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Performance analysis of two-way DF relay selection techniques☆

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Abstract

This work proposes novel bi-directional dual-relay selection techniques based on Alamouti space-time block coding (STBC) using the decode and forward (DF) protocol and analyzes their performance. In the proposed techniques, two- and the three-phase relaying schemes are used to perform bi-directional communication between the communicating terminals via two selected single-antenna relays that employ the Alamouti STBC in a distributed fashion to achieve diversity and orthogonalization of the channels and hence improve the reliability of the system and enable the use of a symbol-wise detector. Furthermore, the network coding strategy applied at all relays is not associated with any power wastage for broadcasting data already known at any terminal, resulting in improved overall performance at the terminals. Our simulations confirm the analytical results and show a substantially improved bit error rate (BER) performance of our proposed techniques compared with the current state of the art.

Keywords: Two way relay networks; Relay selection; Distributed STBC; Cooperative diversity; Digital network coding

1. Introduction

One- and two-way relaying schemes have extensively been considered to enhance the reliability and throughput of relay networks and to overcome channel impairments [1–5]. Using conventional techniques, the relays transmit the received vectors on orthogonal channels or encode them using either an orthogonal code, e.g. STBC [6], to achieve full diversity gain with low decoding complexity or a non-orthogonal code that suffers from a high decoding complexity. Instead of using the latter technique, relay selection for non-orthogonal relay networks can be applied [7–11] to achieve full spatial diversity gain with low decoding complexity.

In [7–11] – and references therein – several powerful single- and dual-relay selection strategies are introduced. Some approaches select a single relay among several relays according to either the optimal SNR or the achievable data rate [8,9]. Others select one or two relays based on a specific criterion, e.g. the max–min or the double-max criterion [8]. Recently, the idea of the hybrid selection criterion was introduced in [7]. It has been proved that dual-relay selection strategies outperform the single-relay ones [8]. In this paper, we have proved through simulations and analytical results that the proposed techniques using two- and three-phase schemes outperform the state of the art two- and three-phase techniques. Moreover, we have shown that the simulated performance of the proposed scheme in terms of BER is very close to the theoretical one.

2. System model

Let us consider a half-duplex relay network comprising two single-antenna terminals $\mathcal{T}_1$ and $\mathcal{T}_2$ that exchange their messages via two relays selected from R single-antenna nodes $(\mathcal{R}_1, \ldots, \mathcal{R}_R)$ as shown in Fig. 1. The nodes $\mathcal{T}_1$, $\mathcal{T}_2$, $\mathcal{R}_1, \ldots, \mathcal{R}_R$ have limited average transmit powers $P_{\mathcal{T}_1}$, $P_{\mathcal{T}_2}$, $P_{\mathcal{R}_1}, \ldots, P_{\mathcal{R}_R}$, respectively. We denote the channels, which are assumed to be reciprocal for transmissions from the relays to the terminals and vice versa, from $\mathcal{T}_1$ to $\mathcal{R}_r$ and from $\mathcal{T}_2$ to $\mathcal{R}_r$ as f_r and g_r, respectively. Throughout this paper, $|\cdot|$, $\lfloor\cdot\rfloor$, $(\cdot)^*$, $\mathrm{mod}(a,b)$, $\|\cdot\|$, $[\mathbf{a}]_i$, $\mathbf{I}_T$, σ^2, and $\mathrm{E}\{\cdot\}$ stand for the absolute value, the floor function which rounds toward zero, the complex conjugate, the remainder of the division of a by b, the Frobenius norm, the ith element of a vector $\mathbf{a}$, the $T \times T$ identity matrix, the noise variance, and the statistical expectation, respectively.

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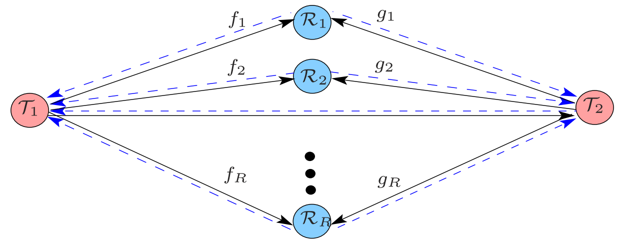


Fig. 1. Two-way relay network.

