Adaptive Distributed Space-Time Coding for Cooperative MIMO Relaying Systems

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***Abstract*—An adaptive distributed space-time coding (DSTC) scheme and algorithms are proposed for two-hop cooperative MIMO networks. Linear minimum mean square error (MMSE) receivers and an amplify-and-forward (AF) cooperation strategy are considered. In the proposed DSTC scheme, an adjustable matrix obtained by a feedback channel is employed to transform the space-time coded matrix at the relay node. Linear MMSE expressions are devised to compute the parameters of the adaptive matrix and the linear receive filter. A stochastic gradient algorithm is also developed to compute the parameters of the adaptive matrix with reduced computational complexity. We also derive the upper bound of the error probability of a cooperative MIMO system employing the randomized space-time coding scheme first. The simulation results show that the proposed algorithms obtain significant performance gains as compared to existing DSTC schemes.**

I. Introduction

Multiple-input and multiple-output (MIMO) communication systems employ multiple collocated antennas at both the source node and the destination node in order to obtain the diversity gain and combat multi-path fading in wireless links. The different methods of space-time coding (STC) schemes, which can provide a higher diversity gain and coding gain compared to an uncoded system, are also utilized in MIMO wireless systems for different numbers of antennas at the transmitter and different conditions of the channel. Cooperative MIMO systems, which employ multiple relay nodes with antennas between the source node and the destination node as a distributed antenna array, apply distributed diversity gain and provide copies of the transmitted signals to improve the reliability of wireless communication systems [1]. Among the links between the relay nodes and the destination node, cooperation strategies, such as Amplify-and-Forward (AF), Decode-and-Forward (DF), and Compress-and-Forward (CF) [2] and various distributed STC (DSTC) schemes in [3], [4] and [15] can be employed.

The utilization of a DSTC at the relay node in a cooperative network, providing more copies of the desired symbols at the destination node, can offer the system diversity gains and coding gains to combat the interference. The recent focus on the DSTC technique lies in the design of delay-toleration codes and full-diversity schemes with the minimum outage probability. An opportunistic DSTC scheme with the minimum outage probability is designed for a DF cooperative network and compared with the fixed DSTC schemes in [5]. An adaptive distributed-Alamouti (D-Alamouti) STBC design is proposed in [6] for the non-regenerative dual-hop wireless system which achieves the minimum outage probability. DSTC schemes for the AF protocol are discussed in [7]-[8]. In [7], the GABBA STC scheme is extended to a distributed MIMO network with full-diversity and full-rate, while an optimal algorithm for design of the DSTC scheme to achieve the optimal diversity and multiplexing tradeoff is derived in [8].

The performance of cooperative networks using different strategies has been widely discussed in the literature. In [9], an exact pairwise error probability of the D-Alamouti STBC scheme is derived according to the position of the relay node. In [10], a bit error rate (BER) analysis of the D-Alamouti STBC scheme is proposed. The difference between these two works lies in the different cooperative schemes considered. A maximum likelihood (ML) detection algorithm for a MIMO relay system with DF protocol is derived in [11] with its performance analysis as well. The symbol error rate and diversity order upper bound for the scalar fixed-gain AF cooperative protocol are given in [12]. The use of single-antenna relay nodes and the DF cooperative protocol is the main difference in scenario between [12] and this work. An STC encoding process is implemented at the source node in [13], which decreases the output of the system and increases the computational complexity of the decoding at the destination node. In [14], the BER upper bound is given without a STC scheme at the relay node.

In this paper, we propose an adaptive distributed space-time coding scheme and algorithms for a two-hop cooperative MIMO relaying system with the AF protocol and linear MMSE receivers. We focus on how the adaptive code matrix affects the DSTC during the encoding and how to optimize the parameters in the matrix. It is shown that the use of an adaptive code matrix benefits the performance of the system by lowering the upper bound compared to using traditional STC schemes. Linear MMSE expressions are devised to compute the parameters of the adaptive matrix and the linear receive filter. Then an adaptive optimization algorithm is derived based on the MSE criterion, with the stochastic gradient (SG) algorithm in order to reduce the computational complexity of the optimization process. The updated randomized matrix is transmitted to the relay node through a feedback channel that is assumed in this work error free and delay free. The upper bound pairwise error probability of the proposed and the randomized-STC schemes (RSTC) in a cooperative MIMO system which employs multi-antenna relay nodes with the AF protocol is also analyzed.

