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TR2011-008 January 2011

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IEEE Consumer Communications and Networking Conference (CCNC)

Comparison of Analog and Digital Network Coding Approaches for Bidirectional Relaying with Private Messages to the Relay

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***Abstract*—In this paper, a multi-antenna two-way relaying protocol is proposed whereby two source nodes wishing to exchange information via a relay node additionally send private messages intended solely for the relay. In particular, we investigate the performance of this bidirectional relaying protocol over fading channels when the relay and source nodes are equipped with multiple antennas thus enabling them to leverage diversity and/or multiplexing gains. Specifically, provided enough antennas are available at the relay, the latter may opt for a demodulate-and-forward approach whereby it demodulates all incoming streams before broadcasting solely the messages to be exchanged between the source nodes or it may opt for a generalized analog network coding approach whereby it only demodulates the private messages destined for the relay's own sake while treating the messages to be exchanged between the source nodes as colored noise, subtracting the demodulated information from the overall received signal and then broadcasting the remaining part of the received signal. We compare how the two approaches fare when coupled with different multiple-input multiple-output (MIMO) detection techniques thus striking suitable tradeoffs between performance and implementation complexity for the generalized multi-antenna two-way relaying channel under consideration.**

I. Introduction

Half duplex bidirectional communications whereby a pair of nodes S_1 and S_2 exchanges independent messages W_1 and W_2 via a relay node R has received much consideration of late [1]–[5]. The most basic information exchange protocol requires four time slots or (orthogonal resource units) to perform one full cycle of information exchange between the source nodes. Various protocols have been put forward in the literature to improve upon this basic communication paradigm, perhaps the most spectrally efficient one requires only two time slots to complete and consists of one multiple access (MA) phase followed by a broadcast (BC) phase. During the initial MA phase, the source nodes simultaneously send their messages (bit-sequences) W_1 and W_2 to the relay which is restricted to a listening mode owing to the half-duplex assumption. The relay then employs either a demodulate-and-forward (DF) scheme to demodulate W_1 and W_2 and broadcast (re-encoded) versions thereof or adopts an amplify-and-forward (AF) approach to broadcast an analog version of the received signal, thereby yielding the so-called analog network coding concept (ANC) [1]. Multiple-antenna variants of the ANC protocol have been proposed and analyzed in the literature [5]–[7]. Specifically, a minimum-mean-square-error (MMSE)-based ANC protocol, termed MMSE-BAF[1], has been shown to provide good performance in terms of achievable capacity and bit error rates when deployed in the context of an IEEE 802.16e network, as evidenced by the exhaustive set of link level simulation results documented in [7].

In this contribution, we focus on a modified bidirectional relaying problem where the source nodes, in addition to exchanging information messages W_1 and W_2 via the relay node, also send, during the initial MA phase, private messages intended solely for the relay node, termed V_1 and V_2, and originating from S_1 and S_2, respectively. These messages can for example consist of training symbols to assist the relay acquiring real-time channel state information (CSI) from the source nodes. Such a generalized two-way relay channel has received little consideration in the literature so far despite it being quite useful for practical implementation purposes. To the best of our knowledge, only the authors in [8] have considered the very same problem from an information-theoretic view-point and strived to determine the capacity region of this channel using a decode-and-forward approach. However, no multiple antenna capability was taken into account therein. A closely related problem, where the relay piggybacks a common message in a multicast fashion during the BC phase, was studied in [9]. Two different schemes are proposed herein based on DF and AF relaying approaches, which we refer to as DF and generalized ANC, respectively. The aforementioned schemes allow for different degrees of performance versus implementation complexity tradeoffs that also hinge on the kind of multiple-input multiple-output (MIMO) detection technique adopted at the relay. Such tradeoffs are underlined in this paper. In particular, we show that the DF scheme which requires prior knowledge of the modulation signals sent by each source node does yield better performance than the simpler generalized ANC scheme but only when coupled with the maximum-likelihood (ML) detection at the relay. However, generalized ANC which does not necessitate any prior knowledge of the sources' modulation signals is shown to outperform DF when used in conjunction with simple linear receivers at the relay.

