In this paper, we consider an amplify-and-forward cooperative wireless network in which network nodes use multiple input multiple output (MIMO) spatial division multiplexing (SDM) to communicate with one another. We examine the problem of distributed cooperative relay selection and signal combining at the destination. First, we propose three distributed relay selection algorithms based on the maximum channel gains, the maximum harmonic mean of the channel gains, and the minimum mean squared error (MSE) of the signal estimation. Second, we propose a minimum mean square error (MMSE) signal combining scheme which jointly serves as the optimal signal combiner and interference canceler. It is shown that the MSE selection together with the MMSE combining achieves the maximal diversity gain. We also show that in MIMO-SDM cooperative networks increasing the number of candidate nodes does not help to improve the BER performance as opposed to the cooperative networks where each node is equipped with only single antenna. A practical approach to implementation of the combiner based on the current wireless access network protocols will also be presented.

**key words:** relay selection, cooperative communication, MIMO, MMSE, linear combining

### 1. Introduction

Multiple input multiple output (MIMO) wireless communication systems have been known as an attractive solution to increase the channel capacity over rich scattering fading environment [1][2]. Among MIMO systems, spatial division multiplexing (SDM) is a typical approach to achieving high spectral efficiency while requiring only moderate hardware complexity [2]. Apart from being employed in a point-to-point MIMO communication link between the user equipment (UE) and the base station (BS), MIMO systems are also being considered to implement in a distributed mode via ad hoc relaying links between UEs [3]. This cooperative communication allows the achievement of spatial diversity and thus helps to increase the system performance. As a result, combining MIMO-SDM and cooperative communications is a natural approach to achieving both spectral efficiency and improved system performance. However, research on MIMO-SDM cooperative communications is still quite limited. Most previous works considered only the case of cooperative communication systems in which UEs are equipped with only a single antenna. Only some results are reported recently for the case of MIMO cooperative communication systems in which UEs transmit and cooperate with one another using MIMO spatial division multiplexing (SDM) [4]–[6].

In cooperative communication systems, the amplify-and-forward (AF) relaying scheme has attracted increasing attention due to its simple processing. In an AF cooperative network, there are three important problems which need to be considered: (i) How to select a relaying node? (ii) How to amplify the received signals at the relay? and (iii) How to combine the signals at the destination? Since the objective of amplifying the received signals at the relay is simply to compensate the signal energy loss in the previous link, the amplification factor was derived straightforwardly in [4] and [5]. Much recent attention has been paid in the relay selection problem [7]–[13]. In [7] the authors proposed two distributed node selection schemes based on the maximum channel gains and the maximum harmonic mean of the channel gains for the case in which cooperative nodes are equipped with only a single antenna. Extension of this work to the case of adaptive selection was then proposed in [8]. In [11] the authors proposed a relay selection scheme based on the partial channel state information in order to achieve the tradeoff between the bandwidth efficiency and diversity order. Relay selection schemes which minimize the energy consumption were considered in [12]. In a recent work [13], Jing and Jafarkhani generalized the problem of single relay selection to the multiple case. For the case of MIMO cooperative networks, several results related to the relay selection problem were reported in [5] and [6]. In [6] the authors proposed a distributed orthogonal relay selection based on the maximum harmonic mean of the channel gains. In contrast, the work of [5] considered the problem of combining relay and antenna selection and proposed a greedy antenna selection based on the MMSE criterion. However, MIMO-SDM was not assumed for the relays in [5]. Concerning the third problem, combining and then detecting the received signals from two time slots should be done in such a way that fully exploits diversity gain from the two diversity paths. Since the previous works only considered the case in which network nodes are equipped with a single antenna, maximal ratio combining (MRC) was proposed to use as the optimal combining for maximizing the diversity gain [7], [8]. However, MRC is not applicable to the case of the MIMO-SDM cooperative communications since there is inherent interfer-
quence among transmit streams. To the best knowledge of the authors there has not been any work concerning the problem of signal combining design for the case of MIMO-SDM cooperative communications.