3. Two-phase two-way DF relay selection

In this scheme, both terminals exchange their symbols in two phases. During the first phase from time-slot 1 to T, $\mathcal{T}_1$ and $\mathcal{T}_2$ simultaneously send their $T \times 1$ vectors $\mathbf{s}_{\mathcal{T}_1}$ and $\mathbf{s}_{\mathcal{T}_2}$, respectively, to the relays, so that the received vector at $\mathcal{R}_r$ is

$$\mathbf{y}_{\mathcal{R},r} = \sqrt{2P_{\mathcal{T}_1}}\ f_r \mathbf{s}_{\mathcal{T}_1} + \sqrt{2P_{\mathcal{T}_2}} g_r \mathbf{s}_{\mathcal{T}_2} + \mathbf{n}_{\mathcal{R},r} \tag{1}$$

where $[\mathbf{s}_{\mathcal{T}_1}]_i \in \mathcal{S}_{\mathcal{T}_1}$, $[\mathbf{s}_{\mathcal{T}_2}]_i \in \mathcal{S}_{\mathcal{T}_2}$, $\mathrm{E}\left\{|[\mathbf{s}_{\mathcal{T}_1}]_i|^2\right\} = 1$, $\mathrm{E}\left\{|[\mathbf{s}_{\mathcal{T}_2}]_i|^2\right\} = 1$, $\mathcal{S}_{\mathcal{T}_1}$ and $\mathcal{S}_{\mathcal{T}_2}$ are two, possibly different, constellations, and $\mathbf{n}_{\mathcal{R},r}$ stands for the relay noise vector in the first phase. During the second phase, the received symbols of the terminals are detected at $\mathcal{R}_r$ using the following maximum likelihood (ML) detector

$$\arg\min_{\mathbf{s}_{\mathcal{T}_1},\mathbf{s}_{\mathcal{T}_2}} \left\| \mathbf{y}_{\mathcal{R},r} - \left(\sqrt{2P_{\mathcal{T}_1}} f_r \mathbf{s}_{\mathcal{T}_1} + \sqrt{2P_{\mathcal{T}_2}} g_r \mathbf{s}_{\mathcal{T}_2} \right) \right\|. \tag{2}$$

In order not to waste power transmitting known information to the destination terminals, $\mathcal{R}_r$ combines the detected symbol vectors of both terminals, $\tilde{\mathbf{s}}_{\mathcal{T}_1,r}$ and $\tilde{\mathbf{s}}_{\mathcal{T}_2,r}$, in a single vector of the same constellation, given by

$$\mathbf{s}_{\mathcal{R},r} = \mathcal{F}(\tilde{\mathbf{s}}_{\mathcal{T}_1,r}, \tilde{\mathbf{s}}_{\mathcal{T}_2,r}) \tag{3}$$

where $\mathcal{F}(\cdot,\cdot)$ stands for a combination function. Recently, several combination functions have been proposed to combine the symbols, e.g., modular arithmetic (MA) [2,12]–and references therein. Note that $\mathbf{s}_{\mathcal{R},r} \in \mathcal{S}_{\mathcal{R}}$ where $\mathcal{S}_{\mathcal{R}}$ stands for the constellation of the transmitted symbols from the relays and $|\mathcal{S}_{\mathcal{R}}| = \max\{|\mathcal{S}_{\mathcal{T}_1}|, |\mathcal{S}_{\mathcal{T}_2}|\}$. We denote the jth entry s of a constellation $\mathcal{S}$ as $\mathcal{S}(j)$ where $j \in \{0, 1, \dots, |\mathcal{S}| - 1\}$ and the inverse as $\mathcal{S}^{-1}(s) = j$. Let us define $\mathbf{k}_{\mathcal{T}_1}$ and $\mathbf{k}_{\mathcal{T}_2}$ such that $\mathcal{S}_{\mathcal{T}_1}(\mathbf{k}_{\mathcal{T}_1}) = \mathbf{s}_{\mathcal{T}_1}$ and $\mathcal{S}_{\mathcal{T}_2}(\mathbf{k}_{\mathcal{T}_2}) = \mathbf{s}_{\mathcal{T}_2}$; the MA function is defined as $\mathcal{F}_{\mathrm{m}}(\mathbf{s}_{\mathcal{T}_1}, \mathbf{s}_{\mathcal{T}_2}) = \mathcal{S}_{\mathcal{R}}(\mathrm{mod}(\mathcal{S}_{\mathcal{T}_1}^{-1}(\mathbf{s}_{\mathcal{T}_1}) + \mathcal{S}_{\mathcal{T}_2}^{-1}(\mathbf{s}_{\mathcal{T}_2}), |\mathcal{S}_{\mathcal{R}}|)) = \mathcal{S}_{\mathcal{R}}(\mathrm{mod}(\mathbf{k}_{\mathcal{T}_1} + \mathbf{k}_{\mathcal{T}_2}, |\mathcal{S}_{\mathcal{R}}|))$. The XOR function explained in [1] and the combination function proposed in [2] can also be used to compute the superimposed symbol. Let us now consider that the proposed technique selects two relays, the mth relay $\mathcal{R}_m$ and the nth relay $\mathcal{R}_n$ among all relays based on the following *hybrid* selection criteria

