# Co-ordinate Interleaved Amplify-and-forward Relaying with a Multi-antenna Relay

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***Abstract*— Amplify-and-forward (AF) relaying protocols are an important class of cooperative relaying protocols. Non-orthogonal AF (NAF) relaying, where the source sends new information while the relay forwards previously transmitted information, can achieve higher transmission rates than orthogonal relaying, where the source and relay do not transmit simultaneously. However, all the transmitted symbols in NAF relaying do not achieve full cooperative diversity. Precoding of symbols can address this problem. Recently, a coordinate interleaved NAF (CINAF) protocol has been proposed for NAF relaying with a single-antenna relay. In this paper, we extend this protocol to the multi-antenna relay (or multiple cooperative relays) setting. The linear transformation F used for amplifying at the relay is identified as an important component. Four designs for F are presented and compared extensively using simulations. The importance of channel state information (CSI) at the relay is studied. While full CSI about the source-relay channel is used, limited CSI about the relay-destination channel combined with antenna selection at the relay is observed to be sufficient to achieve most of the performance gain.**

## I. INTRODUCTION

Cooperative relaying and transmission is seen as an important component of current and future wireless communication systems [1], [2], [3]. Cooperative relaying can efficiently use distributed resources, spatial diversity and the broadcast nature of the wireless channel to provide improved reliability and spectral efficiency.

Amplify-and-forward (AF) relaying has been extensively studied because of its low complexity and potential ease of implementation [1], [4]. AF relaying in the context of multi-antenna nodes has also been extensively studied [5], [6]. In the orthogonal AF protocol for half-duplex relaying, the source and relay do not transmit simultaneously to avoid interference. The non-orthogonal AF (NAF) protocol [4] can achieve higher rates since the source transmits new information while the relay forwards previously transmitted information. However, in the NAF protocol, transmissions directly from source to destination do not utilize the spatial diversity and are less reliable than transmissions that are also forwarded by the relay.

Precoded NAF protocols can enable all transmissions to achieve full spatial diversity. Such precoding schemes for NAF relaying have been studied in [7], [8]. These precoding schemes are based on coupling symbols using a linear transformation prior to transmission using the NAF protocol. While this coupling of symbols improves the diversity of all symbols, joint decoding of these symbols is usually required at the receiver. Coordinate interleaving has shown to provide diversity improvement without increasing the decoding complexity in multiple-input multiple-output (MIMO) systems in [9], [10], [11]. Recently, a coordinate interleaved NAF (CINAF) protocol has been proposed and analyzed for the single-antenna relay case in [12].

In this work, we consider the setting where multiple antennas may be available at the relay or multiple cooperative relays are available. We extend the CINAF protocol in [12] to this setting. The design of the linear transformation (amplifying matrix) $\mathbf{F}$ at the relay is identified as an important component determining the performance of the protocol. Four potential choices for this matrix $\mathbf{F}$ are presented. These require different amounts of channel state information (CSI) at the relay about the source-relay and relay-destination channels. The four schemes are compared extensively using simulations. A QR-SIC receiver based on the QR decomposition and successive interference cancellation (SIC) [13] is used at the destination to decode the transmissions. In the simulations, we observe that: (1) coordinate interleaving is effective in this multi-antenna relay setting as well, (2) CSI about the source-relay and relay-destination channels is required to achieve an increase in diversity with increasing number of relay antennas, (3) limited CSI about the relay-destination channel is sufficient to achieve performance close to the full CSI scheme. An antenna selection scheme at the relay achieves performance close to the scheme with full CSI at the relay.

## II. SYSTEM MODEL

We consider the half-duplex relay channel in Fig. 1. Let $h_{SD}$ denote the channel from source S to destination D, $\mathbf{h}_{SR} = [h_{SR_1} \;\; h_{SR_2} \;\; \cdots \;\; h_{SR_N}]^T$ denote the $N \times 1$ single-input multiple-output channel from source S to relay R, and $\mathbf{h}_{RD}^H = [h_{RD_1} \;\; h_{RD_2} \;\; \cdots \;\; h_{RD_N}]$ denote the multiple-input single-output channel from relay R to destination D. The destination D is assumed to have perfect knowledge of all channels $h_{SD}$, $\mathbf{h}_{SR}$ and $\mathbf{h}_{RD}^H$, while no channel information is available at the source node S. The relay is assumed to know $\mathbf{h}_{SR}$ perfectly and, in some cases, $\mathbf{h}_{RD}^H$ perfectly or partially. Each channel coefficient $h_{ij}$ is i.i.d. with $h_{ij} \sim CN(0, 1)$. The channel is also assumed to be block fading, i.e., constant in each block and varying independently from block to block.