Motivated by the above open questions, in this paper we consider the problem of distributed relay selection and signal combining for MIMO-SDM cooperative communication networks. Our first contribution includes the proposal of three selection schemes based on the maximum channel gains, the maximum harmonic mean of the channel gains, and the minimum mean squared error (MSE) of the signal estimation. Simulation results show that the proposed MSE based algorithm outperforms the maximum channel gain based and the harmonic mean based algorithm in terms of BER performance. As the second contribution, we propose a minimum mean squared error (MMSE) combiner which can work with the proposed selection schemes to provide the maximum diversity gain. In particular, we derive the optimal solution of the combining weight matrix which allows to combine signals from the direct and the AF relaying path. We also show that the general combining weight matrix can be conveniently broken down into separate combining matrices for the direct and relaying path. This allows for reduced-complexity implementation of the signal combiner at the destination. A practical approach to implementation of the combining algorithm based on the current wireless access network protocols will also be presented. The proposed algorithm can be extended to the AF cooperative networks with multiple relaying hops or multiple relaying nodes.

The remainder of the paper is organized as follows. We present the system model and the cooperative protocol for the MIMO-SDM cooperative networks in Sect. 2. The problem of the distributed relay selection is presented in Sect. 3. Derivation of the combining weight matrix is shown in Sect. 4. Simulation results are analyzed in Sect. 5, and finally conclusions are summarized in Sect. 6.

2. System Model and Cooperative Protocol

2.1 System Model

The system configuration of the considered cooperative network is shown in Fig. 1. We assume that the communication between the source, the intermediate nodes and the destination is affected by flat Rayleigh fading and that there are $K$ capable intermediate nodes willing to act as the relay. In the general case, it is common to assume that each network node is equipped with $N$ antennas which are used for both transmission and reception. However, in order to simplify mathematical representations let us assume in this paper that all nodes are equipped with only $N = 2$ antennas as illustrated in Fig. 1. Extension to the case of $N > 2$ is straightforward. We will also focus on the case in which the relaying path consists of only two hops and are assisted by only one selected node.

Based on the above assumptions, we define the signal vector transmitted from the source as $s = [s_1, s_2]^T$, where $s_n$ is the symbol transmitted from the $n$th antenna of the source and $n = 1, 2$ is the antenna index. The communication between the source and the destination is assumed via the direct path between the two nodes and via a relaying path with the help of a selected intermediate node. The method to select an intermediate node from the $K$ capable intermediate nodes to act as the relay will be presented in the next sections.

2.2 Protocol description

The cooperative protocol is similar to that described in the previous works [7]–[9]. It occurs during 2 phases: (i) relay selection and (ii) data transmission with the help of the relay. Operations during each phase are summarized below.

2.2.1 Phase 1: Relay Selection

Relay selection is done in the distributed mode as proposed in [7]. That is intermediate nodes cooperate with one another through a signaling process to select the best candidate node to act as the relay. The signaling process includes three steps.

- The source initiates the signaling process by sending a Request-to-Send (RTS) message to the destination. Due to the broadcast nature of wireless communications, all capable intermediate nodes receive the same RTS message. Upon receipt of the RTS message each intermediate node is able to estimate the instantaneous channel from the source to itself.
- After receiving the RTS message, the destination replies the source by a Clear-to-Send (CTS) message.

Fig. 1 A cooperative network model.
Again, due to the broadcast nature, all the intermediate nodes receive the same CTS message. Similar to the above step, each intermediate node is now able to estimate the instantaneous channel from the destination to itself. Due to the reciprocity of the channel, it is possible that each intermediate node knows the instantaneous channel from it to the destination. It then follows that each intermediate node knows the relaying channel from the source via itself to the destination. Each intermediate node will calculate the channel quality index (CQI) for the relaying path over it based on a specific measure. Each value of CQI is mapped to an amount of waiting time. The intermediate node associated with the best CQI is allowed to transmit an Apply-for-Relay (AFR) message first to apply for being the relay.

- Upon receipt of the AFR message, the destination replies the candidate node by sending a Select-for-Relay (SFR) message while other intermediate nodes defer sending the AFR message and stay in the standby mode. The function of the AFR and SFR message is to inform the remaining nodes that a capable node has been selected for the relay, which ends the relay selection process.

2.2.2 Phase 2: Data transmission

The data transmission phase is done in the half-duplex mode and happens in two time slots, one for the direct transmission from the source and the other for relaying from the relay to the destination.

- At the first time slot, the source transmits its signal which reaches both the destination and the relay.
- At the next time slot, the source stops transmitting while the relay forwards the received signal at the first time slot to the destination using the amplify-and-forward (AF) relaying. Signals received during the two time slots will be then combined and estimated using an MMSE detector.