The remainder of this paper is structured as follows. Sec-

[1]BAF stands for bidirectional amplify-and-forward. For a thorough description of the MMSE-BAF protocol, the interested reader is referred to [7].

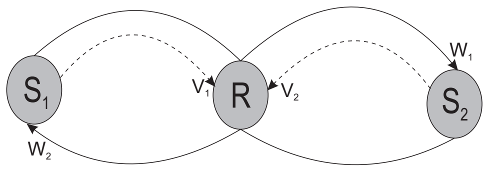
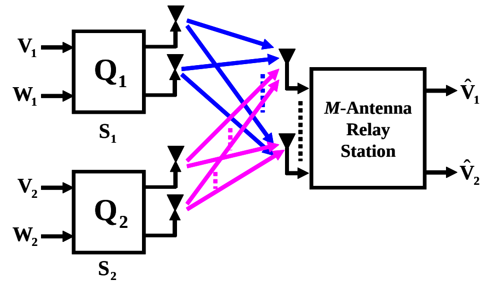
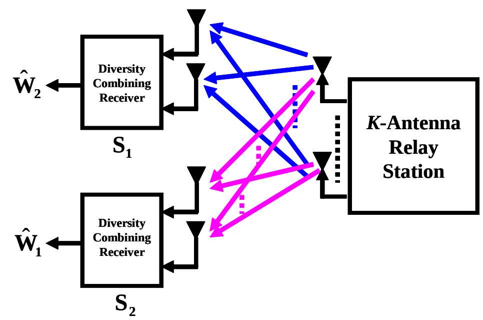


Fig. 1. Classical two-way relay channel (solid lines) compounded with private message communicated from the sources to the relay (dashed lines).



(a) Multiple access phase.



(b) Broadcast phase.

Fig. 2. Two-phase multi-antenna bidirectional relaying protocol with private message for the relay.

tion II briefly describes the system model. In Section III, the proposed protocol and its implementation aspects are detailed along with their analytical modeling. Section IV presents simulation and discussion results whereas Section V concludes this work.[2]

II. System Model

We focus on the generalized two-way relaying channel as illustrated in Fig. 1. The arrows in the figure indicate the destinations of the information messages W_1, W_2, to be exchanged between sources S_1 and S_2 via the relay node R and for the private messages V_1, V_2, to be communicated to the relay from S_1 and S_2, respectively. These are intended for the relay's own use, i.e., they are meant to be decoded by the relay but need not be forwarded any further. We focus on a two-phased protocol consisting of one MA phase schematized in Fig. 2(a) and a succeeding BC phase schematized in Fig. 2(b).

Let the nodes be equipped with multiple antennas as depicted in Fig. 2 and let $N_1^{(.)}$ and $N_2^{(.)}$ be the numbers of antennas at S_1 and S_2, respectively, where the superscript can assume the values Tx or Rx denoting either transmitter or receiver sides. Let M and K be the numbers of receive and transmit antennas at the relay, respectively. We consider frequency-flat block fading between all nodes and denote by

$$\mathbf{H}^{(1)} = [h_{ij}^{(1)}]_{i,j=1}^{M,N_1^{\text{Tx}}} \in \mathbb{C}^{M\times N_1^{\text{Tx}}}$$

and

$$\mathbf{H}^{(2)} = [h_{ij}^{(2)}]_{i,j=1}^{M,N_2^{\text{Tx}}} \in \mathbb{C}^{M\times N_2^{\text{Tx}}}$$

the corresponding channel matrices, where $\mathbb{C}$ is the field of complex numbers and $h_{ij}^{(k)}$, $k = 1,2, i = 1,\ldots,M, j = 1,\ldots,N_k^{\text{Tx}}$ are complex Gaussian fading coefficients. We assume channel reciprocity, which means that the channels from S_1 and S_2 to R are given by $\mathbf{H}^{(1)^{\mathcal{H}}}$ and $\mathbf{H}^{(2)^{\mathcal{H}}}$, respectively, where for the sake of notational simplicity only, all nodes' transmitters and receivers are assumed to be equipped with the same number of Tx and Rx antennas. However, in practical situations and as will indeed be verified in Section IV, a transceiver is sometimes bound to employ different numbers of antennas at its transmitter and receiver fronts, with the number of transmit antennas being usually the smaller one. For instance, in the downlink of a cellular network, transmit antennas are often used sparingly in order to save on the cost of expensive radio-frequency (RF) chains.