$$m = \arg\max_{m} \min(|f_m|, |g_m|), \tag{4}$$

$$n = \begin{cases} \arg\max_{n}(|g_n|), & |f_m| > |g_m| \\ \arg\max_{n}(|f_n|), & |f_m| < |g_m| \end{cases}. \tag{5}$$

We note that the proposed technique selects $\mathcal{R}_m$ and $\mathcal{R}_n$ based on the max–min selection criterion and max selection criterion, respectively. The first selected relay is optimal in the directions of both terminals [9] and is a good one in at least one direction, while the second selected relay is the best relay in the other direction. In case of a small number of relays, m could be equal to n, in which a single relay is selected to forward the received signals. For the sake of simplicity, in the following we consider $T = 2$ and the signals received at $\mathcal{T}_2$. The received signal at $\mathcal{T}_1$ can be recovered correspondingly. In the second phase, $\mathcal{R}_m$ and $\mathcal{R}_n$ precode $\mathbf{s}_{\mathcal{R},m}$ and $(\mathbf{s}_{\mathcal{R},n})^*$, respectively with the following 2×2 Alamouti STBC matrices

$$\mathbf{A}_m = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \mathbf{A}_n = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \tag{6}$$

$$\check{\mathbf{s}}_{\mathcal{R},m} = \mathbf{s}_{\mathcal{R},m}, \qquad \check{\mathbf{s}}_{\mathcal{R},n} = (\mathbf{s}_{\mathcal{R},n})^* \tag{7}$$

before forwarding the resulting vector to both terminals, such that the received signal vector at $\mathcal{T}_2$ is

$$\mathbf{y}_{\mathcal{T}_2} = \sqrt{P_{\mathcal{R}_m}} g_m \mathbf{A}_m \check{\mathbf{s}}_{\mathcal{R},m} + \sqrt{P_{\mathcal{R}_n}} g_n \mathbf{A}_n \check{\mathbf{s}}_{\mathcal{R},n} + \mathbf{n}_{\mathcal{T}_2} \tag{8}$$

where $\mathbf{n}_{\mathcal{T}_2}$ denotes the noise vector at $\mathcal{T}_2$. The ML detector at $\mathcal{T}_2$ can be approximated by assuming error free decoding at the relays, i.e., $\mathbf{s}_{\mathcal{R},m} = \mathbf{s}_{\mathcal{R},n} = \mathbf{s}_{\mathcal{R}}$, such that

$$\hat{\mathbf{s}}_{\mathcal{R},\mathcal{T}_2} = \arg\min_{\mathbf{s}_{\mathcal{R}}} \left\| \mathbf{y}_{\mathcal{T}_2} - \sum_{r=\{m,n\}} \sqrt{P_{\mathcal{R}_r}} g_r \mathbf{A}_r \check{\mathbf{s}}_{\mathcal{R}} \right\|. \tag{9}$$

The detector of $\mathcal{T}_2$ recovers the vector $\hat{\mathbf{s}}_{\mathcal{T}_1}$ using the knowledge of its own transmitted vector and the inverse of $\mathcal{F}$ (denoted as $\mathcal{F}^{-1}$), i.e., $\hat{\mathbf{s}}_{\mathcal{T}_1} = \mathcal{F}^{-1}(\hat{\mathbf{s}}_{\mathcal{R},\mathcal{T}_2}, \mathbf{s}_{\mathcal{T}_2})$. In the case of using the MA function as a combination function, $\hat{\mathbf{k}}_{\mathcal{R},\mathcal{T}_2}$ is defined such that $\mathcal{S}_{\mathcal{R}}(\hat{\mathbf{k}}_{\mathcal{R},\mathcal{T}_2}) = \hat{\mathbf{s}}_{\mathcal{R},\mathcal{T}_2}$, then $\mathcal{T}_2$ recovers the symbol vector of $\mathcal{T}_1$ using $\hat{\mathbf{s}}_{\mathcal{T}_1} = \mathcal{F}_{\mathrm{m}}^{-1}(\hat{\mathbf{s}}_{\mathcal{R},\mathcal{T}_2}, \mathbf{s}_{\mathcal{T}_2}) = \mathcal{S}_{\mathcal{T}_1}(\mathrm{mod}(\hat{\mathbf{k}}_{\mathcal{R},\mathcal{T}_2} - \mathbf{k}_{\mathcal{T}_2}, |\mathcal{S}_{\mathcal{T}_1}|))$ where $\mathcal{F}_{\mathrm{m}}^{-1}$ denotes the inverse of the MA function.