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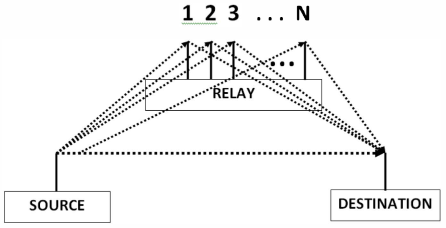

Fig. 1. Relay channel with multi-antenna relay

### A. Non-orthogonal amplify-and-forward (NAF) relaying

The conventional non-orthogonal amplify-and-forward protocol [1], when directly extended to the multi-antenna relay case, works as follows. A *cooperation frame* consists of two successive symbol intervals. During the first symbol interval of the $i^{th}$ cooperation frame, the source broadcasts message symbol $x_{2i-1}$ to destination D and relay R. The received signals at the relay and destination are given by

$$y_{D,2i-1} = h_{SD}\sqrt{P_S}x_{2i-1} + n_{D,2i-1}, \tag{1}$$

$$\mathbf{y}_{R,2i-1} = \mathbf{h}_{SR}\sqrt{P_S}x_{2i-1} + \mathbf{n}_{R,2i-1}, \tag{2}$$

where $y_{D,2i-1}$ and $\mathbf{y}_{R,2i-1}$ denote the received signal during the $(2i-1)^{th}$ symbol interval at destination D and relay R respectively, $n_{D,2i-1} \sim \mathcal{CN}(0,\sigma_D^2)$ and $\mathbf{n}_{R,2i-1} \sim \mathcal{CN}(0,\sigma_R^2\mathbf{I})$ denote the additive noise at destination D and relay R respectively, and $P_S$ is the transmit power of the source S. During the next symbol interval of the cooperation frame, the source transmits a new symbol $x_{2i}$ and the relay forwards a linearly transformed version of the $\mathbf{y}_{R,2i-1}$ to the destination simultaneously. Thus, at the end of the second symbol interval, the destination receives

$$y_{D,2i} = h_{SD}\sqrt{P_S}x_{2i} + \mathbf{h}_{RD}^H(\mathbf{F}\mathbf{y}_{R,2i-1}) + n_{D,2i}, \tag{3}$$

where $\mathbf{F}$ is the amplifying matrix (linear transformation) employed at the relay. The matrix $\mathbf{F}$ is constrained to be such that an average power constraint is satisfied at the relay.

### B. Equivalent representation under the NAF protocol

The functioning of the conventional NAF protocol over one cooperation frame can be expressed by a single matrix equation as follows.

$$\underbrace{\begin{bmatrix} y_{D,2i-1} \\ y_{D,2i} \end{bmatrix}}_{\mathbf{y}_i} = \underbrace{\begin{bmatrix} \sqrt{P_S}h_{SD} & 0 \\ \sqrt{P_S}\mathbf{h}_{RD}^H\mathbf{F}\mathbf{h}_{SR} & \sqrt{P_S}h_{SD} \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} x_{2i-1} \\ x_{2i} \end{bmatrix}}_{\mathbf{x}_i} + \underbrace{\begin{bmatrix} w_{2i-1} \\ w_{2i} \end{bmatrix}}_{\mathbf{w}_i}, \tag{4}$$

where $w_{2i-1} = n_{D,2i-1}$ and $w_{2i} = n_{D,2i} + \mathbf{h}_{RD}^H\mathbf{F}\mathbf{n}_{R,2i-1}$. $\mathbf{H}$ is the equivalent channel matrix and $\mathbf{x}_i$ is the symbol vector transmitted during the $i^{th}$ cooperation frame. Under the block fading assumption, $\mathbf{H}$ is assumed to remain constant over all cooperation frames in a block and independently change from block to block. Hence, $\mathbf{H}$ is not indexed by $i$.

## III. PROPOSED PRECODED NON-ORTHOGONAL AMPILFY AND FORWARD RELAYING SCHEMES

In the conventional NAF protocol, the symbols transmitted in the second symbol interval of the cooperation frame are received only through the S-D channel and can achieve only a diversity of one. The first symbol of the cooperation frame is received through both the S-R-D and S-D paths and could potentially achieve a maximum diversity of two. Precoding schemes that couple the two symbols transmitted in a single cooperation frame can potentially improve the diversity of the second symbol as well. Interleaving the real and imaginary components of the two symbols, called coordinate interleaving, is one such scheme. Coordinate interleaving has been shown to provide diversity improvement without increasing the decoding complexity (which may happen due to the coupling of symbols) in multiple-input multiple-output (MIMO) systems in [9], [10], [11]. In [12], a coordinate interleaved NAF (CINAF) protocol has been proposed and analyzed for the single-antenna relay case. Here, we consider the multi-antenna relay case. Since the equivalent model in (4) is similar to the single-antenna relay case, the same coordinate interleaved protocol CINAF can be applied here. However, the choice of matrix $\mathbf{F}$ is important in the multi-antenna case. We will address this problem in this paper and study CINAF protocols with difference choices for the relay amplification matrix $\mathbf{F}$.