Complex baseband notation is adopted throughout the paper. During the MA phase, both S_1 and S_2 transmit simultaneously to the relay R, hence the received signal at the latter can be expressed as:

$$\mathbf{y}_R = \sum_{k=1}^{2} \mathbf{H}^{(k)}\mathbf{Q}^{(k)}\mathbf{u}^{(k)} + \mathbf{n}_R, \tag{1}$$

where the additive noise vector $\mathbf{n}_R \in \mathbb{C}^{M\times 1}$ is distributed according to $\mathbf{n}_R \sim \mathcal{N}(\mathbf{0}_{M\times 1}, \sigma_R^2 \boldsymbol{I}_M)$, $\mathbf{u}^{(k)} = [V_k W_k]^T$ $k = 1, 2$, $\mathbf{Q}^{(k)}$ $k = 1, 2$ are spatial filtering matrices to be applied at the sources, assuming CSI availability. For notational convenience in the subsequent sections, (1) can further be expressed as

$$\mathbf{y}_R = \mathbf{HQu} + \mathbf{n}_R, \tag{2}$$

where $\mathbf{H} = [\mathbf{H}^{(1)}\mathbf{H}^{(2)}]$, $\mathbf{Q} = \begin{bmatrix} \mathbf{Q}^{(1)} & \mathbf{0}_{2,2} \\ \mathbf{0}_{2,2} & \mathbf{Q}^{(2)} \end{bmatrix}$ and $\mathbf{u} = [\mathbf{u}^{(1)^T}\mathbf{u}^{(2)^T}]^T$. Alternatively, (1) can also be expanded as:

$$\mathbf{y}_R = \sum_{k=1}^{2} \mathbf{H}^{(k)}\left(\mathbf{q}_1^{(k)} V_k + \mathbf{q}_2^{(k)} W_k\right) + \mathbf{n}_R \tag{3}$$

$$= \underbrace{\left[\mathbf{H}^{(1)}\mathbf{q}_1^{(1)} \quad \mathbf{H}^{(2)}\mathbf{q}_1^{(2)}\right]}_{:=\mathbf{H}_V} \underbrace{\begin{bmatrix} V_1 \\ V_2 \end{bmatrix}}_{:=\mathbf{v}} + \underbrace{\left[\mathbf{H}^{(1)}\mathbf{q}_2^{(1)} \quad \mathbf{H}^{(2)}\mathbf{q}_2^{(2)}\right]}_{:=\mathbf{H}_W} \underbrace{\begin{bmatrix} W_1 \\ W_2 \end{bmatrix}}_{:=\mathbf{w}} + \mathbf{n}_R \tag{4}$$

$$= \mathbf{H}_V \mathbf{v} + \mathbf{H}_W \mathbf{w} + \mathbf{n}_R, \tag{5}$$

[2]The following notations are used in this paper: Boldface upper- and lower-case symbols are used to denote matrices and column-vectors, respectively. $\boldsymbol{I}_m$ denotes the identity matrix of order m, $\mathbf{0}_{a\times b}$ denotes the all-zero matrix of size $a \times b$, and $\mathcal{CN}(.,.)$ denotes the complex normal circularly symmetric distribution with mean and variance given as the first and second parameters, respectively. Moreover, $(.)^*$, $(.)^T$, $(.)^{\mathcal{H}}$ and $\mathrm{E}[.]$ stand for conjugate, transpose, transpose-conjugate and expectation operators, respectively. Finally, the covariance matrix of a random vector $\mathbf{x}$ is denoted as $\mathbf{R}_\mathbf{x} = \mathrm{E}\left[\mathbf{x}\mathbf{x}^{\mathcal{H}}\right]$ and the variance of a scalar random variable y is denoted as $\sigma_y^2 = \mathrm{E}\left[|y|^2\right]$.

