\sqrt{2(MSE_{A_{i,i}}^{-1} - 1)}) + \\ &\quad \sum_{i=1}^{L_A} Q(\sqrt{2(MSE_{B_{i,i}}^{-1} - 1)}\ ) \end{aligned} \tag{17}$$

where BER_{A_i} and BER_{B_j} respectively denote the BERs for the i^{th} stream at A and the j^{th} stream at B, and $Q(.)$ denotes the Q-function with (17) being valid for QPSK constellation [5] at A and B, and the summation is over the number of streams transmitted by A and B.

We proceed in an iterative manner to converge upon the source precoders as well as $\mathbf{G}$. Firstly, for fixed $\mathbf{G}$, the optimization problems that need to be solved for the AMSE and ABER criteria are as follows

(i) AMSE criterion

$$\begin{aligned} &\min_{\mathbf{F_i}|i=A,B} \ f_{AMSE} \\ &\text{subject to} \\ &Tr\{\mathbf{F_i}\mathbf{F_i}^H\} \leq P_i \end{aligned} \tag{18}$$

(ii) ABER criterion

$$\begin{aligned} &\min_{\mathbf{F_i}|i=A,B} \ f_{ABER} \\ &\text{subject to} \\ &Tr\{\mathbf{F_i}\mathbf{F_i}^H\} \leq P_i \end{aligned} \tag{19}$$

For fixed $\mathbf{G}$, the design of source precoders $\mathbf{F_A}$ and $\mathbf{F_B}$ becomes decoupled. We present the solution for $\mathbf{F_B}$. The solution for $\mathbf{F_A}$ can be obtained in an identical manner. The optimal precoder structures for (18) and (19), as demonstrated in [2], is given by

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(i) AMSE

$$\mathbf{F_B} = \mathbf{U_B}\mathbf{\Sigma_B} \tag{20}$$

(ii) ABER

$$\mathbf{F_B} = \mathbf{U_B}\mathbf{\Sigma_B}\mathbf{V}^H \tag{21}$$

Here, $\mathbf{U_B} \in \mathbb{C}^{M_B \times L_B}$ contains the left eigenvectors corresponding to the highest L_B eigenvalues of $\mathbf{R_B}$ in ascending order, and $\mathbf{\Sigma_B} \in \mathbb{C}^{L_B \times L_B}$ denotes the diagonal matrix containing the corresponding powers allocated to the various streams. The water-filling algorithm used to allocate the powers is given in [4] and $\mathbf{V} \in \mathbb{C}^{L_B \times L_B}$ is any unitary matrix like the DFT matrix or the Hadamard matrix.

Given $\mathbf{F_A}$ and $\mathbf{F_B}$, f_{AMSE} and f_{ABER} become non-linear functions of $\mathbf{G}$, with quadratic constraints involving $\mathbf{G}$. A closed form solution for $\mathbf{G}$ is as yet unknown. Thus, we resort to numerical techniques and propose two SQP (sequential quadratic programming) based methods for the design of the relay precoder - i) with implicit interference suppression and ii) with explicit interference suppression.

A. Relay Precoder with Implicit Interference Suppression

In the analysis presented so far, the effects of interference suppression as well as relay precoding are combined into one effective relay amplification matrix $\mathbf{G}$. Thus, the optimization problems for the AMSE and the ABER criteria have the following form

(i) AMSE criterion

$$\begin{aligned} &\min_{\mathbf{G}} \ f_{AMSE} \\ &\text{subject to} \\ &Tr\{\mathbf{G}[\mathbf{H_A}\mathbf{F_A}\mathbf{F_A}^H\mathbf{H_A}^H + \mathbf{H_B}\mathbf{F_B}\mathbf{F_B}^H\mathbf{H_B}^H \\ &\quad + \mathbf{R_{i+n}}]\mathbf{G}^H\} \leq P_R \end{aligned} \tag{22}$$

(ii) ABER criterion

$$\begin{aligned} &\min_{\mathbf{G}} \ f_{ABER} \\ &\text{subject to} \\ &Tr\{\mathbf{G}[\mathbf{H_A}\mathbf{F_A}\mathbf{F_A}^H\mathbf{H_A}^H + \mathbf{H_B}\mathbf{F_B}\mathbf{F_B}^H\mathbf{H_B}^H \\ &\quad + \mathbf{R_{i+n}}]\mathbf{G}^H\} \leq P_R \end{aligned} \tag{23}$$

For (22) and (23), the solution for $\mathbf{G}$ is obtained through SQP. The joint source-relay precoding algorithm with implicit interference suppression is summarized in Table I.