The paper is organized as follows. Section II introduces a two-hop cooperative MIMO system with multiple relays applying the AF strategy and the RSTC scheme. In Section III the proposed MMSE expressions and the SG algorithm for the adaptive matrix are derived, and the analysis of the

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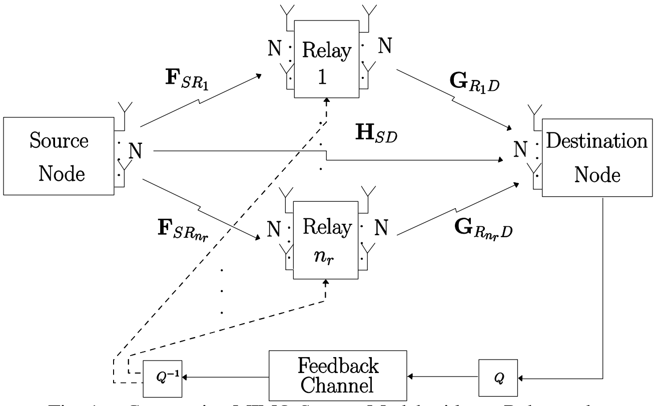

Fig. 1. Cooperative MIMO System Model with n_r Relay nodes

upper bound of pairwise error probability using the RSTC is shown in Section IV. Section V focuses on the results of the simulations and Section VI leads to the conclusion.

II. Cooperative MIMO System Model

The communication system under consideration is a two-hop cooperative MIMO system which employs multiple relay nodes and communicates over channels from the source node to the relay nodes and the destination node, and from the relay nodes to the destination nodes as shown in Fig. 1. A modulation scheme is used in our system to generate the transmitted symbol vector $\boldsymbol{s}[i]$ at the source node and all nodes have N antennas. There are n_r relay nodes that employ the AF cooperative strategy as well as a DSTC scheme. The system broadcasts symbols from the source to n_r relay nodes as well as to the destination node in the first phase. The symbols are amplified and re-encoded at each relay node prior to transmission to the destination node in the second phase. We consider only one user at the source node in our system that has N Spatial Multiplexing (SM)-organized data symbols contained in each packet. The received symbols at the $k-th$ relay node and the destination node are denoted as $\boldsymbol{r}_{SR_k}$ and $\boldsymbol{r}_{SD}$, respectively, where $k = 1, 2, ..., n_r$. The received symbols $\boldsymbol{r}_{SR_k}$ are amplified before mapped into an STC matrix. We assume that the synchronization at each node is perfect. The received symbols at the destination node and each relay node are described by

$$\boldsymbol{r}_{SR_k}[i] = \boldsymbol{F}_k[i]\boldsymbol{s}[i] + \boldsymbol{n}_{SR_k}[i], \tag{1}$$

$$\boldsymbol{r}_{SD}[i] = \boldsymbol{H}[i]\boldsymbol{s}[i] + \boldsymbol{n}_{SD}[i], \tag{2}$$

$$i = 1, 2, \ \ldots\ , N, \quad k = 1, 2, \ \ldots\ n_r,$$

where the $N \times 1$ vector $\boldsymbol{n}_{SR_k}[i]$ and $\boldsymbol{n}_{SD}[i]$ denote the zero mean complex circular symmetric additive white Gaussian noise (AWGN) vector generated at each relay and the destination node with variance σ^2. The transmitted symbol vector $\boldsymbol{s}[i]$ contains N parameters, $\boldsymbol{s}[i] = [s_1[i], s_2[i], ..., s_N[i]]$, which has a covariance matrix $E\big[\boldsymbol{s}[i]\boldsymbol{s}^H[i]\big] = \sigma_s^2\boldsymbol{I}$, where $E[\cdot]$ stands for expected value, $(\cdot)^H$ denotes the Hermitian operator, σ_s^2 is the signal power which we assume to be equal to 1 and $\boldsymbol{I}$ is the identity matrix. $\boldsymbol{F}_k[i]$ and $\boldsymbol{H}[i]$ are the $N \times N$ channel gain matrices between the source node and the kth relay node, and between the source node and the destination node, respectively.