The input symbols are chosen from a unit energy *rotated* QAM constellation, denoted by $e^{j\theta}\chi$, where $\chi$ is the conventional un-rotated QAM constellation. Thus, an input symbol $x_l \in e^{j\theta}\chi$ can be expressed as

$$x_l = e^{j\theta}(a_l + jb_l) = (a_l\cos\theta - b_l\sin\theta) + j(a_l\sin\theta + b_l\cos\theta)$$

where $a_l + jb_l \in \chi$, a unit energy un-rotated QAM constellation, and the rotated angle $\theta$ is chosen such that [14] [15]

$$\Re x_l \neq \Re x_i \text{ and } \Im x_l \neq \Im x_i, \forall x_l, x_i \in e^{j\theta}\chi, l \neq i. \tag{5}$$

Such constellations are known as *full diversity* constellations in 2- dimensions [14].

### A. Precoding: Coordinate Interleaving

Let $\{x_k\}_{k=1}^K$ be the input symbols to be transmitted, chosen from a unit energy rotated QAM signal set. The symbols are precoded by interleaving the real and imaginary terms of two consecutive symbols to obtain $\{\tilde{x}_k\}_{k=1}^K$ where

$$\tilde{x}_k = \begin{cases} \Re x_k + j\Im x_{k+1} & \text{when } k = 2l-1, l \in \mathbb{N} \\ \Re x_k + j\Im x_{k-1} & \text{otherwise.} \end{cases} \tag{6}$$

### B. Transmission scheme for each cooperation frame

The transmit symbol vector during the $i^{th}$ cooperation frame is given by

$$x_i = \begin{cases} [\tilde{x}_1 \; 0]^T, & i = 1 \\ [\tilde{x}_{2i-1} \; \tilde{x}_{2i-2}]^T, & i > 1 \end{cases}. \tag{7}$$

If the symbol vectors transmitted over successive cooperation frames are arranged into a matrix, it results in the following transmission matrix:

$$\begin{bmatrix} \tilde{x}_1 & \tilde{x}_3 & \cdots & \cdots \\ 0 & \tilde{x}_2 & \tilde{x}_4 & \cdots \end{bmatrix}. \tag{8}$$

In the above transmission matrix, symbols along a diagonal are coupled together through precoding. During the initial cooperation frame, the protocol behaves like an orthogonal protocol. This helps in simplifying the decoding algorithm and using a successive interference cancellation scheme instead of joint decoding. If the transmission ends after $F$ cooperation frames, then $x_F = [x_K\ \tilde{x}_{K-1}]^T$ if K is an odd number and $x_F = [0\ \tilde{x}_K]^T$ , if $K$ is an even number. Thus, it takes a maximum of $K+2$ symbol intervals to transmit $K$ symbols and the worst case spectral efficiency is given by $\eta = \frac{K}{K+2}$ symbols/ channel use. For higher values of $K$, $\eta$ approaches 1.

### *C. Design of the Relay Amplifying Matrix*

We propose and study four different choices for $\mathbf{F}$. They are explained in this section. Each of schemes requires a different amount of channel state information (CSI) at the relay. This is summarized in the following table.

| **Scheme** | **S-R channel CSI** | **R-D channel CSI** |
|---|---|---|
| Scheme 1 | Not required | Not required |
| Scheme 2 | Full CSI | Not required |
| Scheme 3 | Full CSI | Full CSI |
| Scheme 4 | Full CSI | Limited CSI for antenna selection |

**Scheme 1:** This scheme is a simple extension of the amplifying scheme in the single-antenna case in [12]. The matrix $\mathbf{F}$ introduces a fixed gain at each relay antenna that does not depend on the instantaneous channel state information. Only knowledge of the channel statistics is used. An average power constraint of $P_{R_i}$ is imposed on the $i^{th}$ antenna at the relay. The matrix $\mathbf{F}$ is chosen to be the diagonal matrix $\mathbf{F}_1$ given by:

$$\mathrm{F}_1 = \begin{bmatrix} a_1 & 0 & \cdots & 0 \\ 0 & a_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & \cdots & a_N \end{bmatrix},$$

where

$$a_i = \sqrt{\frac{P_{R_i}}{P_S + \sigma_R^2}}.$$

**Scheme 2:** Here, we consider a scheme that uses the source-relay channel information in designing the $\mathbf{F}$ matrix. Such a scheme can possibly take advantage of the antenna diversity in the source-relay link. The matrix $\mathbf{F}$ is chosen to be the matrix $\mathbf{F}_2$ given by:

$$\mathrm{F}_2 = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix} \mathbf{h}_{SR}^H,$$

where

$$a_i = \sqrt{\frac{P_{R_i}}{P_S\left(\sum_{i=1}^{N} |h_{SR_i}|^2\right)^2 + \sigma_R^2 \sum_{i=1}^{N} |h_{SR_i}|^2}}. \tag{9}$$

This choice for $a_i$ satisfies the average power constraint at each relay antenna and is a generalized form of the choice for channel state dependent amplifying gain in [1] for the single antenna relay. In the generalized form above, the received signal at the relay antennas are combined using maximal ratio combining and forwarded on each antenna after applying an antenna specific gain to satisfy the power constraint.