2.3 Channel Model

Denote the channel matrix between the source and the destination as

\[ H^{sd} = \begin{bmatrix} h_{11}^{sd} & h_{12}^{sd} \\ h_{21}^{sd} & h_{22}^{sd} \end{bmatrix}, \]

where \(h_{ij}^{ab}\) represents the channel between the \(i\)th antenna of node \(b\) to the \(j\)th antenna of \(a\). The channel between the source and an intermediate node \(k\), and between node \(k\) and the destination are defined, respectively, as

\[ H^{sk} = \begin{bmatrix} h_{11}^{sk} & h_{12}^{sk} \\ h_{21}^{sk} & h_{22}^{sk} \end{bmatrix}, \quad H^{kd} = \begin{bmatrix} h_{11}^{kd} & h_{12}^{kd} \\ h_{21}^{kd} & h_{22}^{kd} \end{bmatrix}. \]

Using these notations, the received signals at the destination and a node \(k\) during the first time slot of phase 2 are given by

\[ y_1 = H^{sd}s + z_1, \]

\[ x_k = H^{kd}s + z_k, \]

where \(z_1\) and \(z_k\) are the noise vector affecting the receiver of the destination and the intermediate node \(k\) during the first time slot, respectively. It is assumed that after the first time slot, the \(K\) capable intermediate nodes have successfully cooperated with one another to select a most capable node \(r\) as the relay. The method of selection will be presented in the next section.

During the second time slot, the relay will amplify and forward the received signal \(x_r\) to the destination. The amplification factor is chosen such that it can compensate the power loss occurred in the link between the source and the relay. The amplification factor used for the reception branch associated with the 4th antenna of the relay is denoted by \(5\)

\[ g_r = \sqrt{\frac{E_s}{N(\frac{1}{4}||h_{r}^{rd}||^2 + 1)}} \]

where \(E_s = \text{E}[||x_r||^2]\) is the transmit symbol energy, \(1/N\) is the power normalization factor, and \(h_{r}^{rd}\) is the \(r\)th row of the channel matrix \(H^{rd}\). Here \(E[\cdot]\) denotes the expectation operation. The amplification matrix used by the relay is then given by

\[ G_r = \begin{bmatrix} g_{r1} & 0 \\ 0 & g_{r2} \end{bmatrix}. \]

The received signal at the destination during the second time slot is given by

\[ y_2 = H^{rd}G_rx_r + z_2 \]

\[ = H^{rd}G_rH^{rd}s + H^{rd}G_rz_r + z_2. \]

The received signal vector at the destination during the first and second time slot will be then given by

\[ y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H^{sd}s \\ H^{rd}s \end{bmatrix} + \begin{bmatrix} z_1 \\ H^{rd}G_rz_r + z_2 \end{bmatrix} \]

where \(H^{rd} = H^{rd}G_rH^{rd}\). Define the following matrices and vectors

\[ H = \begin{bmatrix} H^{sd} \\ H^{rd} \end{bmatrix}, \quad z = \begin{bmatrix} z_1 \\ H^{rd}G_rz_r + z_2 \end{bmatrix} \]

we have the system equation as follows

\[ y = Hs + z. \]

3. Distributed Relay Selection for Cooperative Communications

In the distributed selection method, each intermediate node will calculate CQI of the relaying path via itself using the
estimated channel state information (CSI). This means that CQI used by node \( k \) is defined as a function of the channels between the source and the relay \( H^{sk} \), and the relay and the destination \( H^{kd} \), i.e., \( Q_k = f(H^{sk}, H^{kd}) \). In fact, each intermediate node \( k \) does not know the channel from the source to itself \( H^{sk} \) but only from itself to the source \( H^{kd} \). However, using the reciprocity of the channel it is assumed that the intermediate node can have information on the channel \( H^{sk} \) from \( H^{kd} \). From the calculated CQIs, the \( K \) intermediate nodes coordinate with one another to select the best candidate node to serve as the relay as follows

\[
r = \arg\max_k \{Q_k\}. \tag{12}\]

In the following sections, we will extend the previously proposed maximum channel gains, and maximum harmonic mean of the channel gains to the case of MIMO relaying channels, and propose a novel MSE based selection scheme.

### 3.1 Norm-based selection

This norm-based selection algorithm is extended from the maximum channel gains, and extends the channel harmonic mean to the case of MIMO relaying channels, and propose a novel MSE based selection scheme.