After processing and amplifying the received vector $\boldsymbol{r}_{SR_k}[i]$ at the kth relay node, the signal vector $\tilde{\boldsymbol{s}}_{SR_k}[i] = \boldsymbol{A}_{R_kD}[i](\boldsymbol{F}_k[i]\boldsymbol{s}[i] + \boldsymbol{n}_{SR_k}[i])$ can be obtained and then forwarded to the destination node. The amplified symbols in $\tilde{\boldsymbol{s}}_{SR_k}[i]$ will be re-encoded by a $N \times T$ DSTC scheme $\boldsymbol{M}(\tilde{\boldsymbol{s}}[i])$ and then multiplied by an $N \times N$ randomized matrix $\boldsymbol{\mathfrak{R}}[i]$ in [18], then forwarded to the destination node. The randomized matrix, achieving the diversity order and providing lower error probability [18], contains elements generated using $e^{j\theta}$ where θ is uniformly distributed in $[0, 2\pi)$. The relationship between the $k-th$ relay and the destination node can be described as

$$\boldsymbol{R}_{R_kD}[i] = \boldsymbol{G}_k[i]\boldsymbol{\mathfrak{R}}[i]\boldsymbol{M}_{R_kD}[i] + \boldsymbol{N}_{R_kD}[i], \tag{3}$$
$$k = 1, 2, ..., n_r,$$

where the $N \times T$ matrix $\boldsymbol{M}_{R_kD}[i]$ is the DSTC matrix employed at the relay nodes whose elements are the amplified symbols in $\tilde{\boldsymbol{s}}_{SR_k}[i]$. The $N \times T$ received symbol matrix $\boldsymbol{R}_{R_kD}[i]$ in (3) can be written as an $NT \times 1$ vector $\boldsymbol{r}_{R_kD}[i]$ given by

$$\boldsymbol{r}_{R_kD}[i] = \boldsymbol{\mathfrak{R}}_{eq_k}[i]\boldsymbol{G}_{eq_k}[i]\tilde{\boldsymbol{s}}_{SR_k}[i] + \boldsymbol{n}_{R_kD}[i], \tag{4}$$

where the block diagonal $NT \times NT$ matrix $\boldsymbol{\mathfrak{R}}_{eq_k}[i]$ denotes the equivalent adjustable matrix and the $NT \times N$ matrix $\boldsymbol{G}_{eq_k}[i]$ stands for the equivalent channel matrix which is the DSTC scheme $\boldsymbol{M}(\tilde{\boldsymbol{s}}[i])$ combined with the channel matrix $\boldsymbol{G}_{R_kD}[i]$. The $NT \times 1$ equivalent noise vector $\boldsymbol{n}_{R_kD}[i]$ generated at the destination node contains the noise parameters in $\boldsymbol{N}_{R_kD}[i]$. After rewriting $\boldsymbol{R}_{R_kD}[i]$ we can consider the received symbol vector at the destination node as a $N(n_r+1)$ vector with two parts, one is from the source node and another one is the superposition of the received vectors from each relay node. Therefore, the received symbol vector for the cooperative MIMO system can be written as

$$\begin{aligned}\boldsymbol{r}[i] &= \begin{bmatrix} \boldsymbol{H}[i]\boldsymbol{s}[i] \\ \sum_{k=1}^{n_r} \boldsymbol{\mathfrak{R}}_{eq_k}[i]\boldsymbol{G}_{eq_k}[i]\tilde{\boldsymbol{s}}_{SR_k}[i] \end{bmatrix} + \begin{bmatrix} \boldsymbol{n}_{SD}[i] \\ \boldsymbol{n}_{RD}[i] \end{bmatrix} \\ &= \boldsymbol{D}_D[i]\tilde{\boldsymbol{s}}_D[i] + \boldsymbol{n}_D[i],\end{aligned} \tag{5}$$