**Scheme 3:** Here, we consider a scheme that uses both the source-relay channel information and the relay-destination channel information in designing the $\mathbf{F}$ matrix. The matrix $\mathbf{F}$ is chosen to be the matrix $\mathbf{F}_3$ given by:

$$\mathrm{F}_3 = \begin{bmatrix} h_{RD_1}^* & 0 & \cdots & 0 \\ 0 & h_{RD_2}^* & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & \cdots & h_{RD_N}^* \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{bmatrix} \mathbf{h}_{SR}^H,$$

where

$$a_i = \frac{1}{|h_{RD_i}|} \sqrt{\frac{P_{R_i}}{P_S\left(\sum_{i=1}^{N} |h_{SR_i}|^2\right)^2 + \sigma_R^2 \sum_{i=1}^{N} |h_{SR_i}|^2}}. \tag{10}$$

The signals received at the relay are combined using maximal ratio combining and the R-D transmission uses equal-gain beamforming.

**Scheme 4:** This scheme also uses both source-relay and relay-destination channel information. However, only limited information about the relay-destination channel is needed. Let $i^*$ denote the index of the antenna with the largest $|h_{RD_i}|$, i.e.,

$$i^* = \arg\max_i |h_{RD_i}|.$$

Only $i^*$ is needed about the relay-destination channel to construct the $\mathbf{F}$ matrix. The matrix $\mathbf{F}$ is chosen to be the matrix $\mathbf{F}_4$ given by:

$$\mathrm{F}_4 = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ a_{i^*} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \mathbf{h}_{SR}^H,$$

where

$$a_{i^*} = \sqrt{\frac{P_R}{P_S\left(\sum_{i=1}^{N} |h_{SR_i}|^2\right)^2 + \sigma_R^2 \sum_{i=1}^{N} |h_{SR_i}|^2}}, \tag{11}$$

and $P_R$ is the power constraint at the relay.

### *D. Receiver at the destination*

We adopt a receiver based on the QR decomposition and successive interference cancellation technique developed in [12] for the CINAF protocol with a single-antenna relay. Since the equivalent channel representation for each cooperation frame is similar for both the single-antenna and the multi-antenna relay cases, the same receiver structure can be adopted. The noise covariance matrix used in the receiver needs to be appropriately modified to account for the choice of relay amplifying matrix $\mathbf{F}$. We will call this receiver the QR-SIC receiver.

We note that this choice may be sub-optimal. However, this receiver has lower decoding complexity than joint maximum likelihood decoding. Furthermore, for the single-antenna relay CINAF protocol, this receiver is able to achieve symbol error rate of the order $\log \mathrm{SNR}/\mathrm{SNR}^2$ which is close to the diversity upper bound of 2 [12]. The details of the receiver are presented below.

**QR-SIC receiver:** For the receiver to estimate the transmitted symbols $\tilde{x}_{2i-1}$ and $\tilde{x}_{2i}$, $i = 1, 2, \ldots$, it needs both the received vectors $\mathbf{y}_i$ and $\mathbf{y}_{i+1}$ (see (8)).

At the end of the second cooperation frame, destination has $\mathbf{y}_1$ and $\mathbf{y}_2$ and can obtain $\hat{x}_1$ and $\hat{x}_2$, the estimates of transmitted symbols $x_1$ and $x_2$, by following the procedure described below.

1) Compute QR decomposition of $\mathbf{H}$ (where $\mathbf{H}$ is given in (4)) as $\mathbf{H} = \mathbf{QR}$, and compute $\mathbf{Q}^H\mathbf{y}_1 = [\tilde{z}_{D,1} \;\; \tilde{z}_{D,2}]^T$ and $\mathbf{Q}^H\mathbf{y}_2 = [\tilde{z}_{D,3} \;\; \tilde{z}_{D,4}]^T$ ; i.e.,

$$\left[\begin{array}{cc} \tilde{z}_{D,1} & \tilde{z}_{D,3} \\ \tilde{z}_{D,2} & \tilde{z}_{D,4} \end{array}\right] = \underbrace{\left[\begin{array}{cc} r_{11} & r_{12} \\ 0 & r_{22} \end{array}\right]}_{R} \left[\begin{array}{cc} \tilde{x}_1 & \tilde{x}_3 \\ 0 & \tilde{x}_2 \end{array}\right] + \left[\begin{array}{cc} w_{D,1} & w_{D,3} \\ w_{D,2} & w_{D,4} \end{array}\right], \tag{12}$$

where

$$\left[\begin{array}{c} w_{D,1} \\ w_{D,2} \end{array}\right] = \mathbf{Q}^H\mathbf{w}_1 \text{ and } \left[\begin{array}{c} w_{D,3} \\ w_{D,4} \end{array}\right] = \mathbf{Q}^H\mathbf{w}_2. \tag{13}$$