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#### 3.2 Harmonic-mean based selection

Similar to the maximum channel gain, the maximum harmonic mean of the channel gains was also proposed in [7] for relay selection in the single antenna cooperative systems. The algorithm calculates CQI for the \( k \)th intermediate node \( Q_k \) as

\[
Q_k = \frac{2}{|H^{sk}|^2 + |H^{kd}|^2} = \frac{2|h^{sk}|^2|h^{kd}|^2}{|H^{sk}|^2 + |H^{kd}|^2}. \tag{15}\]

This selection algorithm is also simple, but it was shown in [7] and [8] that this algorithm is inferior to the norm-based selection in case there exists a strongly bad single channel even if how good are the remaining channels.

To apply this selection criterion to the case of MIMO channels, we will calculate the channel harmonic mean of the MIMO channels from the source to the destination via the relay as

\[
Q_k = \frac{2N^2}{\sum_{i=1}^{N} \sum_{j=1}^{N} \frac{1}{|h_{ij}^s|^2} + \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{1}{|h_{ij}^d|^2}}. \tag{16}\]

This expression is similar to that presented in [6]. Upon obtaining this CQI, the best candidate node \( r \) will be selected using (12).

### 3.3 MSE-based selection

In this section, we propose a relay selection algorithm which is based on MSE. Using the proposed criterion, each intermediate node assumes that the destination will employ a linear MMSE combining scheme to combine the signals from the direct and the relaying path via the selected node \( r \) coherently. The objective of the MSE-based selection is to choose an intermediate node as the relay so that the detection error at the destination is minimized. Since the MSE based selection together with the MMSE combiner help to minimize the interference [14], the proposed selection scheme promises improved BER performance for the system. Denote the combining weight matrix used for the received signal via the relaying path of node \( k \) as \( W_k \). Before calculating the associated MSE we need to find the optimal solution for \( W_k \) based on the MMSE criterion. The optimal weight matrix is the solution of the following cost function

\[
W_k = \arg\min_{W_k} \mathbb{E}\left\{ \|s - (W_k^H y_{2}^k)^2\| \right\}, \tag{17}\]

where \( y_{2}^k \) is similar to \( y_2 \) in (8) except that the relay index \( r \) is replaced by the node index \( k \). Extending the argument of (17), i.e. the error covariance matrix, we have

\[
R_{u}^{c} = \mathbb{E}\left\{ (s - (W_k^H y_{2}^k)) (s - (W_k^H y_{2}^k))^H \right\}, \tag{18}\]

\[
= \mathbb{E}\left\{ (s(y_{2}^k)^H - (W_k^H y_{2}^k)) (s(y_{2}^k)^H - (W_k^H y_{2}^k))^H \right\} \tag{19}\]

Calculating each term of the above equation gives us

\[
\mathbb{E}\left\{ s y_{2}^k H \right\} W_k = \frac{E_{r}^c}{N} (H^{skd})^H W_k \tag{20}\]

\[
(W_k^H) H \mathbb{E}\left\{ y_{2}^k (y_{2}^k)^H \right\} W_k = \frac{E_{r}^c}{N} (H^{skd})^H W_k \tag{21}\]

\[
(W_k^H) H \mathbb{E}\left\{ y_{2}^k (y_{2}^k)^H \right\} W_k = \frac{E_{r}^c}{N} (H^{skd})^H W_k \tag{22}\]

where

\[
H^{skd} = H^{skd} G_{1} H^{kd} \tag{24}\]

\[
R_{u}^{c} = \frac{E_{r}^c}{N} \tilde{H}^{skd} \tag{25}\]

\[
R_{u}^{c} = \frac{E_{r}^c}{N} \tilde{H}^{skd} + \sigma_{e}^2 \tilde{H}^{skd} (H^{kd})^H I_2 \tag{26}\]

\[
H^{skd} = H^{skd} G_{1} H^{kd} \tag{24}\]

\[
R_{u}^{c} = \frac{E_{r}^c}{N} \tilde{H}^{skd} \tag{25}\]

\[
R_{u}^{c} = \frac{E_{r}^c}{N} \tilde{H}^{skd} + \sigma_{e}^2 \tilde{H}^{skd} (H^{kd})^H I_2 \tag{26}\]
and $I_M$ denotes an identity matrix of size $M$. In (26) $G_k^2$ denotes the square of each element of $G_k$; $\sigma^2$ and $\sigma^2_d$ are the noise variance at the intermediate nodes and the destination, respectively.