where the $(T+1)N \times (n_r+1)N$ block diagonal matrix $\boldsymbol{D}_D[i]$ denotes the channel gain matrix of all the links in the network which contains the $N \times N$ channel coefficients matrix $\boldsymbol{H}[i]$ between the source node and the destination node, the $NT \times N$ equivalent channel matrix $\boldsymbol{G}_{eq_k}[i]$ for $k = 1, 2, ..., n_r$ between each relay node and the destination node. The $(n_r+1)N \times 1$ noise vector $\boldsymbol{n}_D[i]$ contains the received noise vector at the destination node and the amplified noise vectors from each relay node, which can be modeled as additive white Gaussian noise (AWGN) with zero mean and covariance matrix $\sigma^2(1+ \parallel \boldsymbol{\mathfrak{R}}_{eq_k}[i]\boldsymbol{G}_{eq_k}[i]\boldsymbol{A}_{R_kD}[i] \parallel_F^2)\boldsymbol{I}$, where $\parallel \boldsymbol{X} \parallel_F = \sqrt{\mathrm{Tr}(\boldsymbol{X}^H \cdot \boldsymbol{X})} = \sqrt{\mathrm{Tr}(\boldsymbol{X} \cdot \boldsymbol{X}^H)}$ is the Frobenius norm.

III. Design of Linear MMSE Receivers and Adaptive DSTC Schemes

In this section, we design an adaptive linear MMSE receive filter and an MMSE randomized matrix for use with the proposed DSTC scheme. An adaptive SG algorithm [16] for determining the parameters of the adjustable matrix with reduced complexity is also devised. The DSTC scheme used at the relay node employs an MMSE randomized matrix, which is computed at the destination node and obtained by a feedback channel and processes the data symbols prior to transmission to the destination node.

A. Optimization Method Based on the MSE Criterion

Let us consider the MMSE design of the receive filter and the adjustable matrix according to the optimization problem

$$[\boldsymbol{W}[i], \boldsymbol{\mathfrak{R}}_{eq}[i]] = \arg \min_{\boldsymbol{W}[i], \boldsymbol{\mathfrak{R}}_{eq}[i]} E\left[\|\boldsymbol{s}[i] - \boldsymbol{W}^H[i]\boldsymbol{r}[i]\|^2\right],$$

where $\boldsymbol{r}[i]$ is the received symbol vector at the destination node which contains the adjustable matrix to be optimized. If we only consider the received symbols from the relay node, the received symbol vector at the destination node can be derived as

$$\begin{aligned} \boldsymbol{r}[i] &= \boldsymbol{D}_D[i]\tilde{\boldsymbol{s}}_D[i] + \boldsymbol{n}_D[i] \\ &= \boldsymbol{\mathfrak{R}}_{eq}[i]\boldsymbol{G}_{eq}[i]\boldsymbol{A}[i]\boldsymbol{F}[i]\boldsymbol{s}[i] + \boldsymbol{\mathfrak{R}}_{eq}[i]\boldsymbol{G}_{eq}[i]\boldsymbol{A}[i]\boldsymbol{n}_{SR}[i] \\ &\quad + \boldsymbol{n}_{RD}[i] \\ &= \boldsymbol{\mathfrak{R}}_{eq}[i]\boldsymbol{C}[i]\boldsymbol{s}[i] + \boldsymbol{n}_D[i], \end{aligned} \tag{6}$$

where $\boldsymbol{C}[i]$ is an $NT \times N$ matrix that contains all the complex channel gains and the amplified matrix assigned to the received vectors at the relay node, and the noise vector $\boldsymbol{n}_D$ is a Gaussian noise with zero mean and variance $\sigma^2(1+ \parallel \boldsymbol{\mathfrak{R}}_{eq}[i]\boldsymbol{G}_{eq}[i]\boldsymbol{A}[i] \parallel_F^2)$. We can then recast the optimization as

$$\begin{aligned} &[\boldsymbol{W}[i], \boldsymbol{\mathfrak{R}}_{eq}[i]] = \\ &\arg \min_{\boldsymbol{W}[i], \boldsymbol{\mathfrak{R}}_{eq}[i]} E\left[\|\boldsymbol{s}[i] - \boldsymbol{W}^H[i](\boldsymbol{\mathfrak{R}}_{eq}[i]\boldsymbol{C}[i]\boldsymbol{s}[i] + \boldsymbol{n}_D[i])\|^2\right]. \end{aligned} \tag{7}$$