B. Relay Precoder with Explicit Interference Suppression

Since a closed form solution for the relay precoder $\mathbf{G}$ is unavailable, the interference suppressing capabilities of the relay precoders obtained as solutions to (22) and (23) may be restricted. In this section, we propose the use of MMSE-based interference suppression at the relay to explicitly take care of the interference, before amplifying the desired signal components using the relay precoder $\mathbf{G}$. The signals of interest therefore at A and B at the end of the second phase are as follows:

Step 1	Set $k = 1$. Fix $\mathbf{G}_k = \gamma_R \mathbf{I}_{M_R}$, $\mathbf{F_A}_k = \gamma_A \mathbf{I}_{M_A}$ and $\mathbf{F_B}_k = \gamma_B \mathbf{I}_{M_B}$, where $\gamma_A = \sqrt{P_A/M_A}$, $\gamma_B = \sqrt{P_B/M_B}$ and $\gamma_R = \sqrt{P_R/Tr\{\mathbf{H_A}\mathbf{F_A}\mathbf{F_A}^H\mathbf{H_A}^H + \mathbf{H_B}\mathbf{F_B}\mathbf{F_B}^H\mathbf{H_B}^H + \mathbf{R_{i+n}}\}}$ (uniform power allocation).
Step 2	Compute $\mathbf{F_B}_{k+1}$ and $\mathbf{F_A}_{k+1}$ using $\mathbf{G}_k$, $\mathbf{H_A}$ and $\mathbf{H_B}$ according to (20) and (21) for the AMSE and ABER criterion, respectively.
Step 3	Using $\mathbf{F_A}_{k+1}$ and $\mathbf{F_B}_{k+1}$, solve for $\mathbf{G}_{k+1}$ by SQP as shown in (22) and (23), for the AMSE and ABER criterion, respectively.
Step 4	If $\lvert f_{AMSE\,k+1} - f_{AMSE\,k}\rvert \geq \epsilon$ for the AMSE criterion, or if $\lvert f_{ABER\,k+1} - f_{ABER\,k}\rvert \geq \epsilon$ for the ABER criterion, then set $k = k + 1$ and repeat from step 2 onwards.

TABLE I
SUMMARY OF JOINT SOURCE-RELAY PRECODING WITH IMPLICIT INTERFERENCE SUPPRESSION

$$\tilde{\mathbf{y}}_\mathbf{A} = \mathbf{H_A}^T\mathbf{G}\mathbf{W}\mathbf{H_B}\mathbf{F_B}\mathbf{s_B} + \mathbf{H_A}^T\mathbf{G}\mathbf{W}\mathbf{z} + \mathbf{H_A}^T\mathbf{G}\mathbf{W}\eta_R + \eta_A \tag{24}$$

$$\tilde{\mathbf{y}}_\mathbf{B} = \mathbf{H_B}^T\mathbf{G}\mathbf{W}\mathbf{H_A}\mathbf{F_A}\mathbf{s_A} + \mathbf{H_B}^T\mathbf{G}\mathbf{W}\mathbf{z} + \mathbf{H_B}^T\mathbf{G}\mathbf{W}\eta_R + \eta_B \tag{25}$$

where $\mathbf{W}$ denotes the MMSE-interference suppression matrix, acting on the signal at the relay at the end of the first phase before the relay precoder $\mathbf{G}$. $\mathbf{W}$ has the following form:

$$\mathbf{W} = (\mathbf{H_A}\mathbf{F_A}\mathbf{F_A}^H\mathbf{H_A}^H + \mathbf{H_B}\mathbf{F_B}\mathbf{F_B}^H\mathbf{H_B}^H)\mathbf{R_{i+n}}^{-1} \tag{26}$$