The total estimation MSE is defined as

$$E[\|\Delta_k\|^2] = \text{trace}(R_{\Delta k}^k) = \text{trace} \left\{ P - (R_k^k)H^WR_k^k + (W_k^k)H^WR_k^k W_k^k \right\}$$

(28)

where $\|\cdot\|^2$ denotes the Frobenius norm. Using the trace property and taking derivative of the trace of $R_{\Delta k}^k$ and then setting it equal to zero, i.e.

$$\frac{\partial \text{trace}(R_{\Delta k}^k)}{\partial (W_k^k)^H} = 0$$

(29)

we obtain the optimal weight matrix to estimate the transmit signal via the intermediate node $k$

$$W_k^k = (R_k^k)^{-1} R_k^c.$$  

(30)

Replacing (30) into (18) we have the error covariance matrix

$$R_{\Delta k}^k = P - (R_k^k)H^WR_k^k + (W_k^k)H^WR_k^k W_k^k$$

(31)

$$= \frac{E}{N} \left\{ I - (H_{add})_n^H w_k^k \right\},$$

(32)

The detection MSE at the receiver is given by

$$\text{MSE} = \text{trace}(R_{\Delta k}^k).$$

(33)

Then the MSE associated with $s_n$ transmitted via the $k$th relaying path is the $n$th element in the main diagonal of the error covariance matrix $R_{\Delta k}^k$, i.e.

$$\text{MSE}_n = \frac{E}{N} \left\{ 1 - (H_{add})_n^H w_k^k \right\},$$

(34)

where $(H_{add})_n^H$ is the $n$th column of $H_{add}$, and $w_k^k$ is the $n$th column of $W_k^k$. In fact, $\text{MSE}_n$ is the $n$th element in the main diagonal of the error covariance matrix $R_{\Delta k}^k$.

As there are two symbols $s_1$ and $s_2$ transmitted via the $k$th relaying path, the MSE associated with the path can be selected as

$$\text{MSE}_k = \max \{ \text{MSE}_1, \text{MSE}_2 \}.$$  

(35)

In order to use the selection equation (12), the CQI of the $k$th relaying path can be defined as $Q_k = 1/\text{MSE}_k$, which results in the min-max selection algorithm.

It is worth noting that compared with the other selection schemes, the MSE based requires larger computational complexity due to matrix inversion in computing the weight matrix $w_k^k$.

4. MMSE Combining

It is assumed that after the relay selection phase (Phase 1), a node $r$ has been selected as the relay to forward the received signal from the source to the destination. The receiver needs to use an effective detector (combiner) to combine received signals from the first and second time slot of Phase 2. In the previous cooperative communication systems, MRC has been proposed as a coherent combining scheme to obtain the maximum diversity order. However, for the MIMO-SDM cooperative system, MRC is no longer applicable due to the presence of co-channel interference among transmit streams. In order to cope with this problem, we propose a linear combining scheme based on the MMSE criterion. The MMSE combiner will serve jointly as the signal combiner and interference canceler. Moreover, as the linear MMSE combing was proposed to use in the point-to-point MIMO-SDM systems [2], it can be easily modified to adapt to the case of cooperative communications.

4.1 Combining Weight Matrix

Assuming that after Phase 1, a node $r$ has been successfully selected as the relay. The receiver will employ a linear combiner to combine the received signal from the direct and relaying path via relay $r$ as illustrated in Fig. 2. The principle of the linear combining is to use an weight matrix $W$ to combine the received signals during the two time slots $y_1$ and $y_2$ to estimate the transmitted signal vector $s$, i.e.

$$\hat{s} = W^H y.$$  

(36)

Using the MMSE method, $W$ should be designed such that the mean square error (MSE) between the transmitted signal and the estimated signal is minimized. This means that the combining weight matrix is the solution of the following cost function

$$W = \arg \min_W \mathbb{E} \left\{ \|s - W^H y\|^2 \right\}$$

(37)

Using the similar approach to obtain $W_k^k$, we start by calculating the error covariance matrix

$$R_{\Delta k}^k = [s - W^H y] [s - W^H y]^H$$

(38)

$$= s^H - W^H y s^H - s y^H W + W^H y y^H W.$$  

(39)

The total estimation MSE is given by

$$E[\|\Delta_k\|^2] = E\left\{ \text{trace}(R_{\Delta k}) \right\}$$

(40)
where each term is given as follows

\[
W^H E\{y y^H\} = W^H R_e,
\]

\[
E\{s s^H\} - W H E\{y^y\} - E\{s y^H\} W = W^H R_e W,
\]

