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Outage Performance of Selective Dual-Hop MIMO Relaying with OSTBC and Transmit Antenna Selection in Rayleigh Fading Channels

In-Ho Lee*, Hyun-Ho Choi*, and Howon Lee*

Abstract

For dual-hop multiple-input multiple-output (MIMO) decode-and-forward relaying systems, we propose a selective relaying scheme that uses orthogonal space-time block code (OSTBC) and transmit antenna selection with maximal-ratio combining (TAS/MRC) or vice versa at the first and second hops, respectively. The aim is to achieve an asymptotically identical performance to the dual-hop relaying system with only TAS/MRC, while requiring lower feedback overhead. In particular, we give the selection criteria based on the antenna configurations and the average channel powers for the first and second hops, assuming Rayleigh fading channels. Also, the numerical results are shown for the outage performance comparison between the dual-hop DF relaying systems with the proposed scheme, only TAS/MRC, and only OSTBC.

Keywords

Dual-Hop Relaying, Orthogonal Space-Time Block Code, Outage Probability, Rayleigh Fading, Transmit Antenna Selection

1. Introduction

Orthogonal space-time block code (OSTBC) and transmit antenna selection (TAS) schemes have been widely known as multiple-input multiple-output (MIMO) techniques for achieving full diversity [1,2]. TAS with maximal ratio combining (TAS/MRC) provides more signal-to-noise power ratio (SNR) gain than OSTBC [2]. However, for OSTBC, the transmitter requires no channel state information, whereas for TAS/MRC, it requires the information of the transmit antenna selected at the receiver. Hence, TAS/MRC is superior to OSTBC in terms of the performance, but not in terms of the complexity due to the feedback overhead.

In order to enhance the diversity gain, MIMO techniques have been introduced into multi-hop relaying systems [3-9]. In [3-6], the outage probability and error rate of dual-hop relaying systems with OSTBC have been studied for amplify-and-forward (AF) and decode-and-forward (DF) relaying in Rayleigh and Nakagami-m fading channels. In [7-9], the outage probability and the error rate of dual-hop AF and DF relaying systems with TAS/MRC have been investigated for Rayleigh and Nakagami-m fading channels.

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As in [3-9], most researchers have concentrated on AF and DF relaying systems using only either OSTBC or TAS/MRC at all hops. However, in this paper, we focus on the dual-hop DF relaying system with both OSTBC and TAS/MRC, and propose a selective relaying scheme that uses OSTBC and TAS/MRC or vice versa at the first and second hops, respectively. The purpose is to attain asymptotically the same performance as a scheme using only TAS/MRC. In the proposed scheme, OSTBC is used at one of two hops instead of TAS/MRC, and hence the feedback overhead is lower than the one using only TAS/MRC. The proposed scheme is based on the facts that for the dual-hop MIMO DF relaying systems, the maximum diversity order is equal to a minimum of diversity orders achieved at the first and the second hops [10], and the end-to-end outage performance is dominated by the weakest hop [11]. In particular, in this paper, we present the selection criteria based on the antenna configurations and average channel powers for the first and second hops, assuming Rayleigh fading channels. Also, the numerical results are provided to verify the analysis and compare the outage performances of dual-hop DF relaying systems with the proposed scheme, only TAS/MRC, and only OSTBC. In addition, we present the impacts of spatially correlated MIMO channels and feedback delay for TAS on the outage performance of the proposed scheme.

This paper is organized as follows: Section 2 describes the system model, and proposes a selective relaying scheme using both OSTBC and TAS/MRC. In Section 3, we present the outage probability analysis for the proposed scheme. In Section 4, the proposed scheme is compared with the conventional DF relaying systems with OSTBC or TAS/MRC in terms of the outage probability. In Section 5, we investigate the impacts of spatially correlated channels and feedback delay on the outage performance of the proposed scheme. Section 6 concludes this paper.

2. System Model

As shown in Fig. 1, we consider a dual-hop MIMO relaying system with a source, relay, and destination. The source that is equipped with n_1^t transmit (Tx) antennas communicates with the destination that is equipped with n_2^r receive (Rx) antennas through the relay equipped with n_1^r Rx and n_2^t Tx antennas. In this paper, the direct link between the source and the destination is assumed to be unavailable due to high shadowing or large path loss, and DF relaying is employed, in which the relay decodes the received signals from the source, and encodes and forwards the decoded signals to the destination.