The solutions for $\mathbf{F_A}$, $\mathbf{F_B}$, $\mathbf{G}$ and $\mathbf{W}$ are jointly computed iteratively in a manner similar to the one described in the above section. For fixed $\mathbf{G}$ and $\mathbf{W}$, the source precoder $\mathbf{F_B}$ is computed as given in (20) and (21), except that $\mathbf{R_B}$ has the following structure instead of the one given in the previous section

$$\mathbf{R_B} = (\mathbf{H_A}^T\mathbf{G}\mathbf{W}\mathbf{H_B})^H[(\mathbf{H_A}^T\mathbf{G}\mathbf{W})\mathbf{R_{i+n}}(\mathbf{H_A}^T\mathbf{G}\mathbf{W})^H + \sigma_A^2\mathbf{I}_{M_A}]^{-1}(\mathbf{H_A}^T\mathbf{G}\mathbf{W}\mathbf{H_B})$$

The expression for $\mathbf{F_A}$ can be obtained in a similar manner as well. For fixed $\mathbf{F_A}$ and $\mathbf{F_B}$, $\mathbf{W}$ can be computed as given in (26), and $\mathbf{G}$ can then be computed by SQP using the knowledge of $\mathbf{F_A}$, $\mathbf{F_B}$ and $\mathbf{W}$, similar to (22) and (23). The joint source-relay precoding algorithm with explicit MMSE-based interference suppression at the relay is summarized in Table II.

It can be observed in both the above-mentioned methods that, with perfect knowledge of the channels $\mathbf{H_A}$ and $\mathbf{H_B}$, all three nodes can independently run the above mentioned algorithms at their end and arrive at the same set of source and relay precoders. Of course, the second-order statistics of the interference, i.e., $\mathbf{R_{i+n}}$, need to be made available at both A and B as well. However, since the covariance matrix is Hermitian Toeplitz, the amount of overhead required to communicate it is quite small and can be easily accomplished.

Step 1	Set $k = 1$. Fix $\mathbf{F_A}_k = \gamma_A \mathbf{I}_{M_A}$, $\mathbf{F_B}_k = \gamma_B \mathbf{I}_{M_B}$, where $\gamma_A = \sqrt{P_A/M_A}$, $\gamma_B = \sqrt{P_B/M_B}$. Set $\mathbf{W}_k = (\mathbf{H_A F_A}_k \mathbf{F_A}_k^H \mathbf{H_A}^H + \mathbf{H_B F_B}_k \mathbf{F_B}_k^H \mathbf{H_B}^H)\mathbf{R_{i+n}}^{-1}$. Fix $\mathbf{G_k} = \gamma_R \mathbf{I}_{M_R}$, where $\gamma_R = \sqrt{\frac{P_R}{Tr\{\mathbf{W}_k[\mathbf{H_A F_A F_A}^H \mathbf{H_A}^H + \mathbf{H_B F_B F_B}^H \mathbf{H_B}^H + \mathbf{R_{i+n}}]\mathbf{W}_k^H\}}}$.
Step 2	Compute $\mathbf{F_B}_{k+1}$ and $\mathbf{F_A}_{k+1}$ using $\mathbf{G}_k$, $\mathbf{W}_k$, $\mathbf{H_A}$ and $\mathbf{H_B}$ according to (20) and (21), for the AMSE and ABER criterion, respectively.
Step 3	Using $\mathbf{F_A}_{k+1}$ and $\mathbf{F_B}_{k+1}$, compute $\mathbf{W}_{k+1}$ as given in (26).
Step 4	Using $\mathbf{F_A}_{k+1}$, $\mathbf{F_B}_{k+1}$ and $\mathbf{W}_{k+1}$, solve for $\widehat{\mathbf{G}}_{k+1}$ by SQP as shown in (22) and (23), for the AMSE and ABER criterion, respectively.
Step 5	If $\lvert f_{AMSE\,k+1} - f_{AMSE\,k}\rvert \geq \epsilon$ for the AMSE criterion, or if $\lvert f_{ABER\,k+1} - f_{ABER\,k}\rvert \geq \epsilon$ for the ABER criterion, then set $k = k+1$ and repeat from step 2 onwards.