where $\mathbf{q}_1^{(k)}$ and $\mathbf{q}_2^{(k)}$, are the column vectors of $\mathbf{Q}^{(k)}$ $k = 1, 2$. Transmit energy constraints at S_k, $k = 1, 2$ can be expressed as

$$\mathrm{E}\left[\mathbf{u}^{(k)^{\mathcal{H}}}\mathbf{Q}^{(k)^{\mathcal{H}}}\mathbf{Q}^{(k)}\mathbf{u}^{(k)}\right] = P_{\mathrm{T}}. \tag{6}$$

Assuming that the spatial filters $\mathbf{Q}^{(k)}$ are diagonal matrices with positive and real scalar elements, i.e. $\mathbf{Q}^{(k)} = D(\mathbf{q}^{(k)})$ where $D(\mathbf{q}^{(k)})$ denotes a diagonal matrix with diagonal elements given by the vector $\mathbf{q}^{(k)} = [\alpha^{(k)}\beta^{(k)}]^T$, then the average power constraint (6) can be written as

$$\alpha^{(k)^2}\sigma_V^{(k)^2} + \beta^{(k)^2}\sigma_W^{(k)^2} = P_{\mathrm{T}} \tag{7}$$

where $\sigma_V^{(k)^2} = \mathrm{E}\left[|V_k|^2\right]$ and $\sigma_W^{(k)^2} = \mathrm{E}\left[|W_k|^2\right]$ are the average energies of the private and exchange information message constellation signals, respectively.

III. Relay Forwarding Schemes and Data Detection

After receiving the data during the initial MA phase, the relay node R follows one of the two forwarding schemes that we describe hereafter.

A. Demodulate-And-Forward Scheme

According to this approach, the relay demodulates all incoming streams, keeps a copy of the private message $\mathbf{v}$ before broadcasting solely the message $\mathbf{w}$ to be exchanged between the source nodes. The relay receives a total of four streams and thus needs at least four receive antennas with linear processing algorithms to achieve a diversity order of one per stream. With more sophisticated non-linear near ML (sphere) detectors, we could yet achieve fourth order diversity per stream at the cost of additional receiver complexity at the relay. Positioning of the two source nodes relative to the relay might also influence the choice of which MIMO detection mechanism is more suitable to be applied.

In case of linear receivers, the relay applies a linear filter $\mathbf{A}_R$ to the received signal (2), thus obtaining the estimated signal vector

$$\begin{aligned}\hat{\mathbf{u}}_R &:= [\hat{\mathbf{u}}_R^{(1)^T}\hat{\mathbf{u}}_R^{(2)^T}]^T \\ &:= [\hat{V}_1\hat{W}_1\hat{V}_2\hat{W}_2]^T \\ &= \mathbf{A}_R\mathbf{y}_R \\ &= \mathbf{A}_R(\mathbf{H}\mathbf{Q}\mathbf{u} + \mathbf{n}_R),\end{aligned} \tag{8}$$

where $\mathbf{A}_R$ can be chosen according to different criteria, such as matched filtering (MF), zero-forcing (ZF) or Wiener filtering (WF). In the latter two cases, closed-form expressions for the relay receiving filter are given by

$$\mathbf{A}_R^{\mathrm{ZF}} = (\mathbf{Q}^{\mathcal{H}}\mathbf{H}^{\mathcal{H}}\mathbf{H}\mathbf{Q})^{-1}\mathbf{Q}^{\mathcal{H}}\mathbf{H}^{\mathcal{H}}, \tag{9}$$

and

$$\mathbf{A}_R^{\mathrm{WF}} = (\mathbf{R}_{\mathbf{u}}\mathbf{Q}^{\mathcal{H}}\mathbf{H}^{\mathcal{H}}\mathbf{R}_{\mathbf{n}_R}^{-1}\mathbf{H}\mathbf{Q} + \boldsymbol{I}_M)^{-1}\mathbf{R}_{\mathbf{u}}\mathbf{Q}^{\mathcal{H}}\mathbf{H}^{\mathcal{H}}\mathbf{R}_{\mathbf{n}_R}^{-1}, \tag{10}$$