(41)

where each term is given as follows

\[
W^H E\{y y^H\} = W^H R_e,
\]

\[
E\{s y^H\} W = R^H W,
\]

(42)

\[
W^H E\{y y^H\} W = W^H R_e W,
\]

(43)

\[
W^H E\{y y^H\} W = W^H R_e W,
\]

(44)

with

\[
R_e = \frac{E_s}{N} \begin{bmatrix} H^{sd} \\ N \end{bmatrix},
\]

(45)

\[
R_a = \begin{bmatrix} \frac{E_s}{N} H^{sd} (H^{sd})^H \\ 0 \end{bmatrix},
\]

(46)

\[
+ \begin{bmatrix} \sigma^2_1 I_2 \\ 0 \end{bmatrix} \begin{bmatrix} 0 \\ \sigma^2_2 H^{rd} G_2^2 (H^{rd})^H + \sigma^2_2 I_2 \end{bmatrix}.
\]

The closed form of \(R_a\) is given by (47) presented in the next page. This gives us

\[
E\{[\hat{\alpha}, \hat{\nu}]^2\} = \text{trace} \left\{ P - W^H R_e - R^H W + W^H R_e W \right\}.
\]

(48)

Similar to the above section, in order to find \(W\) we take the derivative of \(E\{[\hat{\alpha}, \hat{\nu}]^2\}\) with respect to \(W\) and set it to zero, i.e.

\[
\frac{\partial E\{[\hat{\alpha}, \hat{\nu}]^2\}}{\partial W^H} = 0.
\]

(49)

Using the trace derivative property to solve the above equality we have the final solution of \(W\) given by (51) presented in the next page. Note that (51) can be conveniently expressed as

\[
W = R_a^{-1} R_e.
\]

(50)

4.2 Estimation of weight matrix

From the above derived combining matrix we have the following important observations. First, in order to use the combining weight matrix as analyzed by (51), it is required that the destination know the channel matrices \(H^{sd}, H^{rd}\) and \(H^{rd}\). These can be easily estimated for \(H^{sd}\) and \(H^{rd}\) as there are direct links from the destination to the source and to the relay. The barrier lies in \(H^{rd} = H^{rd} G_r H^r\) as it is difficult for the destination to know the backward channel \(H^r\) and the amplifying matrix \(G_r\) which is also a function of the backward channel. However, based on our analysis in (50) we notice that in fact \(W = R_a^{-1} R_e\), where we recall here \(R_e = E\{yy^H\}\) and \(R_e = E\{y^H\}\). From this representation it is certain that the destination can easily estimate the signal covariance matrix \(R_e\) using the received signal vector \(y\). It is also possible to estimate the cross-correlation matrix \(R_e\) if \(s\) is known a priori. This can be done by making use of the training symbols similar those in the IEEE 802.11 standard [15],[16]. The difference is that the destination uses these pilot symbols to estimate the \(W\) to combine the cooperative signals from two time slots during the data period. Moreover, notice from (51) that the covariance matrix \(R_e\) can be expressed in the form

\[
R_e = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}^{-1}
\]

(52)

where \(A\) and \(B\) are two square matrices of size \(2 \times 2\). Therefore, we can apply the following matrix inverse property to \(R_e^{-1}\)

\[
\begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}^{-1} = \begin{bmatrix} A^{-1} & 0 \\ 0 & B^{-1} \end{bmatrix}.
\]

(53)

Then it can be shown easily from (51) that the weight matrix \(W\) can be decomposed into two component weight matrices \(W_1\) and \(W_2\) as

\[
W = \begin{bmatrix} W_1 \\ W_2 \end{bmatrix}.
\]

(54)

It is clear that

\[
W_2 = W^r
\]

(55)

\[
W_1 = \left[ \frac{E_s}{N} H^{rd} (H^{rd})^H + \sigma^2_2 H^{rd} G_2^2 (H^{rd})^H + \sigma^2_2 I_2 \right]^{-1} \frac{E_s}{N} H^{rd}
\]

(56)

is in fact the combining weight matrix for the relaying path as compared to (25), (26), and (30). It is also not difficult to prove that

\[
W_1 = \left[ \frac{E_s}{N} H^{rd} (H^{rd})^H + \sigma^2_2 I_2 \right]^{-1} \frac{E_s}{N} H^{rd}
\]

(57)

is the combining weight matrix for the direct path between the source and the destination. This decomposition is particularly important for the following reasons.