4. Three-phase two-way df relay selection

In the three-phase two-way relaying scheme, the communicating terminals exchange their symbols in three phases. In the first and second phase from 1 to T and from $T+1$ to $2T$, $\mathcal{T}_1$ and $\mathcal{T}_2$ forward their $T \times 1$ symbol vectors $\mathbf{s}_{\mathcal{T}_1}$ and $\mathbf{s}_{\mathcal{T}_2}$, respectively, $\mathcal{R}_r$ receives the following $T \times 1$ vectors

$$\mathbf{y}_{\mathcal{R}_1,r} = \sqrt{3P_{\mathcal{T}_1}}\ f_r\ \mathbf{s}_{\mathcal{T}_1} + \mathbf{n}_{\mathcal{R}_1,r} \tag{10}$$

$$\mathbf{y}_{\mathcal{R}_2,r} = \sqrt{3P_{\mathcal{T}_2}}\ g_r\ \mathbf{s}_{\mathcal{T}_2} + \mathbf{n}_{\mathcal{R}_2,r} \tag{11}$$

where $\mathbf{n}_{\mathcal{R}_1,r}$ and $\mathbf{n}_{\mathcal{R}_2,r}$ stand for the $T \times 1$ noise vectors at $\mathcal{R}_r$ during the first and the second phase, respectively. Similar to Section 3, the received symbols of $\mathcal{T}_1$ and $\mathcal{T}_2$ are detected at $\mathcal{R}_r$ by making use of (10) and (11), such that

$$\hat{\mathbf{s}}_{\mathcal{T}_1,r} = \operatorname{argmin}_{\mathbf{s}_{\mathcal{T}_1}} \left\| \mathbf{y}_{\mathcal{R}_1,r} - \sqrt{3P_{\mathcal{T}_1}} f_r \mathbf{s}_{\mathcal{T}_1} \right\|, \tag{12}$$

$$\hat{\mathbf{s}}_{\mathcal{T}_2,r} = \operatorname{argmin}_{\mathbf{s}_{\mathcal{T}_2}} \left\| \mathbf{y}_{\mathcal{R}_2,r} - \sqrt{3P_{\mathcal{T}_2}} g_r \mathbf{s}_{\mathcal{T}_2} \right\|. \tag{13}$$

From (12) and (13), we note that a symbol-wise detector with linear decoding complexity is used to detect the received vectors at the relays, while the use of the two-phase scheme explained in Section 3 increases the decoding complexity of the decoder quadratically with the increase of the constellation size. Similarly as in Section 3, $\mathcal{R}_r$ combines $\tilde{\mathbf{s}}_{\mathcal{T}_1,r}$ and $\tilde{\mathbf{s}}_{\mathcal{T}_2,r}$ in a single vector using (3). Two relays, $\mathcal{R}_m$ and $\mathcal{R}_n$ are then selected based on the proposed *hybrid* selection criterion defined in (4) and (5). The selected relays, $\mathcal{R}_m$ and $\mathcal{R}_n$ precode $\mathbf{s}_{\mathcal{R},m}$ and $(\mathbf{s}_{\mathcal{R},n})^*$ defined in (3), respectively, with the 2×2 Alamouti STBC matrices $\mathbf{A}_m$ and $\mathbf{A}_n$ given in (6) before forwarding the combined vector to $\mathcal{T}_1$ and $\mathcal{T}_2$ in the third phase from $2T+1$ to $3T$, so that $\mathcal{T}_2$ receives

$$\mathbf{y}_{\mathcal{T}_2} = \sqrt{P_{\mathcal{R}_m}} g_m \mathbf{A}_m \mathbf{s}_{\mathcal{R},m} + \sqrt{P_{\mathcal{R}_n}} g_n \mathbf{A}_n (\mathbf{s}_{\mathcal{R},n})^* + \mathbf{n}_{\mathcal{T}_2} \tag{14}$$