Let $n_{D,i} \sim \mathcal{CN}(0, \sigma_D^2)$ and $n_{R,i} \sim \mathcal{CN}(0, \;\sigma_R^2)$. Then, $\mathbf{w}_i \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{C}\right)$ and $\mathrm{Q}^H\mathbf{w}_i \sim \mathcal{CN}\left(\mathbf{0}, \mathbf{K}\right)$, where

$$\mathbf{C} = \begin{bmatrix} \sigma_D^2 & 0 \\ 0 & \sigma^2 \end{bmatrix},$$

where $\sigma^2$ depends on the choice of $\mathbf{F}$ at the relay and $\mathbf{K} = \mathbf{Q}^H\mathbf{CQ}$. For $\mathbf{F}_1$, we get

$$\sigma^2 = \sigma_D^2 + \sum_{i=1}^{N} |a_i h_{RD_i}|^2 \sigma_R^2.$$

For $\mathbf{F}_2$, we get

$$\sigma^2 = \sigma_D^2 + \left|\sum_{i=1}^{N} a_i h_{RD_i}\right|^2 \left(\sum_{i=1}^{N} |h_{SR_i}|^2\right) \sigma_R^2.$$

For $\mathbf{F}_3$, we get

$$\sigma^2 = \sigma_D^2 + \left(\sum_{i=1}^{N} a_i |h_{RD_i}|^2\right)^2 \left(\sum_{i=1}^{N} |h_{SR_i}|^2\right) \sigma_R^2.$$

For $\mathbf{F}_4$, we get

$$\sigma^2 = \sigma_D^2 + |a_{i^*} h_{RD_{i^*}}|^2 \left(\sum_{i=1}^{N} |h_{SR_i}|^2\right) \sigma_R^2.$$

Once the appropriate $\mathbf{C}$ matrix has been determined for the chosen $\mathbf{F}$ the remaining steps are similar to the single-antenna relay case in [12]. These steps are briefly summarized below for completeness.

$$\text{Let} \quad \mathbf{K} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix},$$

$$\mathbf{J_1} \triangleq \begin{bmatrix} \frac{K_{11}}{2} & 0 \\ 0 & \frac{K_{22}}{2}, \end{bmatrix}^{-1}, \qquad \mathbf{J_2} \triangleq \begin{bmatrix} \frac{K_{22}}{2} & 0 \\ 0 & \frac{K_{11}}{2} \end{bmatrix}^{-1},$$

$$\mathbf{M_1} \triangleq \begin{bmatrix} r_{11} & 0 \\ 0 & r_{22}. \end{bmatrix} \text{ and } \qquad \mathbf{M_2} \triangleq \begin{bmatrix} r_{22} & 0 \\ 0 & r_{11} \end{bmatrix}.$$

2) De-interleave $\tilde{z}_{D,1}$ and $\tilde{z}_{D,4}$ to obtain $z_{D,1}$ and $z_{D,4}$ :

$$\begin{aligned} z_{D,1} &= \Re\tilde{z}_{D,1} + j\Im\tilde{z}_{D,4} \\ &= r_{11}\Re x_1 + jr_{22}\Im x_1 + \Re w_{D,1} + j\Im w_{D,4} \end{aligned} \tag{14}$$

$$\begin{aligned} z_{D,4} &= \Re\tilde{z}_{D,4} + j\Im\tilde{z}_{D,1} \\ &= r_{22}\Re x_2 + jr_{11}\Im x_2 + \Re w_{D,4} + j\Im w_{D,1} \end{aligned} \tag{15}$$

After de-interleaving, from (14) and (15), we note that the real and imaginary parts of noise term in $z_{D,1}$ and $z_{D,4}$ have different variances. Thus, we have

$$\Re w_{D,1} \sim \mathcal{N}(0, \tfrac{K_{11}}{2}) \text{ and } \Im w_{D,4} \sim \mathcal{N}(0, \tfrac{K_{22}}{2}), \text{ and}$$
$$\Re w_{D,4} \sim \mathcal{N}(0, \tfrac{K_{22}}{2}) \text{ and } \Im w_{D,1} \sim \mathcal{N}(0, \tfrac{K_{11}}{2}).$$

3) *Decoding $x_1$ and $x_2$*: Let $\mathbf{y}_1 \triangleq [\Re z_{D,1} \quad \Im z_{D,1}]^T$. Then, ML decoding for the first symbol gives

$$\hat{\mathbf{x}}_1 = \arg\min_{\mathbf{x} \in \mathcal{X}^R} \left\{ (\mathbf{y}_1 - \mathbf{M}_1\mathbf{x})^T \mathbf{J_1} (\mathbf{y}_1 - \mathbf{M}_1\mathbf{x}) \right\}, \tag{16}$$

where $\hat{\mathbf{x}}_1$ is the estimate of $\mathbf{x}_1$, and $\mathbf{x}_1$ is the input symbol $x_1$ denoted in vector form as $\mathbf{x}_1 = [\Re x_1 \quad \Im x_1]^T$.