- Firstly, since the \(W_1\) and \(W_2\) can be computed independently instead of (51), it helps to reduce the complexity as the size of the matrix \(R_e\) to be inverted reduces by a half.
- In addition, when the relaying node is extended to multiple, i.e. there are multiple of relays, this decomposability allows to divide the problem of computing a complex combining weight matrix into multiple reduced ones. It is well known that the complexity of computing the MMSE combining matrix mainly depends on the complexity associated with inverting the covariance matrix \(R_e\) and is proportional to \((KN)^3\). Therefore, this decomposability allows to reduce the computational complexity by approximately \(K^3\) times.
Finally, as revealed from (51) that the combining matrix \( W = R^{-1} R_a \) depends only on the received signals and the pilot symbols, this combining weight can be extended to use for multiple-hop AF cooperative networks. Examples of this extension will be illustrated in the below section.

5. Performance Evaluation

5.1 Effect of selection scheme on BER performance

In order to evaluate performance of the proposed selection schemes, we have set up Monte-Carlo simulations in different scenarios. In the first scenario, simulation was performed for the case in which there are the source, the destination, and two intermediate nodes willing to serve as the relay. The two intermediate nodes are randomly generated between the source and the destination. The three selection schemes were invoked to select the best among the two nodes to relay the signal from the source to the destination. The channels between all nodes are assumed to undergo quasi-static flat Rayleigh fading. All nodes are assumed to use two antennas for both transmission and reception. This assumption realizes a 2 \( \times \) 2 MIMO-SDM cooperative network. It is also assumed that all nodes use BPSK for modulation and transmit at the same symbol energy of \( E_s \). The noise at the intermediate nodes and the destination are assumed independent and identically distributed (i.i.d.) with the same variance \( \sigma_n^2 = \sigma_d^2 = N_0/2 \). At the receiver, the proposed MMSE combiner is used to estimate the transmitted signal. It is assumed that the receiver has perfect knowledge (perfect CSI) of all the channel matrices \( H^{sd}, H^{sr}, \) and \( H^{rd} \) to compute the weight matrix \( W \) based on (51).

Figure 3 compares BER performance of the three selection schemes. As a reference BER performance of the case without using cooperative communications (i.e. only direct communication between the source and the destination) and the case of the two-branch Alamouti space-time block code (STBC) [17] are also shown in the figure for comparison. It can be clearly realized from the figure that cooperation with a relay improves the BER performance significantly. Particularly, at the region of high \( E_b/N_0 \), it can achieve up to 10dB gain compared with the case without using cooperation. It can also be seen that among the three schemes the MSE based provides the best performance, while the norm based exhibits the worst. The performance difference between the MSE based and the norm based is about 2.5dB at BER = \( 10^{-4} \). Comparing with the case of 2 \( \times \) 1 Alamouti STBC, we can see that the MSE selection provides similar performance. This means that the MSE selection scheme also allows the cooperative communication system to achieve diversity order two. Since the cooperative communication system contains of one relaying and one direct path, it is equivalent to a two-node spatial diversity and thus has the maximum diversity order two. This leads us to the conclusion that the proposed MSE selection scheme with the MMSE combining allows to achieve maximum diversity gain. Therefore, the MIMO-SDM cooperative communication system can provide the best trade-off between multiplexing gain and diversity gain. In fact, it can provide the maximum order of two in terms of both multiplexing and diversity gain.

In the second scenario, we evaluate the system BER performance when increasing the number of candidate nodes to select the relay. Figure 4 illustrates BER versus the number of candidate nodes for the same system parameters of the first scenario. The BER curves were plotted for two \( E_b/N_0 \) values of 10dB and 20dB. It is interesting to note that increasing the number of candidate nodes from 2 to 6 does not help to improve the BER performance. This observation can be explained by using the fact that communication
via the relaying path is done using a $2 \times 2$ MIMO-SDM and thus there always exists interference between the two transmit streams. Therefore, selecting a better relay from a larger group of intermediate nodes helps to improve signal energy for one stream but in contrast also increases interference level to the other. In order to clarify this explanation let us consider the signal to interference plus noise ratio (SINR) at the input of the detector. Without loss of generality, assume that the MMSE detector needs to estimate $s_1$ under the presence of $s_2$. As explained above this is done by combining the signals from the direct and relaying path. Denote the average power of $s_1$ via the direct and relaying path as $P_1^d$ and $P_1^r$, respectively. Similarly, let $P_2^d$ and $P_2^r$ be the average power of $s_2$, and $P_z$ the noise power at the receiver. The SINR$_1$ associated with $s_1$ at the input of the detector is given by