respectively. Observe that the Wiener filter consists of a MF followed by an interference canceller [10]. After detection, the relay proceeds to forward the estimated information messages $\hat{\mathbf{w}} = [\hat{W}_1\hat{W}_2]$ to the sources. It can do so either via spatial multiplexing or superposition coding, i.e. by sending a linear combination of $\hat{W}_1$ and $\hat{W}_2$ using a single transmit antenna with proper power scaling. In the former case, the receiver at the sources will need to spatially separate the signals. With a linear receiver this would require at least two receive antennas to achieve a first order diversity per stream. It is to be noted that the receiver complexity burden at the sources can be shifted to the relay node provided sufficient knowledge of the downlink channel is available at the relay [6]. In case the relay broadcasts a linear combination of $\hat{W}_1$ and $\hat{W}_2$, the source nodes can decode their desired signal by first extracting self-interference generated by their own signal.

B. Generalized Analog Network Coding Scheme

According to this approach, the relay demodulates the private message $\mathbf{v}$ while treating the message to be exchanged between the source nodes $\mathbf{w}$ as colored noise, subtracts the decoded information from the overall received signal and then broadcasts the remaining part of the received signal. Starting from (5), the relay wants to demodulate the private message $\mathbf{v}$ and therefore sees an effective noise of

$$\tilde{\mathbf{n}}_R = \mathbf{H}_W\mathbf{w} + \mathbf{n}_R, \tag{11}$$

with a covariance matrix given by

$$\begin{aligned}\mathbf{R}_{\tilde{\mathbf{n}}_R} &= \mathbf{H}_W\mathbf{R}_{\mathbf{w}}\mathbf{H}_W^{\mathcal{H}} + \mathbf{R}_{\mathbf{n}_R}, \\ &= \mathbf{P}\boldsymbol{\Lambda}\mathbf{P}^{\mathcal{H}}\end{aligned} \tag{12}$$

where (12) denotes the eigenvalue decomposition of the effective noise matrix $\mathbf{R}_{\tilde{\mathbf{n}}_R}$ with $\boldsymbol{\Lambda}$ being a diagonal matrix containing the eigenvalues of $\mathbf{R}_{\tilde{\mathbf{n}}_R}$ and $\mathbf{P}$ the unitary matrix having the associated eigenvectors as its columns. The relay R then proceeds to a whitening operation of the colored noise, thus leading to a modified version of the received signal

$$\begin{aligned}\check{\mathbf{y}}_R &= \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\mathbf{y}_R \\ &= \hat{\mathbf{H}}_V\mathbf{v} + \hat{\mathbf{n}}_R\end{aligned} \tag{13}$$

where

$$\hat{\mathbf{H}}_V := \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\mathbf{H}_V$$

and

$$\begin{aligned}\hat{\mathbf{n}}_R &:= \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\tilde{\mathbf{n}}_R \\ &= \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}(\mathbf{H}_W\mathbf{w} + \mathbf{n}_R)\end{aligned} \tag{14}$$

is a whitened noise vector. Equation (13) is the starting point for the MIMO detector at the relay which can for example apply ML detection or similar linear filtering operations as described in Section III-A.

Having detected the private information message $\hat{\mathbf{v}}$, the relay cancels out the interference caused by this message from the received signal $\check{\mathbf{y}}_R$, thus leading to

$$\begin{aligned}\hat{\mathbf{y}}_R &= \check{\mathbf{y}}_R - \hat{\mathbf{H}}_V\hat{\mathbf{v}} \\ &= \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\mathbf{H}_V(\mathbf{v} - \hat{\mathbf{v}}) + \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\tilde{\mathbf{n}}_R \\ &= \underbrace{\boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\mathbf{H}_W}_{:=\tilde{\mathbf{H}}_W}\mathbf{w} \\ &\quad + \underbrace{\boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\mathbf{H}_V(\mathbf{v} - \hat{\mathbf{v}}) + \boldsymbol{\Lambda}^{-1/2}\mathbf{P}^{\mathcal{H}}\mathbf{n}_R}_{:=\check{\mathbf{n}}_R} \\ &= \tilde{\mathbf{H}}_W\mathbf{w} + \check{\mathbf{n}}_R.\end{aligned} \tag{15}$$

From (15), we can now apply the so-called MMSE-BAF protocol, proposed in [7].