By expanding the righthand side of (7) and taking the gradient with respect to $\boldsymbol{W}^*[i]$ and equating the terms to zero, we can obtain the linear MMSE receive filter

$$\boldsymbol{W}[i] = \left(E\left[\boldsymbol{r}[i]\boldsymbol{r}^H[i]\right]\right)^{-1} E\left[\boldsymbol{r}[i]\boldsymbol{s}^H[i]\right], \tag{8}$$

where the first term denotes the inverse of the auto-correlation matrix and the second one is the cross-correlation matrix. Define $\tilde{\boldsymbol{r}} = \boldsymbol{C}[i]\boldsymbol{s}[i] + \boldsymbol{C}[i]\boldsymbol{n}_{SR}$, then the adjustable matrix can be calculated by taking the gradient with respect to $\boldsymbol{\mathfrak{R}}^*[i]$ and equating the terms to zero, resulting in

$$\boldsymbol{\mathfrak{R}}[i] = \left(\boldsymbol{W}^H[i](E\left[\tilde{\boldsymbol{r}}[i]\tilde{\boldsymbol{r}}^H[i]\right])\boldsymbol{W}[i]\right)^{-1} E\left[\boldsymbol{s}[i]\tilde{\boldsymbol{r}}^H[i]\right]\boldsymbol{W}[i], \tag{9}$$

where $E\left[\tilde{\boldsymbol{r}}[i]\tilde{\boldsymbol{r}}^H[i]\right]$ is the auto-correlation of the space-time coded received symbol vector at the relay node, and $E\left[\boldsymbol{s}[i]\tilde{\boldsymbol{r}}^H[i]\right]$ is the cross-correlation. The expression above requires a matrix inversion with a high computational complexity.

B. Adaptive Matrix Optimization Algorithm

In order to reduce the computational complexity and achieve the optimal performance, an adaptive robust matrix optimization (ARMO) algorithm based on an SG algorithm is devised. The MMSE problem is derived in (7), and the MMSE filter matrix can be calculated by (8) first during the optimization process. The simple ARMO algorithm can be obtained by taking the instantaneous gradient term of (7) with respect to the adjustable matrix $\boldsymbol{\mathfrak{R}}_{eq}{}^*[i]$, which is given by

$$\begin{aligned} &\nabla \mathrm{L}_{\boldsymbol{\mathfrak{R}}_{eq}{}^*[i]} \\ &= \nabla E\left[\|\boldsymbol{s}[i] - \boldsymbol{W}^H[i](\boldsymbol{\mathfrak{R}}_{eq}[i]\boldsymbol{C}[i]\boldsymbol{s}[i] + \boldsymbol{n}_D[i])\|^2\right]_{\boldsymbol{\mathfrak{R}}_{eq}{}^*[i]} \\ &= -(\boldsymbol{s}[i] - \boldsymbol{W}^H[i]\boldsymbol{r}[i])\boldsymbol{s}^H[i]\boldsymbol{C}^H[i]\boldsymbol{W}[i] \\ &= -\boldsymbol{e}[i]\boldsymbol{s}^H[i]\boldsymbol{C}^H[i]\boldsymbol{W}[i], \end{aligned} \tag{10}$$

where $\boldsymbol{e}[i]$ stands for the detected error vector. After computing (10), the ARMO algorithm can be obtained by introducing a step size into an SG algorithm to update the result until the convergence is reached as given by

$$\boldsymbol{\mathfrak{R}}[i+1] = \boldsymbol{\mathfrak{R}}[i] + \mu(\boldsymbol{e}[i]\boldsymbol{s}^H[i]\boldsymbol{C}^H[i]\boldsymbol{W}[i]), \tag{11}$$

where μ stands for the step size of the ARMO algorithm. By making use of the iterative algorithm in [17] the ARMO algorithm is achieved. The complexity of calculating the adjustable matrix is $O(2N)$, which is much less than that of the calculation method derived in (9). As mentioned in Section I, the adjustable matrix will be sent back to the relay nodes via a feedback channel which is assumed to be error-free in this work. However, in practical circumstances, the errors caused by the broadcasting and the diversification of the feedback channel with time changes will affect the accuracy of the received adjustable matrix at the relay nodes.

IV. Probability of Error Analysis

In this section, the upper bound of the pairwise error probability of the system employing the proposed STC will be derived. As we mentioned in the first section, the randomized matrix will be considered in the derivation as it affects the performance by reducing the upper bound of the pairwise error probability. For the sake of simplicity, we consider a 2 by 2 MIMO system with 1 relay node, and the direct link is ignored in order to concentrate on the effect of the desired matrix. The expression of the upper bound is also stable for the increase of the system size and the number of relay nodes.