$$
\text{SINR}_1 = \frac{P_1^d + P_1^r}{P_2^d + P_2^r + P_z}.
$$

Now assume that we can select a better relay. This means that we will have large values of $P_1^d$ and $P_2^r$. Since the signal power is much larger than the noise power, it can be realized from (58) that the SINR$_1$ remains almost unchanged. Since BER is a function of the input SINR, it is clear that the BER performance is not improved significantly. Consequently, the overall BER performance is not benefited from increasing the candidate selection group size as opposed to the case of the conventional single-antenna relay cooperative networks. This effect is similar to the case of increasing the number of antennas in the MIMO-SDM systems. For example, a $4 \times 4$ MIMO-SDM system does improve the BER performance compared with a $2 \times 2$ system, but only doubles multiplexing gain. The difference in BER performance between the three selection schemes is also observed from the figure at $E_b/N_0 = 20$ dB. It is also noted from the figure that the MSE selection exhibits slightly fluctuated BER at $E_b/N_0 = 20$ dB when changing the number of candidate nodes.

5.2 Effect of weight matrix estimation error on BER performance

In the next experiment, we evaluate performance of the MMSE combiner using the estimated weight matrix based on $R_{\phi} = E\{yy^H\}$, and $R_{\phi} = E\{yp^H\}$ for the case the training vector $p$ contains 16 bit and 8 bit pilot sequence, respectively. In the simulations, each transmit stream contains a pilot bit sequence $p(n)$ which is randomly generated and modulated using BPSK. In this simulation scenario we assume that there is only one candidate node to serve as the relay. This assumption aims to ignore the effect of the selection schemes on the combiner performance. Figure 5 shows the BER performance of the MMSE combiner for different pilot lengths.

In the next simulation, we prove the third property of the weight matrix decomposability, i.e. extension of the combiner to the case of the AF multiple-hop cooperative system. The number of relaying hops is increased to demonstrate the capability of our proposed combiner. The training sequence has 16 pilot bits. Figure 6 illustrates the BER performance.
The proposed MMSE combiner was demonstrated to be de-
erative networks increasing the number of candidate nodes
than the other norm based and the channel harmonic mean
eration scheme was shown to exhibit better BER performance
scheme outperforms the conventional transmission scheme significantly. It is clear
mission efficiency is reduced to a half. In addition, the co-
operative communication also utilizes another time period
(Phase 1) for relay selection. This would further decrease
mission efficiency. The length of this period is not
fixed but mainly dependent on the number of nodes and the
distance between network nodes as well. As a result, the
use of the cooperative communication is recommended for
the case which is possible to sacrifice the transmission efficiency for the improvement in the BER performance.

5.3 Performance versus efficiency

In Sect. 5.1 we have seen that the cooperative communication using the three relay selection schemes outperforms the conventional transmission scheme significantly. It is clear that this improvement is achieved under the fact that the cooperative communication utilizes two time slots for transmission to achieve the diversity order two. However, this improvement would lead to the reduction in transmission efficiency. By using two time slots this means that the transmission efficiency is reduced to a half. In addition, the cooperative communication also utilizes another time period (Phase 1) for relay selection. This would further decrease the transmission efficiency. The length of this period is not fixed but mainly dependent on the number of nodes and the distance between network nodes as well. As a result, the use of the cooperative communication is recommended for the case which is possible to sacrifice the transmission efficiency for the improvement in the BER performance.

6. Conclusions

In this paper, we have proposed three relay selection schemes and an MMSE combiner for MIMO-SDM cooperative communications. The proposed MSE based selection scheme was shown to exhibit better BER performance than the other norm based and the channel harmonic mean based. It was also shown that in the MIMO-SDM cooperative networks increasing the number of candidate nodes does not help to improve the BER performance as opposed to the case of the conventional single-antenna relay system. The proposed MMSE combiner was demonstrated to be decomposed into separate combiners for the direct and the relaying path, which facilitates its implementation in hardware. The proposed implementation of the combiner based on 16 bit pilot transmission exhibits similar performance with the case of perfect CSI and is easy to integrate into the IEEE802.11n standard. Finally, the proposed MSE based selection scheme together with the MMSE combiner was demonstrated to achieve full diversity of order two. Therefore, the proposed cooperative communication system will achieve both maximum multiplexing and diversity gain.

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References


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