As per the MMSE-BAF protocol, the relay R computes a beamforming weight vector $\mathbf{w}_{\text{opt}}$ based on a joint MMSE criterion to be specified shortly. The relay then estimates an amplification factor β subject to an average power constraint. The detailed set of operations performed at the relay are summarized as follows:

1) Jointly minimize the mean square error (MSE) between the whitened received signal $\hat{\mathbf{y}}_R$ and the transmitted signals W_1 and W_2, thus performing a joint linear-MMSE filtering of the received signal, using the following metric:

$$\mathbf{w}_{\text{opt}} = \underset{\mathbf{w}\in\mathbb{C}^M}{\text{argmin}}\Big\{\delta_1 \ \mathrm{E}\left[\left|W_1 - \mathbf{w}^{\mathcal{H}}\hat{\mathbf{y}}_R\right|^2 |\tilde{\mathbf{H}}_W\right] + \delta_2 \ \mathrm{E}\left[\left|W_2 - \mathbf{w}^{\mathcal{H}}\hat{\mathbf{y}}_R\right|^2 |\tilde{\mathbf{H}}_W\right]\Big\} \quad (16)$$

where δ_1, δ_2 $\delta_1 \geq 0$, $\delta_2 \geq 0$, $\delta_1 + \delta_2 = 1$, are two design constants that control the relative weight assigned to the signals originating from S_1 and S_2. The minimization problem in (16) is a modified Wiener filtering problem whose solution can be easily found using the orthogonality principal in linear mean square estimation and is given by:

$$\mathbf{w}_{\text{opt}} = \left(\sigma_W^{(1)^2}\tilde{\mathbf{h}}_{W,1}\tilde{\mathbf{h}}_{W,1}^{\mathcal{H}} + \sigma_W^{(2)^2}\tilde{\mathbf{h}}_{W,2}\tilde{\mathbf{h}}_{W,2}^{\mathcal{H}} + \sigma_R^2\boldsymbol{I}_M\right)^{-1} \times \left(\delta_1\sigma_W^{(1)^2}\tilde{\mathbf{h}}_{W,1} + \delta_2\sigma_W^{(2)^2}\tilde{\mathbf{h}}_{W,2}\right), \quad (17)$$

where $\tilde{\mathbf{h}}_{W,1}$ and $\tilde{\mathbf{h}}_{W,2}$ are the two column vectors of $\tilde{\mathbf{H}}_W$.

2) Amplify the linear MMSE-filter output to maintain a constant average transmit power P_{T} which leads to computing the amplification gain factor

$$\beta = \sqrt{\frac{P_{\text{T}}}{\mathrm{E}\left[\left|\mathbf{w}^{\mathcal{H}}\hat{\mathbf{y}}_R\right|^2 |\tilde{\mathbf{H}}_W\right]}} = \sqrt{\frac{P_{\text{T}}}{\sigma_W^{(1)^2}\left|\mathbf{w}_{\text{opt}}^{\mathcal{H}}\tilde{\mathbf{h}}_{W,1}\right|^2 + \sigma_W^{(2)^2}\left|\mathbf{w}_{\text{opt}}^{\mathcal{H}}\tilde{\mathbf{h}}_{W,2}\right|^2 + \sigma_R^2\|\mathbf{w}_{\text{opt}}\|^2}}. \quad (18)$$