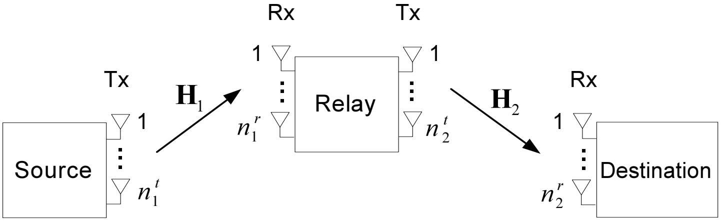


Fig. 1. A dual-hop MIMO relaying system.

The $n_1^r \times n_1^t$ and $n_2^r \times n_2^t$ channel matrices for the first and second hops are represented by $\mathbf{H}_1 = \{h_{ij}^{(1)}\}_{n_1^r \times n_1^t}$ and $\mathbf{H}_2 = \{h_{ij}^{(2)}\}_{n_2^r \times n_2^t}$, respectively, where $h_{ij}^{(1)}$ and $h_{ij}^{(2)}$ denote the channel coefficients between the j-th Tx and i-th Rx antennas at the first and second hops, respectively. We assume that the elements of $\mathbf{H}_1$ and $\mathbf{H}_2$ are independent complex Gaussian random variables with mean zero and variance β_1 and β_2, respectively. Then, β_1 and β_2 represent the average powers of $h_{ij}^{(1)}$ and $h_{ij}^{(2)}$, respectively. It means that the channels for each hop are independent and identically distributed, but the channels between the first and second hops are independent and non-identically distributed. It is also assumed that the transmit powers of the source and relay are equal, denoted as P, and the noise powers per Rx antenna at the relay and destination are equal, denoted as σ^2.

In the dual-hop MIMO relaying system, OSTBC and TAS/MRC are considered as MIMO transmission techniques that achieve full diversity. When OSTBC is used at the first hop (or the second hop), the source (or relay) sends signals to the relay (or destination) using the block codes given in [1], and the relay (or destination) decodes the received signals using the squaring method in [12]. On the other hand, when TAS/MRC is used at the first hop (or the second hop), the relay (or destination) selects the single Tx antenna of the source (or relay) providing the best MRC-output SNR, and feeds this information back to the source (or relay). Then, the source (or relay) sends the signals to the relay (or destination) via the selected Tx antenna, and the relay (or destination) combines the received signals with MRC and decodes the combined one. Although both OSTBC and TAS/MRC attain full diversity, TAS/MRC has more SNR gain than OSTBC [2]. However, OSTBC requires no feedback overhead, whereas TAS/MRC requires feedback overhead to inform the transmitter about the selected Tx antenna.

Therefore, in comparing OSTBC and TAS/MRC, there is a tradeoff between performance and overhead.

The maximum diversity order of the dual-hop MIMO DF relaying systems is a minimum of diversity orders achieved at the first and second hops [10], i.e., min $\{n_1^t n_1^r, n_2^t n_2^r\}$. Furthermore, the end-to-end outage performance of the dual-hop DF relaying systems is dominated by the weakest hop [11]. Thus, when the diversity orders for the first and second hops in the dual-hop DF relaying system with OSTBC and TAS/MRC are not equal, we propose using TAS/MRC at the hop with the smallest diversity order while using OSTBC at the other hop. On the other hand, when the diversity orders for the first and second hops are equal, we propose using OSTBC at the hop with the largest average channel power while using TAS/MRC at the other hop. The criteria for selecting either OSTBC or TAS/MRC at each hop, based on the diversity orders and average channel powers at the first and second hops, are given in Section 3. When compared with the dual-hop DF relaying system using only TAS/MRC (DF-TAS), the proposed scheme requires lower feedback overhead while providing the same diversity order and asymptotically equal outage performance. In this paper, the dual-hop DF relaying system using the proposed scheme is referred to as the selective dual-hop DF relaying system with OSTBC and TAS/MRC (SDF-OSTBC/TAS).