Consider an $N \times N$ STC scheme we use at the relay node with L codewords. The codeword $\boldsymbol{C}^1$ is transmitted and decoded to another codeword $\boldsymbol{C}^i$ at the destination node, where $i = 1, 2, ..., L$. According to [19], the probability of error can be upper bounded by the sum of all the probabilities of incorrect decoding, which is given by

$$\mathrm{P_e} \leq \sum_{i=2}^{L} \mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^i). \tag{12}$$

Assuming the codeword $\boldsymbol{C}^2$ is decoded at the destination node and we know the channel information perfectly at the destination node, we can derive the pairwise error probability as

$$\begin{aligned} &\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{\mathfrak{R}}) \\ &= \mathrm{P}(\parallel \boldsymbol{R}^1 - \boldsymbol{G}\boldsymbol{\mathfrak{R}}\boldsymbol{C}^1 \parallel_F^2 - \parallel \boldsymbol{R}^1 - \boldsymbol{G}\boldsymbol{\mathfrak{R}}\boldsymbol{C}^2 \parallel_F^2 > 0 \mid \boldsymbol{\mathfrak{R}}_{eq}) \\ &= \mathrm{P}(\parallel \boldsymbol{r}^1 - \boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{G}_{eq}\boldsymbol{F}\boldsymbol{s}^1 \parallel_F^2 \\ &\qquad - \parallel \boldsymbol{r}^1 - \boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{G}_{eq}\boldsymbol{F}\boldsymbol{s}^2 \parallel_F^2 > 0 \mid \boldsymbol{\mathfrak{R}}_{eq}), \end{aligned} \tag{13}$$

where $\boldsymbol{F}$ and $\boldsymbol{G}_{eq}$ stand for the channel coefficient matrix between the source node and the relay node, and between the relay node and the destination node, respectively. The adaptive matrix is denoted by $\boldsymbol{\mathfrak{R}}_{eq}$. Define $\boldsymbol{H} = \boldsymbol{G}_{eq}\boldsymbol{F}$, which stands for the total channel coefficients matrix. After the calculation, we can transfer the pairwise error probability expression in (13) to

$$\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{\mathfrak{R}}_{eq}) = \mathrm{P}(\| \boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}(\boldsymbol{s}^1 - \boldsymbol{s}^2) \|_F^2 < \boldsymbol{Y}), \quad (14)$$

where $\boldsymbol{Y} = \mathrm{Tr}(\boldsymbol{n}^{1^H}\boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}(\boldsymbol{s}^1-\boldsymbol{s}^2)+(\boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}(\boldsymbol{s}^1-\boldsymbol{s}^2))^H\boldsymbol{n}^1)$, and $\boldsymbol{n}^1$ denotes the noise vector at the destination node with zero mean and covariance matrix $\sigma^2(1+ \| \boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{G}_{eq} \|_F^2)\boldsymbol{I}$. By making use of the Q function, we can derive the error probability function as

$$\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{\mathfrak{R}}_{eq}) = \mathrm{Q}\left(\sqrt{\frac{\gamma}{2}} \| \boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}(\boldsymbol{s}^1 - \boldsymbol{s}^2) \|_F\right), \quad (15)$$

where

$$\mathrm{Q} = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(-\frac{u^2}{2}\right)\mathrm{d}u, \quad (16)$$

and γ is the received SNR at the destination node assuming the transmit power is equal to 1.

In order to obtain the upper bound of $\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{\mathfrak{R}}_{eq})$ we expand the formula $\| \boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}(\boldsymbol{s}^1-\boldsymbol{s}^2) \|_F^2$. Let $\boldsymbol{U}^H\boldsymbol{\Lambda}_s\boldsymbol{U}$ be the eigenvalue decomposition of $(\boldsymbol{s}^1 - \boldsymbol{s}^2)^H(\boldsymbol{s}^1 - \boldsymbol{s}^2)$, where $\boldsymbol{U}$ is a Hermitian matrix and $\boldsymbol{\Lambda}_s$ contains all the eigenvalues of the difference between two different codewords $\boldsymbol{s}^1$ and $\boldsymbol{s}^2$. Let $\boldsymbol{V}^H\boldsymbol{\Lambda}_{\mathfrak{R}}\boldsymbol{V}$ stand for the eigenvalue decomposition of $(\boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}\boldsymbol{U})^H\boldsymbol{\mathfrak{R}}_{eq}\boldsymbol{H}\boldsymbol{U}$, where $\boldsymbol{V}$ is a random Hermitian matrix and $\boldsymbol{\Lambda}_{\mathfrak{R}}$ is the ordered diagonal eigenvalue matrix. Therefore, the probability of error can be written as