where $\mathbf{n}_{\mathcal{T}_2}$ denotes the noise vector at $\mathcal{T}_2$ in the third phase. Similarly as in Section 3, the ML detector in (9) can be used to detect the symbols at $\mathcal{T}_2$. Note that $\mathcal{T}_2$ can also use a symbol-wise detector to recover the received vector instead of using the ML detector in (9). To recover the vector $\hat{\mathbf{s}}_{\mathcal{T}_1}$, $\mathcal{T}_2$ utilizes the inverse of the combination function $\mathcal{F}^{-1}$ and its own transmitted symbol $\mathbf{s}_{\mathcal{T}_2}$, i.e., $\hat{\mathbf{s}}_{\mathcal{T}_1} = \mathcal{F}^{-1}(\hat{\mathbf{s}}_{\mathcal{R},\mathcal{T}_2}, \mathbf{s}_{\mathcal{T}_2})$.

5. BER performance analysis

In this section, we consider the theoretical BER performance of the proposed techniques using BPSK modulation based on the assumptions in Section 2 and considering ideal relays similarly as in [2,8]. In the case of ideal relays, the two- and the three-phase relaying schemes have similar BER performance. In general, let us consider that the noise vectors in this paper are modeled as spatially, independently, identically, and normally distributed complex circular random variables with zero mean and covariance $\sigma^2 \mathbf{I}_T$ and the proposed selection criterion defined in (4) selects the nth and mth relay with $P_{\mathcal{R}_n} = P_{\mathcal{R}_m} = P_{\mathcal{R}}$. Let sort $\gamma_r^{\mathcal{T}_t}$, $r = 1, \ldots, R$, $t = 1, 2$ in ascending order, such that $\gamma_1^{\mathcal{T}_t} \leq \gamma_2^{\mathcal{T}_t} \leq \cdots \leq \gamma_R^{\mathcal{T}_t}$ and define $w_1^{\mathcal{T}_t} = \gamma_1^{\mathcal{T}_t}$ and $w_l^{\mathcal{T}_t} = \gamma_l^{\mathcal{T}_t} - \gamma_{(l-1)}^{\mathcal{T}_t}$ for $l = 2, \ldots, R$ where $\gamma_r^{\mathcal{T}_1} = \gamma |f_r|^2$, $\gamma_r^{\mathcal{T}_2} = \gamma |g_r|^2$, and $\gamma = P_{\mathcal{R}}/\sigma^2$ denote the received SNR in the link from $\mathcal{R}_r$ to $\mathcal{T}_1$, the received SNR in the link from $\mathcal{R}_r$ to $\mathcal{T}_2$, and the average transmitted SNR at $\mathcal{R}_r$, respectively. The probability distribution function (pdf) of the independent coefficients w_l for $l = 1, \ldots, R$ is given by [8,9]

$$f_{w_l}(w_l) = \frac{R-l-1}{\gamma} \exp\left(-\frac{R-l-1}{\gamma} w_l\right). \tag{15}$$

Let us assume that $\mathcal{R}_n$ is selected according to the max criterion defined in (4) and (5) where g_n and f_n stand for the channel between $\mathcal{R}_n$ and $\mathcal{T}_2$ with $\gamma_R^{\mathcal{T}_2}$ and the channel between $\mathcal{R}_n$ and $\mathcal{T}_1$ with $\gamma_{u_2}^{\mathcal{T}_1}$, respectively, and u_2 could be any uth, i.e., $u = 1, \ldots, R$. $\mathcal{R}_m$ is selected according to the max–min criterion defined in (4) where g_m and f_m denote the channel between $\mathcal{R}_m$ and $\mathcal{T}_2$ with $\gamma_{\lfloor R/2 \rfloor}^{\mathcal{T}_2}$ and the channel between $\mathcal{R}_n$ and $\mathcal{T}_1$ with $\gamma_{u_1}^{\mathcal{T}_1}$ where $\gamma_{u_1}^{\mathcal{T}_1} \geq \gamma_{\lfloor R/2 \rfloor}^{\mathcal{T}_2}$. The average BER for the proposed dual-relay selection technique is expressed as

$$P(\gamma) = \frac{1}{2} \mathrm{E}\left\{ Q\left(\sqrt{\gamma_{\lfloor R/2 \rfloor}^{\mathcal{T}_2} + \gamma_R^{\mathcal{T}_2}}\right) + Q\left(\sqrt{\gamma_{u_1}^{\mathcal{T}_1} + \gamma_{u_2}^{\mathcal{T}_1}}\right)\right\}. \tag{16}$$