3. Outage Probability Analysis

At the k-th hop, the received SNRs for OSTBC and TAS/MRC are respectively given by [2,3]

$$\gamma_k^{ST} = \frac{\rho}{n_k^t R_k^c} \sum_{i=1}^{n_k^r} \sum_{j=1}^{n_k^t} \left|h_{ij}^{(k)}\right|^2, \tag{1}$$

and

$$\gamma_k^{AS} = \max_{j=1,\cdots,n_k^t} \left\{\rho \sum_{i=1}^{n_k^r} \left|h_{ij}^{(k)}\right|^2\right\}, \tag{2}$$

where $\rho = P/\sigma^2$, and R_k^c represents code rate of OSTBC used at the k-th hop. OSTBC for n_k^t=2,3, and 4 are given in [1, eqs. (32), (29), and (40)], respectively, and their code rates are 1, 3/4, and 3/4, respectively. It is noted that the maximum code rates of OSTBCs are 1 for two Tx antennas and 3/4 for more than two Tx antennas [13].

By inserting (1) and (2) into [14, eq. (15)], when $n_1^t n_1^r \neq n_2^t n_2^r$, the end-to-end achievable rate for SDF-OSTBC/TAS is obtained as

$$C^{Pro} = \begin{cases} \frac{1}{2}\min\{R_1^c \log_2(1+\gamma_1^{ST}), \log_2(1+\gamma_2^{AS})\} & \text{for } n_1^t n_1^r > n_2^t n_2^r \\ \frac{1}{2}\min\{\log_2(1+\gamma_1^{AS}), R_2^c \log_2(1+\gamma_2^{ST})\} & \text{for } n_1^t n_1^r < n_2^t n_2^r \end{cases}, \tag{3}$$

where the achievable rate for OSTBC is given in [15, eq. (7.4.43)]. Also, when $n_1^t n_1^r = n_2^t n_2^r$, the end-to-end achievable rate for SDF-OSTBC/TAS is obtained as

$$C^{Pro} = \begin{cases} \frac{1}{2}\min\{R_1^c \log_2(1+\gamma_1^{ST}), \log_2(1+\gamma_2^{AS})\} & \text{for } \beta_1 \geq \nu^* \beta_2 \\ \frac{1}{2}\min\{\log_2(1+\gamma_1^{AS}), R_2^c \log_2(1+\gamma_2^{ST})\} & \text{for } \beta_2 \geq \mu^* \beta_1 \end{cases}, \tag{4}$$

where $\nu^* > 1$ and $\mu^* > 1$ denote the minimum ratios between β_1 and β_2 required to sustain the SNR gain gap between DF-TAS and SDF-OSTBC/TAS within a given threshold. ν^* and μ^* are derived in this section. On the other hand, the end-to-end achievable rate for DF-TAS is obtained as

$$C^{AS} = \frac{1}{2}\min\{\log_2(1+\gamma_1^{AS}), \log_2(1+\gamma_2^{AS})\}, \tag{5}$$

Let the outage probability be defined as the probability that the end-to-end achievable rate falls below a given target data rate in bps/Hz, denoted by R. Letting the capacities achieved at the first and second hops be denoted by C_1 and C_2, respectively, the exact outage probability is expressed as

$$\begin{aligned} O &= \Pr\left\{\tfrac{1}{2}\min\{C_1, C_2\} < R\right\} \\ &= 1 - \Pr\{C_1 > 2R\}\Pr\{C_2 > 2R\} \\ &= F_{C_1}(2R) + F_{C_2}(2R) - F_{C_1}(2R)\, F_{C_2}(2R), \end{aligned} \tag{6}$$

where $F_X(\cdot)$ denotes the cumulative distribution function (CDF) of random variable X. In (6), $F_{C_k}(2R) = F_{\gamma_k^{ST}}(2^{2R/R_k^c} - 1)$ for OSTBC, and $F_{C_k}(2R) = F_{\gamma_k^{AS}}(2^{2R} - 1)$ for TAS/MRC, where the CDFs of γ_k^{ST} and γ_k^{AS} are respectively given by [16]

$$F_{\gamma_k^{ST}}(x) = 1 - e^{-x n_k^t R_k^c/(\rho\beta_k)} \sum_{i=0}^{(n_k^t n_k^r - 1)} \frac{1}{i!}\left(\frac{x n_k^t R_k^c}{\rho\beta_k}\right)^i, \tag{7}$$

and

$$F_{\gamma_k^{AS}}(x) = \left\{1 - e^{-x/(\rho\beta_k)} \sum_{i=0}^{(n_k^r-1)} \frac{1}{i!}\left(\frac{x}{\rho\beta_k}\right)^i\right\}^{n_k^t}. \tag{8}$$

Therefore, substituting (7) and (8) into (6), yields the outage probabilities of SDF-OSTBC/TAS and DF-TAS, denoted by O^{Pro} and O^{AS}, respectively.