$$\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{\mathfrak{R}}_{eq}) = \mathrm{Q}\left(\sqrt{\frac{\gamma}{2}\sum_{m=1}^{NT}\sum_{n=1}^{N}\lambda_{\mathfrak{R}_m}\lambda_{s_n}|\xi_{n,m}|^2}\right), \quad (17)$$

where $\xi_{n,m}$ is the $(n, m) - th$ element in $\boldsymbol{V}$, and $\lambda_{\mathfrak{R}_m}$ and λ_{s_n} are eigenvalues in $\boldsymbol{\Lambda}_{\mathfrak{R}}$ and $\boldsymbol{\Lambda}_s$, respectively. According to [19], a good upper bound assumption of the Q function is given by

$$\mathrm{Q}(x) \leq \frac{1}{2}e^{\frac{-x^2}{2}}. \quad (18)$$

Thus, we can derive the upper bound of the pairwise error probability for an adjustable STC scheme as

$$\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{\mathfrak{R}}_{eq}) \leq \frac{1}{2}\exp\left(-\frac{\gamma}{4}\sum_{m=1}^{NT}\sum_{n=1}^{N}\lambda_{\mathfrak{R}_m}\lambda_{s_n}|\xi_{n,m}|^2\right), \quad (19)$$

while the upper bound of the error probability expression for a traditional STC is given by

$$\mathrm{P}(\boldsymbol{C}^1 \to \boldsymbol{C}^2 \mid \boldsymbol{H}_{eq}) \leq \frac{1}{2}\exp\left(-\frac{\gamma}{4}\sum_{m=1}^{NT}\sum_{n=1}^{N}\lambda_{s_n}|\xi_{n,m}|^2\right). \quad (20)$$

With comparison of (19) and (20), it is obvious to note that the eigenvalue of the adjustable matrix is the difference, which suggests that employing an adjustable matrix for a STC scheme at the relay node can provide an improvement in BER performance.

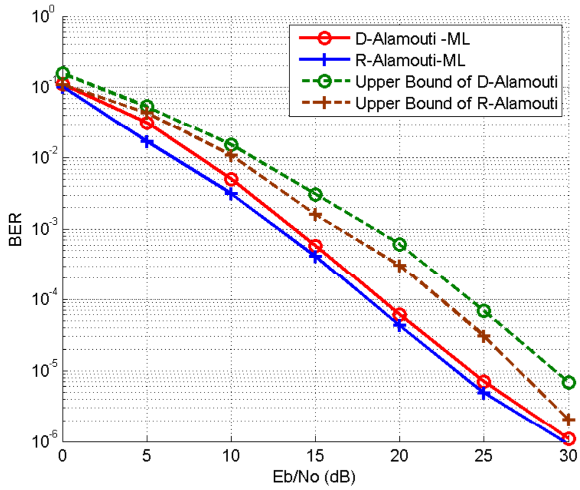

Fig. 2. BER performance v.s. E_b/N_0 for the upper bound of the R-Alamouti scheme without the direct link

V. SIMULATIONS

The simulation results are provided in this section to assess the proposed scheme and algorithms. The cooperative MIMO system considered employs an AF protocol with the Alamouti STBC scheme [19] using QPSK modulation in a quasi-static block fading channel with AWGN. The simulation system with 1 relay node and 2 antennas at each node. In the simulations, we define both the symbol power and the noise variance σ^2 for as equal to 1, and the power of the adaptive matrix in the ARMO algorithm are normalized to the same transmission power of that in the R-Alamouti.

The upper bounds of the D-Alamouti and the R-Alamouti derived in the previous section are shown in Fig. 2. The theoretical pairwise error probabilities provide the largest decoding errors of the two different coding schemes and as shown in the figure, by employing an adaptive matrix at the relay node it decreases the decoding error upper bound. The comparison of the simulation results in BER performance of the R-Alamouti and the D-Alamouti indicates the advantage of using the adaptive matrix using ML detection algorithm.