The first term T_1 of (16) can be calculated using the moment-generation function (MGF) of $Q_1 = \gamma_{\lfloor R/2 \rfloor}^{\mathcal{T}_2} + \gamma_R^{\mathcal{T}_2}$, such that

$$\begin{aligned} Q_1 = \gamma_{\lfloor R/2 \rfloor}^{\mathcal{T}_2} + \gamma_R^{\mathcal{T}_2} &= \sum_{i=1}^{\lfloor R/2 \rfloor} w_i + \sum_{i=1}^{R} w_i \\ &= 2 \sum_{i=1}^{\lfloor R/2 \rfloor} w_i + \sum_{i=\lfloor R/2 \rfloor + 1}^{R} w_i. \end{aligned} \tag{17}$$

The MGF of Q_1 is expressed as [8,13]

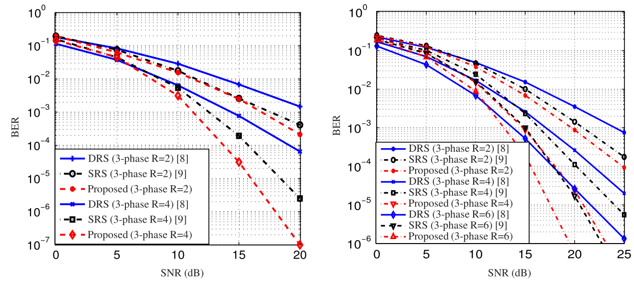
$$\begin{aligned} M_{Q_1}(s) &= \int_0^\infty \cdots \int_0^\infty \left(\prod_{i=1}^{R} f_{w_i}(w_i)\right) \exp(sQ_1) dw_1 \cdots dw_R \\ &= \prod_{i=1}^{\lfloor R/2 \rfloor} \int_0^\infty f_{w_i}(w_i) \exp(2sw_i) dw_i \\ &\quad \times \prod_{i=\lfloor R/2 \rfloor+1}^{R} \int_0^\infty f_{w_i}(w_i) \exp(sw_i) dw_i \\ &= \frac{R!(-1)^R}{2^{\lfloor R/2 \rfloor} \gamma^R} \prod_{i=1}^{\lfloor R/2 \rfloor} \frac{1}{s - \frac{R-i+1}{2\gamma}} \prod_{i=\lfloor R/2 \rfloor+1}^{R} \frac{1}{s - \frac{R-i+1}{\gamma}}. \end{aligned} \tag{18}$$

Making use of partial fraction expansion, (18) can be rewritten as

$$\begin{aligned} M_{Q_1}(s) &= \frac{R!(-1)^R}{2^{\lfloor R/2 \rfloor} \gamma^R} \\ &\quad \times \sum_{i=1}^{\lfloor R/2 \rfloor} \frac{1}{\left(s - \frac{R-i+1}{2\gamma}\right) \prod_{\substack{j=1 \\ j \neq i}}^{\lfloor R/2 \rfloor} \left(\frac{R-i+1}{2\gamma} - \frac{R-j+1}{2\gamma}\right)} \\ &\quad \times \sum_{p=\lfloor R/2 \rfloor+1}^{R} \frac{1}{\left(s - \frac{R-p+1}{\gamma}\right) \prod_{\substack{r=\lfloor R/2 \rfloor+1 \\ j \neq p}}^{R} \left(\frac{R-p+1}{\gamma} - \frac{R-r+1}{\gamma}\right)} \\ &= \frac{R!(-1)^R}{2\gamma^2} \sum_{i=1}^{\lfloor R/2 \rfloor} \sum_{p=\lfloor R/2 \rfloor+1}^{R} \frac{1}{\prod_{\substack{j=1 \\ j \neq i}}^{\lfloor R/2 \rfloor} (j-i) \prod_{\substack{r=\lfloor R/2 \rfloor+1 \\ r \neq p}}^{R} (r-p)} \\ &\quad \times \frac{1}{\left(s - \frac{R-i+1}{2\gamma}\right)\left(s - \frac{R-p+1}{\gamma}\right)}. \end{aligned} \tag{19}$$

The first term T_1 is given using the MGF by [8,13]

$$T_1 = \frac{1}{2\pi} \int_0^{\pi/2} M_{Q_1}\left(\frac{-1}{2\sin^2(\phi)}\right) d\phi. \tag{20}$$



(a) 4-QAM modulation. (b) 8-QAM modulation.