ML decoding for the second symbol gives

$$\hat{\mathbf{x}}_2 = \arg\min_{\mathbf{x} \in \mathcal{X}^R} \left\{ (\mathbf{y}_2 - \mathbf{M}_2\mathbf{x})^T \mathbf{J_2} (\mathbf{y}_2 - \mathbf{M}_2\mathbf{x}) \right\}, \tag{17}$$

where $\mathbf{y_2} \triangleq [\Re z_{D,4} \quad \Im z_{D,4}]^T$.

4) *Interference cancellation step:*

As in [12], consider the received vectors $\mathbf{y}_{D,2}$ and $\mathbf{y}_{D,3}$. $x_3$ and $x_4$ can be decoded from $\tilde{z}_{D,3}$ and $\tilde{z}_{D,6}$. Note that $\tilde{z}_{D,3} = r_{11}\tilde{x}_3 + r_{12}\tilde{x}_2 + w_{D,3}$ and $\tilde{z}_{D,6} = r_{22}\tilde{x}_4 + w_{D,6}$. The interference from $\tilde{x}_2$ in $\tilde{z}_{D,3}$ can be cancelled since we have already decoded $x_2$.

Repeating the four steps above, we can decode $x_{2i-1}$ and $x_{2i}$ for all $i$.

## IV. SIMULATION RESULTS

In all the simulations, the channel coeffcients are assumed independent $\mathcal{CN}(0, 1)$, simulated for $10^6$ symbols, $P_S = 1$ and the total relay power constraint is also 1. For Schemes 1 to 3, each relay antenna is assigned equal average power. For Scheme 4, the selected antenna uses the total available power. Rotated 4-QAM with a rotation angle of $28.5^o$ is used, and the QR-SIC receiver is used for decoding at the destination.

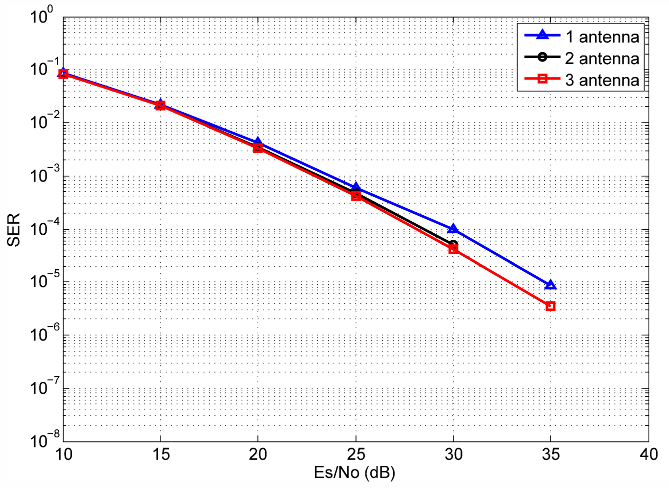

Fig. 2. CINAF Performance for $\mathbf{F}_1$ for different number of antennas at the relay

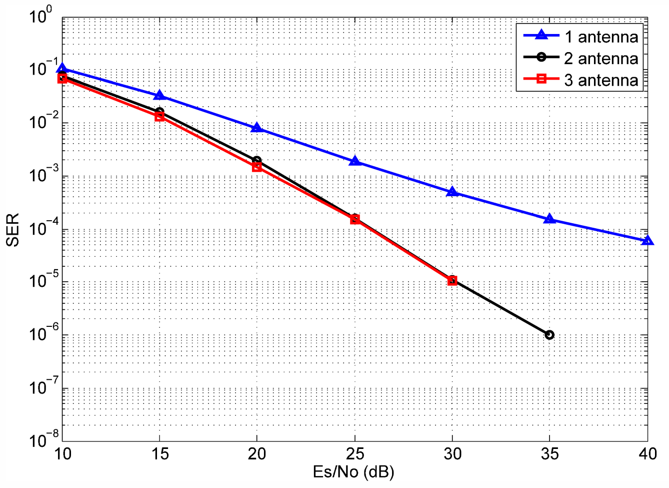

Fig. 3. CINAF Performance for $\mathbf{F}_2$ for different number of antennas at the relay

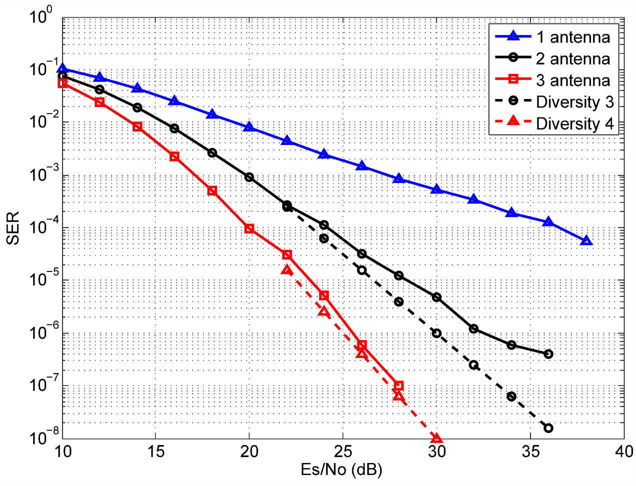

Fig. 4. CINAF Performance for $\mathbf{F}_3$ for different number of antennas at the relay