Proposition 1: When $n_1^t n_1^r \neq n_2^t n_2^r$, the asymptotic outage performance of SDF-OSTBC/TAS is the same as that of DF-TAS.

Proof: Using high SNR approximation (i.e., $\rho \to \infty$), the CDFs of γ_k^{ST} and γ_k^{AS} are respectively approximated by

$$F_{\gamma_k^{ST}}(x) \approx \frac{1}{(n_k^t n_k^r)!}\left(\frac{x n_k^t R_k^c}{\rho\beta_k}\right)^{n_k^t n_k^r}, \tag{9}$$

and

$$F_{\gamma_k^{AS}}(x) \approx \frac{1}{(n_k^r!)^{n_k^t}}\left(\frac{x}{\rho\beta_k}\right)^{n_k^t n_k^r}. \tag{10}$$

Thus, inserting (9) and (10) into (6) and using the high SNR approximation, when $n_1^t n_1^r \neq n_2^t n_2^r$, the asymptotic outage probability of SDF-OSTBC/TAS is obtained as

$$O^{Pro} \approx \begin{cases} \frac{1}{(n_2^r!)^{n_2^t}}\left(\frac{2^{2R}-1}{\rho\beta_2}\right)^{n_2^t n_2^r} & \text{for } n_1^t n_1^r > n_2^t n_2^r \\ \frac{1}{(n_1^r!)^{n_1^t}}\left(\frac{2^{2R}-1}{\rho\beta_1}\right)^{n_1^t n_1^r} & \text{for } n_1^t n_1^r < n_2^t n_2^r \end{cases}. \tag{11}$$

Furthermore, inserting (10) into (6) and using the high SNR approximation, yields the asymptotic outage probability of DF-TAS, which is the same as that of SDF-OSTBC/TAS in (11).

Proposition 2: When $n_1^t n_1^r = n_2^t n_2^r$, the diversity orders of SDF-OSTBC/TAS and DF-TAS are equal, and the SNR gain gap between DF-TAS and SDF-OSTBC/TAS with the following ν^* and μ^* is less than or equal to ϵ [dB], where ϵ [dB] ($>$ 0 dB) denotes the threshold of the SNR gain gap, and $\epsilon[\text{dB}] = 10\log_{10}\epsilon$.

$$\nu^* = \left[\left\{\frac{(z^{AS})^N \epsilon^N}{(n_1^r!)^{n_1^t}} - \frac{(z_1^{ST} n_1^t R_1^c)^N}{N!}\right\} \frac{(n_2^r!)^{n_2^t}}{(z^{AS})^N (1-\epsilon^N)}\right]^{\frac{1}{N}}, \tag{12}$$

and

$$\mu^* = \left[\left\{\frac{\left(z^{AS}\right)^N \epsilon^N}{\left(n_2^r!\right)^{n_2^t}} - \frac{\left(z_2^{ST} n_2^t R_2^c\right)^N}{N!}\right\} \frac{\left(n_1^r!\right)^{n_1^t}}{\left(z^{AS}\right)^N\left(1-\epsilon^N\right)}\right]^{\frac{1}{N}}, \tag{13}$$

where $\mathrm{N} = n_1^t n_1^r = n_2^t n_2^r$, $z_k^{ST} = 2^{2R/R_k^c} - 1$, and $z_k^{AS} = 2^{2R} - 1$.

Proof: Substituting (9) and (10) into (6) and using the high SNR approximation, when $n_1^t n_1^r = n_2^t n_2^r$, the asymptotic outage probability of SDF-OSTBC/TAS is obtained as

$$O^{Pro} \approx \begin{cases} \frac{1}{\rho^N}\left\{\frac{1}{N!}\left(\frac{z_1^{ST} n_1^t R_1^c}{\beta_1}\right)^N + \frac{1}{\left(n_2^r!\right)^{n_2^t}}\left(\frac{z^{AS}}{\beta_2}\right)^N\right\} & \text{for} \quad \beta_1 \geq \nu^*\,\beta_2 \\ \frac{1}{\rho^N}\left\{\frac{1}{\left(n_1^r!\right)^{n_1^t}}\left(\frac{z^{AS}}{\beta_1}\right)^N + \frac{1}{N!}\left(\frac{z_2^{ST} n_2^t R_2^c}{\beta_2}\right)^N\right\} & \text{for} \quad \beta_2 \geq \mu^*\,\beta_1 \end{cases}. \tag{14}$$