The proposed ARMO algorithm is compared with the SM scheme and the traditional RSTC algorithm using the D-Alamouti STBC scheme in [15] with $n_r = 1$ relay nodes in Fig. 3. The number of antennas $N = 2$ at each node and the effect of the direct link are considered. The results illustrate that without the direct link, by making use of the STC or the RSTC technique, a significant performance improvement can be achieved compared to the spatial multiplexing system. The RSTC algorithm outperforms the STC-AF system, while the ARMO algorithm can improve the performance by about 3dB as compared to the RSTC algorithm. With the consideration of the direct link, the results indicate that the cooperative diversity order can be increased, and using the ARMO algorithm achieves an improved performance with 2dB of gain as compared to employing the RSTC algorithm and 3dB of gain as compared to employing the traditional STC-AF algorithm.

The simulation results shown in Fig. 4 illustrate the convergence property of the ARMO algorithm. The SM, D-Alamouti

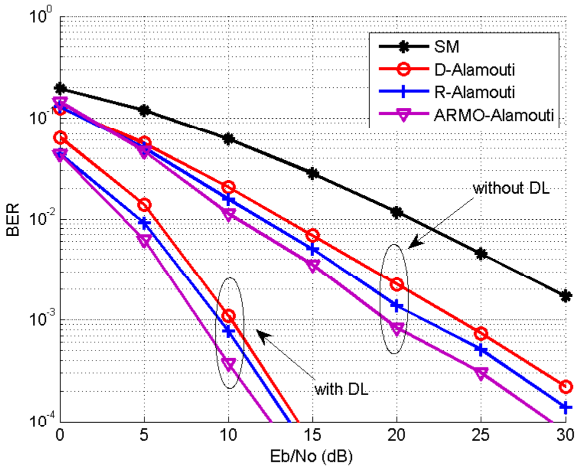

Fig. 3. BER performance v.s. E_b/N_0 for ARMO Algorithm with and without the direct link

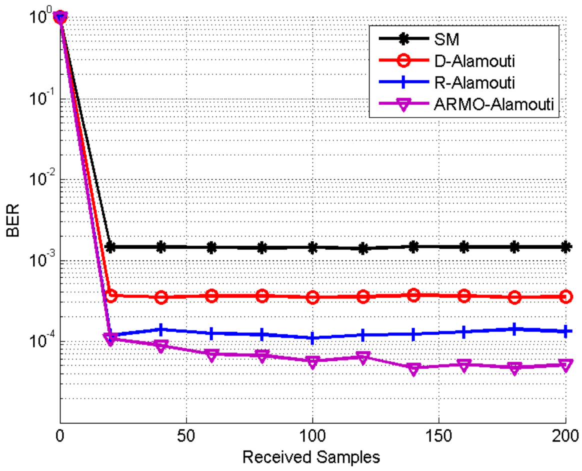

Fig. 4. BER performance v.s. Number of Samples for ARMO Algorithm without the direct link

and the randomized D-Alamouti algorithms obtain nearly flat performance in BER as the utilization of fixed STC scheme and the adaptive matrix. The SM scheme has the worst performance due to the lack of coding gains, while the D-Alamouti scheme can provide a significant performance improvement in terms of the BER improvement, and by employing the adaptive matrix at the relay node the BER performance can be further decreased when the transmission circumstances are the same as that of the D-Alamouti. The ARMO algorithm shows its advantage in a fast convergence and a lower BER achievement. At the beginning of the optimization process with a small number of samples, the ARMO algorithm achieves the BER level of the D-Alamouti one, but with the increase of the received symbols, the ARMO algorithm achieves a better BER performance.

VI. Conclusion

We have proposed an adaptive robust matrix optimization (ARMO) algorithm for the randomized DSTC using a linear MMSE receive filter at the destination node. The pairwise error probability of introducing the adjustable DSTC in a cooperative MIMO network with the AF protocol has been derived. The simulation results illustrate the advantage of the proposed ARMO algorithm by comparing it with the cooperative network employing the traditional DSTC scheme and the fixed randomized STC scheme. The proposed algorithm can be used with different distributed STC schemes using the AF strategy and can also be extended to the DF cooperation protocol.

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