Fig. 2. BER versus SNR for several three-phase single and dual relay selection schemes with $R = 2$, $R = 4$ and $R = 6$.

Substituting (19) in (20), the first term T_1 can be expressed as

$$T_1 = \frac{R!(-1)^R}{4\gamma^2} \sum_{i=1}^{\lfloor R/2 \rfloor} \sum_{p=\lfloor R/2 \rfloor+1}^{R} \frac{1}{\prod_{\substack{j=1\\ j\neq i}}^{\lfloor R/2 \rfloor} (j-i) \prod_{\substack{r=\lfloor R/2 \rfloor+1\\ r\neq p}}^{R} (r-p)} \times \frac{1}{\pi} \int_0^{\pi/2} \frac{1}{\left(\frac{1}{2\sin^2(\phi)} + \frac{R-i+1}{2\gamma}\right)\left(\frac{1}{2\sin^2(\phi)} + \frac{R-p+1}{\gamma}\right)} d\phi. \tag{21}$$

Similar to the first term T_1 of (16) and assuming that $u_1 \geq u_2$, the second term T_2 can also be calculated using the MGF of $Q_2 = \gamma_{u_1}^{\mathcal{T}_1} + \gamma_{u_2}^{\mathcal{T}_1}$, such that

$$Q_2 = \gamma_{u_1}^{\mathcal{T}_1} + \gamma_{u_2}^{\mathcal{T}_1} = \sum_{i=1}^{u_1} w_i + \sum_{i=1}^{u_2} w_i = 2\sum_{i=1}^{u_2} w_i + \sum_{i=u_2+1}^{u_1} w_i. \tag{22}$$

The MGF of Q_2 is expressed as

$$M_{Q_2}(s) = \prod_{i=1}^{u_2} \int_0^{\infty} f_{w_i}(w_i) \exp(2sw_i) dw_i \times \prod_{i=u_2+1}^{u_1} \int_0^{\infty} f_{w_i}(w_i) \exp(sw_i) dw_i. \tag{23}$$

Similar to (18), (23) can be rewritten as

$$M_{Q_2}(s) = \frac{u_1!(-1)^{u_1}}{2\gamma^2} \sum_{i=1}^{u_2} \sum_{p=u_2+1}^{u_1} \frac{1}{\prod_{\substack{j=1\\ j\neq i}}^{u_2} (j-i) \prod_{\substack{r=u_2+1\\ r\neq p}}^{u_1} (r-p)} \times \frac{1}{\left(s - \frac{u_1-i+1}{2\gamma}\right)\left(s - \frac{u_1-p+1}{\gamma}\right)}. \tag{24}$$

Similar to (20), T_2 is given using the MGF by

$$T_2 = \frac{1}{2\pi} \int_0^{\pi/2} M_{Q_2}\left(\frac{-1}{2\sin^2(\phi)}\right) d\phi. \tag{25}$$

Substituting (24) in (25), T_2 can be expressed as

$$T_2 = \frac{u_1!(-1)^{u_1}}{4\gamma^2} \sum_{i=1}^{u_2} \sum_{p=u_2+1}^{u_1} \frac{1}{\prod_{\substack{j=1\\ j\neq i}}^{u_2} (j-i) \prod_{\substack{r=u_2+1\\ r\neq p}}^{u_1} (r-p)} \frac{1}{\pi} \times \int_0^{\pi/2} \frac{1}{\left(\frac{1}{2\sin^2(\phi)} + \frac{u_1-i+1}{2\gamma}\right)\left(\frac{1}{2\sin^2(\phi)} + \frac{u_1-p+1}{\gamma}\right)} d\phi. \tag{26}$$