On the other hand, substituting (10) into (6) and using the high SNR approximation, the asymptotic outage probability of DF-TAS is obtained as

$$O^{AS} \approx \frac{1}{\rho^N}\left\{\frac{1}{\left(n_1^r!\right)^{n_1^t}}\left(\frac{z^{AS}}{\beta_1}\right)^N + \frac{1}{\left(n_2^r!\right)^{n_2^t}}\left(\frac{z^{AS}}{\beta_2}\right)^N\right\}. \tag{15}$$

From (14) and (15), it is determined that the diversity orders for both SDF-OSTBC/TAS and DF-TAS are equal, but the outage probability of SDF-OSTBC/TAS is worse than that of DF-TAS.

First, we focus on determining ν^*. Let $G^{Pro} = \left\{\frac{1}{N!}\left(\frac{z_1^{ST} n_1^t R_1^c}{\beta_1}\right)^N + \frac{1}{\left(n_2^r!\right)^{n_2^t}}\left(\frac{z^{AS}}{\beta_2}\right)^N\right\}^{-1/N}$ and $G^{AS} = \left\{\frac{1}{\left(n_1^r!\right)^{n_1^t}}\left(\frac{z^{AS}}{\beta_1}\right)^N + \frac{1}{\left(n_2^r!\right)^{n_2^t}}\left(\frac{z^{AS}}{\beta_2}\right)^N\right\}^{-1/N}$. Then, (14) and (15) can be simply expressed as $(\rho G^{Pro})^{-N}$ and $(\rho G^{AS})^{-N}$, respectively. As seen in the simplified expressions, G^{Pro} and G^{AS} represent the SNR gains for SDF-OSTBC/TAS and DF-TAS, respectively. Letting $\beta_1 = \nu\,\beta_2$, we find ν that satisfies $G^{AS}/G^{Pro} \leq \epsilon$ as follows:

$$\frac{1}{N!}\left(\frac{z_1^{ST} n_1^t R_1^c}{\nu\beta_2}\right)^N + \frac{1}{\left(n_2^r!\right)^{n_2^t}}\left(\frac{z^{AS}}{\beta_2}\right)^N \leq \epsilon^N\left\{\frac{1}{\left(n_1^r!\right)^{n_1^t}}\left(\frac{z^{AS}}{\nu\beta_2}\right)^N + \frac{1}{\left(n_2^r!\right)^{n_2^t}}\left(\frac{z^{AS}}{\beta_2}\right)^N\right\}$$

$$\Rightarrow \frac{\left(z_1^{ST} n_1^t R_1^c\right)^N}{N!} + \frac{\left(z^{AS}\right)^N\left(1-\epsilon^N\right)\nu^N}{\left(n_2^r!\right)^{n_2^t}} \leq \frac{\left(z^{AS}\right)^N \epsilon^N}{\left(n_1^r!\right)^{n_1^t}}$$

$$\Rightarrow \nu \geq \left[\left\{\frac{\left(z^{AS}\right)^N \epsilon^N}{\left(n_1^r!\right)^{n_1^t}} - \frac{\left(z_1^{ST} n_1^t R_1^c\right)^N}{N!}\right\} \frac{\left(n_2^r!\right)^{n_2^t}}{\left(z^{AS}\right)^N\left(1-\epsilon^N\right)}\right]^{\frac{1}{N}} \triangleq \nu^*. \tag{16}$$

Finally, ν^* is obtained as in (16). Analogous to the above method, letting

$G^{Pro} = \left\{\frac{1}{\left(n_1^r!\right)^{n_1^t}}\left(\frac{z^{AS}}{\beta_1}\right)^N + \frac{1}{N!}\left(\frac{z_2^{ST} n_2^t R_2^c}{\beta_2}\right)^N\right\}^{-1/N}$ and $\beta_2 = \mu\,\beta_1$, we obtain μ^* as follows:

$$\mu \geq \left[\left\{\frac{(z^{AS})^N \epsilon^N}{(n_2^r!)^{n_2^t}} - \frac{(z_2^{ST} n_2^t R_2^c)^N}{N!}\right\}\frac{(n_1^r!)^{n_1^t}}{(z^{AS})^N (1-\epsilon^N)}\right]^{\frac{1}{N}} \triangleq \mu^*. \quad (17)$$

It is noted that SDF-OSTBC/TAS can have asymptotically the same performance as DF-TAS when ϵ[dB] $\approx$ 0 dB.