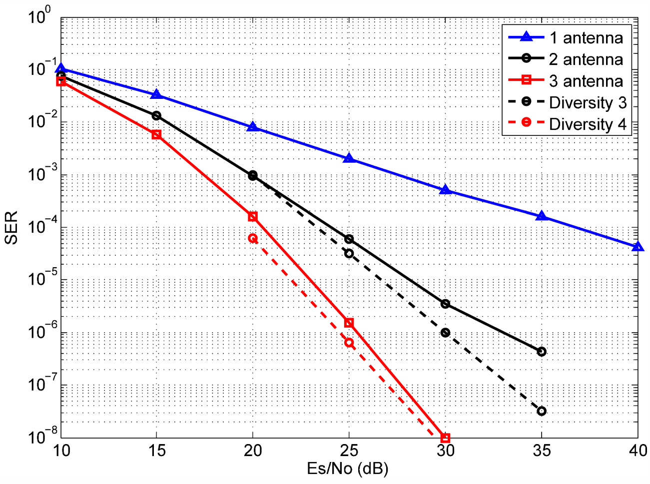

Fig. 5. CINAF Performance for $\mathbf{F}_4$ for different number of antennas at the relay

### A. *Performance for different number of antennas*

Figures 2, 3, 4 and 5 show the symbol error rate versus signal to noise ratio for different number of relay antennas for the CINAF schemes using the 4 different $\mathbf{F}$ matrices: $\mathbf{F}_1$, $\mathbf{F}_2$, $\mathbf{F}_3$, and $\mathbf{F}_4$, respectively.

We make the following observations.

1) Amplifying matrices $\mathbf{F}_3$ and $\mathbf{F}_4$ provide improved performance as the number of relay antennas increase (see Figs. 4 and 5). This is because they use the CSI of both the S-R and R-D channels to improve the diversity for the first symbol of a cooperation frame. From the results, it can be observed that the overall diversity achieved for all symbols for $\mathbf{F}_3$ and $\mathbf{F}_4$ is $N{+}1$, where $N$ is the number of relay antennas. It should be emphasized that this performance is achieved in an NAF protocol, and coordinate interleaving plays an important role in improving the performance of the second symbol in each cooperation frame.

2) Amplifying matrices $\mathbf{F}_1$ and $\mathbf{F}_2$ do not provide improved diversity with increasing number of relay antennas (see Figs. 2 and 3). From the results, it appears that the diversity achieved is close to 2. This is because they are limited by the absence of CSI of the R-D channel.

3) For the single-antenna case, $\mathbf{F}_1$ performs better than $\mathbf{F}_2$ (see Figs. 2 and 3). Note that while $\mathbf{F}_1$ provides a fixed gain and satisfies the power constraint only on average, $\mathbf{F}_2$ has a variable gain which satisfies the power constraint at the relay with high probability for every realization of the S-R channel [1]. Therefore, when the S-R channel is poor, the gain provided may be high and vice versa.

### B. *Comparison of the different schemes*

Fig. 6 compares the performance of $\mathbf{F}_3$ with $\mathbf{F}_4$, i.e., full R-D CSI at the relay versus relay antenna selection with limited R-D CSI. It can be observed that antenna selection with limited CSI is quite close in performance to the case with full R-D CSI.

Fig. 7 compares all the amplifying matrices with and without coordinate interleaving. The impact of coordinate