TABLE II
SUMMARY OF JOINT SOURCE-RELAY PRECODING WITH EXPLICIT (MMSE) INTERFERENCE SUPPRESSION

IV. SIMULATION RESULTS

In this section, we compare the relative performance of implicit and explicit interference suppression at the relay using simulation results. The simulations have been carried out using MATLAB. For a $2-4-2$ case, the MSE performance of both methods is shown in Fig. 3 for AMSE-based precoding. Here, A and B, each having 2 antennas, transmit 2 streams of information each to the relay during the first phase ($L_A = L_B = 2$), along with the presence of a single interferer who is also transmitting 2 streams of information. Hence, the relay, with 4 antennas, receives 6 streams of information during Phase 1. For the same $2-4-2$ configuration, Fig. 4 contains the BER performance of both methods for ABER precoding. For the simulations, Rayleigh fading channels have been assumed for $\mathbf{H_A}$, $\mathbf{H_B}$ and $\mathbf{H_i}$ (all $\in \mathbb{C}^{4\times 2}$) with all channel coefficients being drawn from $\mathcal{CN} \sim (0,1)$. A and B use QPSK constellation for their symbols $\mathbf{s_A}$ and $\mathbf{s_B}$ ($\in \mathbb{C}^{2\times 1}$) and equal power constraints are assumed at all 3 nodes ($P_A = P_B = P_R$). The interferer transmits symbols $\mathbf{s_i} \in \mathbb{C}^{(2x1)}$ having the following property: $\mathbb{E}\{\mathbf{s_i s_i}^H\} = P_{intf}\mathbf{I}$, where P_{intf} denotes the interferer's power and $\mathbf{I}$, the identity matrix. SIR has been defined as $10\log(P_A/P_{intf})$. Additionally, equal noise floors are also assumed at A, B and R ($\sigma_A^2 = \sigma_B^2 = \sigma_R^2 = \frac{P_{intf}}{1000}$), with the noise floor being 30dB below P_{intf} in order to make the system interference-limited. The simulation results have been obtained by averaging over 1000 independent channel realizations.

We observe from Fig. 3 and Fig. 4 that explicit MMSE-based interference suppression at the relay yields better BER and MSE performance when compared to implicit interference suppression using SQP based relay precoders. It can also be observed from the BER curves in Fig. 4 that a $2-4-2$ system is capable of sending 2 streams of information each from A and B in addition to suppressing 2 streams of interference.

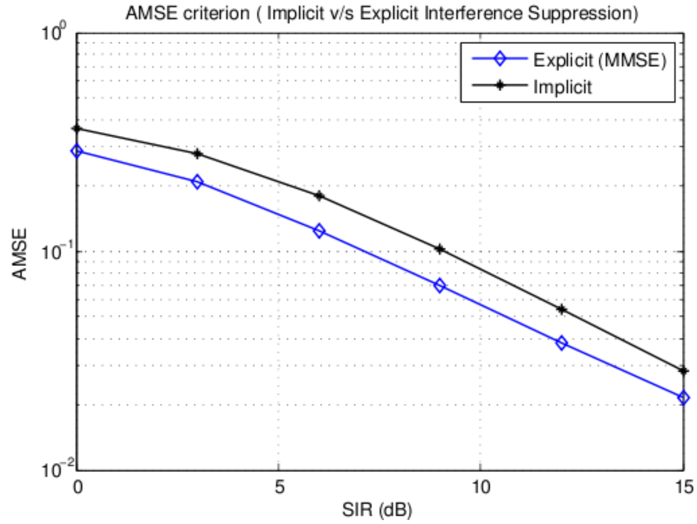

Fig. 3. MSE performance of Implicit and Explicit Interference Suppression at the relay