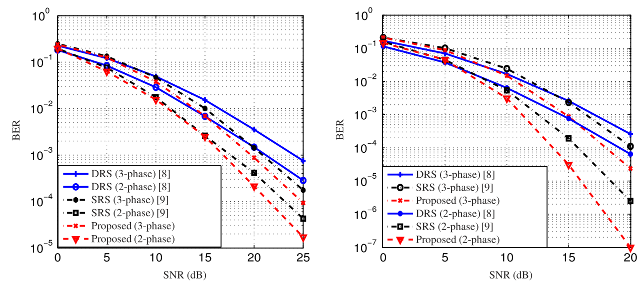
Substituting (21) and (26) in (16), the average BER for the proposed technique is given by

$$P(\gamma) = T_1 + T_2. \tag{27}$$

6. Simulation results

Throughout our simulations, we consider a two-way relay network comprising two terminals that exchange their information via two relays selected from $R = \{2, 4, 6\}$ single-antenna relays with a power distribution equal to $P_{\mathcal{T}_1} = P_{\mathcal{T}_2} = \sum_{r=m,n} P_{\mathcal{R}_r}$. To compare the BER performance of the proposed and the state of the art techniques, the same total transmitted power i.e., $P_{\mathcal{T}} = P_{\mathcal{T}_1} + P_{\mathcal{T}_2} + \sum_{r=m,n} P_{\mathcal{R}_r}$ where $P_{\mathcal{R}_m} = P_{\mathcal{R}_n}$, and transmission rate are used. The abbreviations "SRS", "DRS", "2-phase", "3-phase", and "Proposed" stand for the single-relay selection technique proposed in [9], the dual-relay selection technique proposed in [8], the use of the two-phase strategy, the use of the three-phase strategy, and the proposed technique, respectively. In Figs. 2(a) and 2(b) we consider relay networks with $R = \{2, 4\}$ using 4-QAM modulation and $R = \{2, 4, 6\}$ using 8-QAM modulation, respectively, with no direct link between $\mathcal{T}_1$ and $\mathcal{T}_2$, and we compare the proposed three-phase technique with the three-phase dual-relay selection technique proposed in [8] and the three-phase single-relay selection technique proposed in [9]. From Figs. 2(a) and 2(b), we observe that the proposed three-phase technique outperforms the state of the art three-phase techniques.

In Figs. 2(a) and 3(b), relay networks with $R = \{2, 4\}$ and with no direct link between $\mathcal{T}_1$ and $\mathcal{T}_2$ are considered. In the latter figures, the BER at $\mathcal{T}_2$ is displayed versus the SNR with a total rate of 1 bpcu, where the proposed two- and three-phase techniques using 4-QAM and 8-QAM modulation, respectively, are compared with the two- and the three-phase dual-relay selection techniques proposed in [8] using 4-QAM and 8-QAM



(a) $R = 2$. (b) $R = 4$.

Fig. 3. BER versus SNR for several two and three-phase single and dual relay selection schemes with a rate of 1 bpcu.

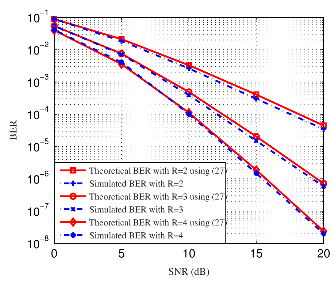


Fig. 4. Theoretical and simulated BER performance versus SNR for the proposed schemes with $R = \{2, 4, 6\}$.

modulation, respectively, and the two- and three-phase single-relay selection techniques proposed in [9] using 4-QAM and 8-QAM modulation, respectively. From Figs. 3(a) and 3(b), the two-phase techniques outperform those which use the three-phase relaying scheme due to the increase of the symbol rate as explained in Section 3. It can also be observed that the proposed two- and three-phase techniques outperform the state of the art two- and three-phase techniques. From Fig. 4, it is observed that the simulated performance of the proposed scheme in terms of BER is very close to the theoretical result obtained from the expressions derived in Section 5.

7. Conclusion

In this paper, we have described novel relay selection techniques based on Alamouti STBC using the DF protocol and two- and three-phase bi-directional relaying schemes together with their performance analyses. In the proposed techniques, two relays are selected based on the proposed *hybrid* selection criterion. The selected relays use the concept of digital network coding in order to avoid wasting power broadcasting redundant information at either terminal, thereby improving the overall system performance of the relay network. Therefore, in our transmission technique, the relays combine the detected symbols of the terminals in a single symbol of the same constellation using a specific combination function and broadcast it to both terminals. Each terminal then detects the symbol of the other terminal from its received signal using its own symbol. Since an orthogonal STBC technique, i.e., Alamouti technique, is applied on the relay network, a symbol-wise detector can be used to detect the symbols.

Conflict of interest

The authors declare that there is no conflict of interest in this paper.

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