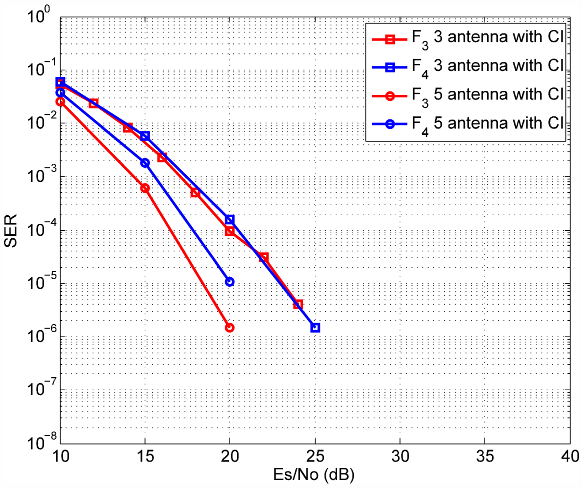

Fig. 6. Comparison of $\mathbf{F}_3$ and $\mathbf{F}_4$

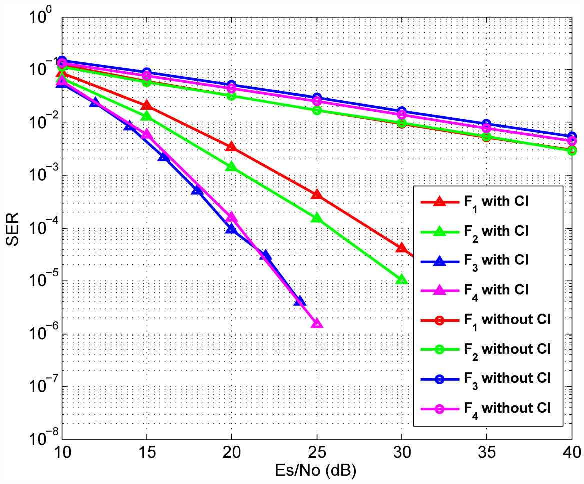

Fig. 7. Comparison of all schemes with and without coordinate interleaving for a 3-antenna relay

interleaving is clearly seen as the second symbol of each cooperation frame also achieves good performance due to interleaving.

## V. CONCLUSIONS AND FUTURE WORK

The CINAF protocol was studied in a multi-antenna relay setting. Four designs for the linear transformation at the relay were presented. They required varying amounts of channel state information at the relay. These schemes were compared extensively using simulations. Limited CSI about the relay-destination channel combined with antenna selection at the relay seems to be sufficient to achieve performance close to the full CSI scenario.

Analysis of the diversity gain of the CINAF protocol for various choices of the linear transformation **F** is an important direction for the future. CINAF protocols could also be explored for the more general setting with multiple antennas at all nodes.

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## REFERENCES

[1] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Trans. on Information Theory*, vol. 50, pp. 3062–3080, Dec 2004.

[2] K. Loa, C.-C. Wu, S.-T. Sheu, Y. Yuan, M. Chion, D. Huo, and L. Xu, “IMT-advanced relay standards [WiMAX/LTE update],” *IEEE Communications Magazine*, vol. 48, no. 8, pp. 40–48, August 2010.

[3] X. Tao, X. Xu, and Q. Cui, “An overview of cooperative communications,” *IEEE Communications Magazine*, vol. 50, no. 6, pp. 65–71, June 2012.

[4] K. Azarian, H. El Gamal, and P. Schniter, “On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels,” *Information Theory, IEEE Transactions on*, vol. 51, no. 12, pp. 4152–4172, 2005.

[5] L. Sanguinetti, A. A. D’Amico, and Y. Rong, “A tutorial on the optimization of amplify-and-forward MIMO relay systems,” *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 8, pp. 1331–1346, 2012.

[6] Y. Rong and F. Gao, “Optimal beamforming for non-regenerative MIMO relays with direct link,” *IEEE Communications Letters*, vol. 13, no. 12, pp. 926–928, 2009.

[7] Y. Ding, J.-K. Zhang, and K. M. Wong, “The amplify-and-forward half-duplex cooperative system: Pairwise error probability and precoder design,” *IEEE Trans. on Signal Processing*, vol. 55, no. 2, pp. 605 –617, feb. 2007.

[8] Q. Ahmed, K.-H. Park, M.-S. Alouini, and S. Aissa, “Linear transceiver design for nonorthogonal amplify-and-forward protocol using a bit error rate criterion,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 4, pp. 1844–1853, April 2014.

[9] J. Harshan and B. S. Rajan, “Coordinate interleaved distributed space-time coding for two-antenna-relay networks,” *IEEE Trans. on Wireless Communications*, vol. 8, pp. 1783–1791, Apr. 2009.

[10] K. V. Srinivas, R. D. Koilpillai, S. Bhashyam, and K. Giridhar, “Co-ordinate interleaved spatial multiplexing with channel state information,” *IEEE Transactions on Wireless Communications,*, vol. 8, no. 6, pp. 2755 –2762, June 2009.

[11] S. A. Ahmadzadeh, S. A. Motahari, and A. K. Khandani, “Signal space cooperative communication,” *IEEE Trans. on Wireless Communications*, vol. 9, pp. 1266–1271, Apr. 2010.

[12] V. P. Sreekanth, K. V. Srinivas, and S. Bhashyam, “Co-ordinate interleaved non-orthogonal amplify and forward relaying protocol,” in *2013 National Conference on Communications (NCC)*, 2013, pp. 1–5.

[13] D. Tse and P. Viswanath, *Fundamentals of wireless communication*. New York, NY, USA: Cambridge University Press, 2005.

[14] J. Boutros and E. Viterbo, “Signal space diversity: a power-and bandwidth-efficient diversity technique for the rayleigh fading channel,” *IEEE Transactions on Information Theory*, vol. 44, no. 4, pp. 1453–1467, 1998.

[15] K. Boulle and J. Belfiore, “Modulation schemes designed for the rayleigh channel,” *Proc. CISS*, pp. 288–293, 1992.