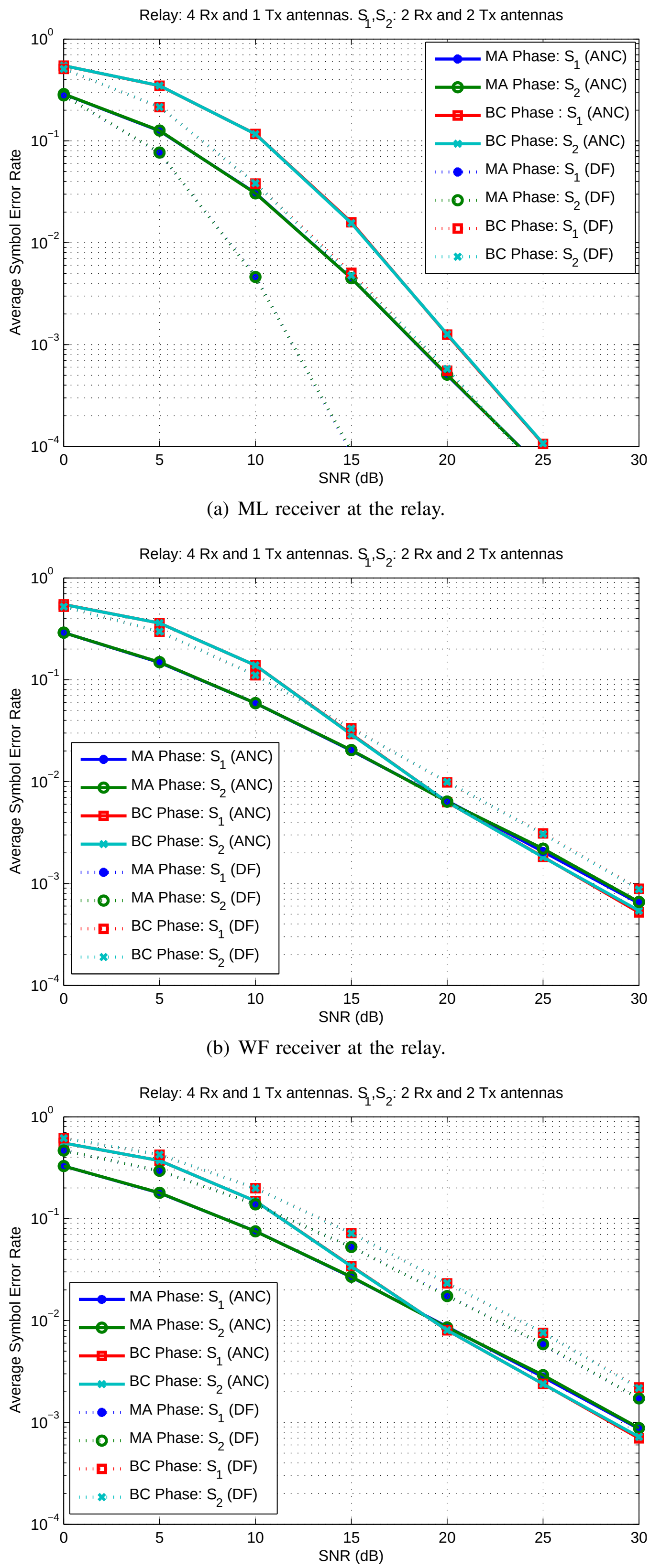
3) Transmit the amplified signal back to the source nodes on one of the Tx antennas available at the relay using an appropriate downlink transmit antenna-selection (TAS) algorithm, based on the uplink channel. One approach inherent to the MMSE-BAF protocol is to select the antenna that has the largest beamformer weight.[3]

IV. Results and Discussion

In this section, we compare the performance of the two relaying schemes described in Section III via simulations. For simplicity, the following simulation setup is assumed: The average SNR from S_1 and S_2 to the relay is the same in both MA and BC phases. Although the modulation format for all transmitted signals can be any of quadrature phase shift keying (QPSK), 16- or 64-quadrature amplitude modulations (QAM), we restrict them to take values from QPSK constellation. The signal constellations are also assumed to be the same across the two streams emanating from each node (private and non-private messages), with equal power allocation across the two streams. That is, $\mathbf{Q}^{(k)} = (1/\sqrt{2}) * \boldsymbol{I}_2$, $\alpha^{(k)} = \beta^{(k)} = 1/\sqrt{2}$ and $\sigma_V^{(k)^2} = \sigma_W^{(k)^2} = P_{\text{T}}$, $k = 1, 2$ as per the notations of Section II. For uplink transmissions from the sources to the relay node, i.e. during the MA phase, the number of transmit antennas is set to $N_k^{\text{Tx}} = 2, k = 1, 2$ whereas the number of receive antennas at the relay is set to $M = 4$. We consider three different types of relay receivers: ZF, WF or ML receivers. In downlink transmissions from the relay to the source nodes, i.e. during the BC phase, we set $K = 1$ and $N_k^{\text{Rx}} = 2$ where the source nodes' receivers apply the maximum-ratio combining (MRC) principle. For the DF scheme, when using one antenna only during the BC phase, the relay employs superposition coding and forwards the signal $(\hat{W}_1 + \hat{W}_2)/\sqrt{2}$. It is worthwhile to mention that the present comparison between the two schemes should extend naturally to the case where the relay uses more than 1 Tx antenna for downlink transmission, e.g. 2 Tx antennas, in which case, the signal $[\hat{W}_1, \hat{W}_2]$ can be broadcast via spatial multiplexing across the transmit antennas. As for the generalized ANC scheme, the relay forwards an analog version of the received signal after canceling out the interference generated by its own private messages. For the MMSE-BAF protocol, we set $\delta_1 = \delta_2 = 1/2$. In all reported results, our figure of merit is uncoded average symbol error rate (SER).