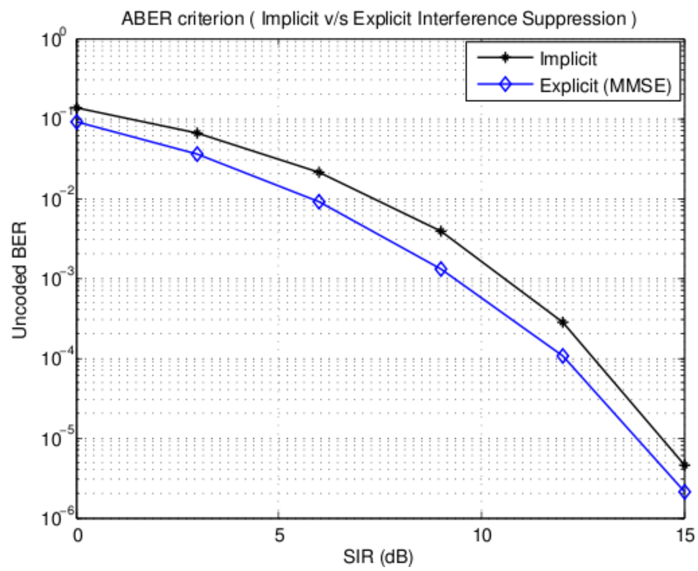

Fig. 4. BER performance of Implicit and Explicit Interference Suppression at the relay

While it is well known that a base station with 4 antennas can handle 4 streams of information in the uplink, it can be gauged from Fig. 4 that when acting as a relay between 2 user pairs, a base station with 4 antennas is capable of handling 6 streams of information on the uplink. Thus, it is of interest to study the effect of number of relay antennas on the diversity order that can be achieved as far as BER performance is concerned.

A. Impact of Relay Antennas on Diversity Order

With A and B transmitting 2 streams of information each, the BER performance of a $2-4-2$ system with 2 streams of interference is compared with that of a $2-5-2$ system with 3 streams of interference and a $2-6-2$ system with 4 streams of interference in Fig. 5. It can be observed from eye-balling the BER curves that they all have the same slope.

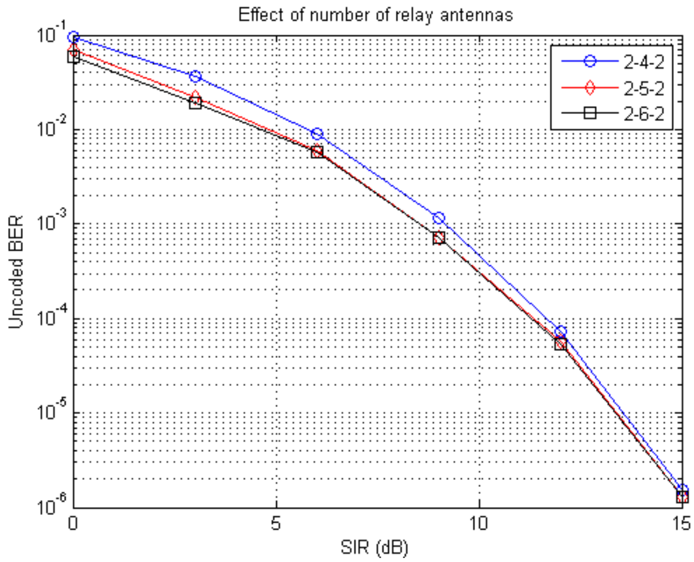

Fig. 5. Diversity-multiplexing trade-off at the relay

Hence, a $2-5-2$ system is able to suppress an extra stream of interference while achieving the same diversity order of a $2-4-2$ system. Likewise, a $2-6-2$ system achieves the same diversity order of a $2-4-2$ system while suppressing 2 additional streams of interference. Thus, in general, additional antennas at the relay help in mitigating more interference at the cost of a loss in diversity. This is a manifestation of the diversity-multiplexing tradeoff in a situation where co-channel interference hampers relay communication during the MAC phase.

V. Conclusion

In this paper, a scenario where relay operation is hampered by the presence of interference in the first MAC phase was considered. In such a situation, the effectiveness of MMSE-based interference suppression at the relay along with joint source-relay precoding was demonstrated using simulation results. It needs to be noted that while there is still some residual interference at the relay even after MMSE interference suppression, the fact that the joint source-relay precoding takes the residual interference into account is what makes our scheme robust even in low SINR regimes. Thus, the joint source-relay precoding scheme proposed in [2] for noise-limited systems is effective even in an interference-limited scenario provided the relay performs MMSE-based interference suppression, for which only the knowledge of second-order statistics of interference is required. The effect of number of relay antennas on the overall diversity order of BER performance in the presence of interference was also studied using simulation results for various configurations, where it was observed that with additional antennas at the relay, it is possible to suppress more streams of interference at the cost of loss in diversity.

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