Fig. 3 shows the SER performance of the DF and generalized ANC schemes with different types of receiver processing at the relay: ML (Fig. 3(a)), WF (Fig. 3(b)) and ZF (Fig.3(c)). As one would expect, the ML receiver at the relay consistently outperforms WF and ZF receivers, however, at the cost of a much higher complexity. In general, it can also be seen that the DF and generalized ANC schemes offer in fact comparable levels of performance in terms of achievable SER. However, the ANC scheme has the important advantage of not requiring prior knowledge of the constellation signals of the two streams W_1 and W_2 to be exchanged between the source nodes. Having a closer look at subfigure Fig. 3(a), we notice that the all-digital DF scheme with superposition coding fares better in terms of achievable SER than the ANC scheme when coupled with ML detection at the relay. However, from subfigures Fig. 3(b) and Fig. 3(c), we notice that generalized ANC along with linear processing at the relay yields a lower SER than DF with superposition coding and similar linear processing at the relay. An intuitive explanation for the improved performance of ANC over DF with linear MIMO detection algorithms at the relay is as follows: With DF approach, when linear processing is considered at the relay, each stream has a diversity of only one. On top of this, ZF introduces noise enhancement on each detected stream. The cumulative effect of these two shortcoming is that the downlink signals sent by the relay are highly unreliable, which leads to imperfect cancellation at each mobile (not only its own data symbol but also the other two data symbols intended for the relay). On the other hand, the combination of ANC and whitening requires the relay to demodulate only two of the four streams with four receive antennas. That is, there is a per-stream diversity of two at the

[3]TAS using the largest beamformer weight requires the channel reciprocity assumption and is thus more suitable for a time-division duplex (TDD) system where this condition is usually satisfied.



(a) ML receiver at the relay.

(b) WF receiver at the relay.

(c) ZF receiver at the relay.

Fig. 3. SER performance comparison for DF and ANC schemes with 4 Rx and 1 Tx antennas at the relay and 3 receiver types: ML, MMSE and ZF.

relay for each of the private symbols. As a result, the imperfect cancellation probability is significantly reduced.

V. Conclusion

A generalized multi-antenna two-way relaying protocol is proposed whereby two source nodes exchange information messages with one another via the help of a relay node in addition to sending private information intended solely for the relay node. We study the performance of a two-phased relay processing scheme which consists of an initial MA phase where the two sources transmit simultaneously both private and exchange information messages to the relay and a subsequent BC phase where the relay broadcasts only the exchange information messages to the source nodes. In order to do so, the relay either adopts a DF-inspired approach by jointly detecting all incoming streams during the initial phase and then forwarding those streams to be exchanged between the source nodes or a generalized ANC approach by detecting only the private information messages while treating the other streams as colored noise, subtracting the decoded information from the overall received signal and then broadcasting an analog version of the remaining signal to the source nodes. We evaluated the performance of both schemes subject to different relay Rx processing types. The DF scheme which requires prior knowledge of the constellation signals at the relay outperforms generalized ANC if one is able to afford the complexity of an ML receiver at the relay whereas the image is reversed when it comes to using linear receivers at the relay where the generalized ANC scheme is shown to provide better performance than DF despite not requiring any prior knowledge about the constellation signals at the relay.

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