4. Numerical Results

In Figs. 2 and 3, the results for the exact outage probability obtained by (6) and those of the asymptotic outage probability obtained by (11), (14) and (15) are verified through Monte Carlo simulations, where DF-OSTBC represents the dual-hop DF relaying system using only OSTBC. Figs. 2 and 3 show the outage probabilities of SDF-OSTBC/TAS, DF-TAS, and DF-OSTBC for various antenna configurations when $\beta_2 = 1$ and $\beta_1 > \beta_2$.

Fig. 2(a) and (b) show the outage performances for $n_1^t = n_1^r = n_2^t = n_2^r = 2, 3$, respectively, where the asymptotic results for SDF-OSTBC/TAS are obtained by using (14) because of $n_1^t n_1^r = n_2^t n_2^r$. In Fig. 2(a), $\beta_1 = 3.66$ for R = 1, 3 is used assuming that ϵ [dB] = 0.01 dB. It is noted that when ϵ [dB] = 0.01 dB, we obtain $\nu^* = 3.66$ by (12), and thus when $\beta_1 = 3.66$ and $\beta_2 = 1$, the SNR gain gap between DF-TAS and SDF-OSTBC/TAS is 0.01 dB. If $\beta_1 > 3.66$ and $\beta_2 = 1$, then the SNR gain gap can be less than 0.01 dB. In Fig. 2(b), $\beta_1 = 2.7, 6.13$ for R = 1, 3 are respectively used assuming that ϵ [dB] = 0.01 dB, as in Fig. 2(a). The values of β_1 are the same as those of ν^*, obtained by (12). Unlike β_1 used in Fig. 2(a), β_1 used in Fig. 2(b) increases with R in order to achieve ϵ [dB] = 0.01 dB. The reason is that the code rate of OSTBC used in SDF-OSTBC/TAS is one when the number of Tx antennas is two (i.e., R_1^c = 1), but less than one when the number of Tx antennas is three (i.e., R_1^c = 3/4). From the results for $n_1^t n_1^r = n_2^t n_2^r$, we can say that SDF-OSTBC/TAS with ϵ [dB] = 0.01 dB provides an asymptotically equal performance to DF-TAS.

Fig. 3(a) and (b) show the outage performances for $n_1^t = n_1^r = n_2^t = 2, 3$, respectively, when $n_2^r = 1$, where the asymptotic results for SDF-OSTBC/TAS are obtained by using (11) because of $n_1^t n_1^r \neq n_2^t n_2^r$. These figures illustrate that the outage probabilities of SDF-OSTBC/TAS and DF-TAS are asymptotically the same regardless of R even though the value of β_1 (i.e., β_1 = 2) is smaller than those used in Fig. 2(a) and (b). In Figs. 2 and 3, it is observed that the outage performance of SDF-OSTBC/TAS is always better than that of DF-OSTBC.

In Fig. 4, we compare the outage probabilities of DF-OSTBC/TAS, DF-TAS, and DF-OSTBC when $n_1^t = n_1^r = n_2^t = n_2^r = 3, \beta_1 = 2$, and $\beta_2 = 1$, where DF-OSTBC/TAS represents a simple selection scheme in which OSTBC and TAS/MRC are used at the first and second hops, respectively, when $\beta_1 > \beta_2$ without any condition like ν^*. The figure demonstrates that an outage performance gap between DF-OSTBC/TAS and DF-TAS increases with R even though β_1 is set to a larger value than β_2. It means that the selection criteria proposed in this paper are needed for efficient selection between OSTBC and TAS/MRC in dual-hop MIMO DF relaying systems.

Fig. 5 shows the minimum ratio between β_1 and β_2, ν^* and μ^*, that satisfy $G^{AS}/G^{Pro} \leq \epsilon$ when ϵ [dB] = 0.1 dB, 0.01 dB. The figure indicates that ν^* and μ^* increase as ϵ [dB] approaches 0 dB, and with increasing R when the code rate of OSTBC is less than one. Notably, when $n_1^t = n_2^r = 2$ and $n_1^r = n_2^t = 3$, ν^* and μ^* are different because R_1^c = 1 for ν^*, but R_2^c = 3/4 for μ^*.

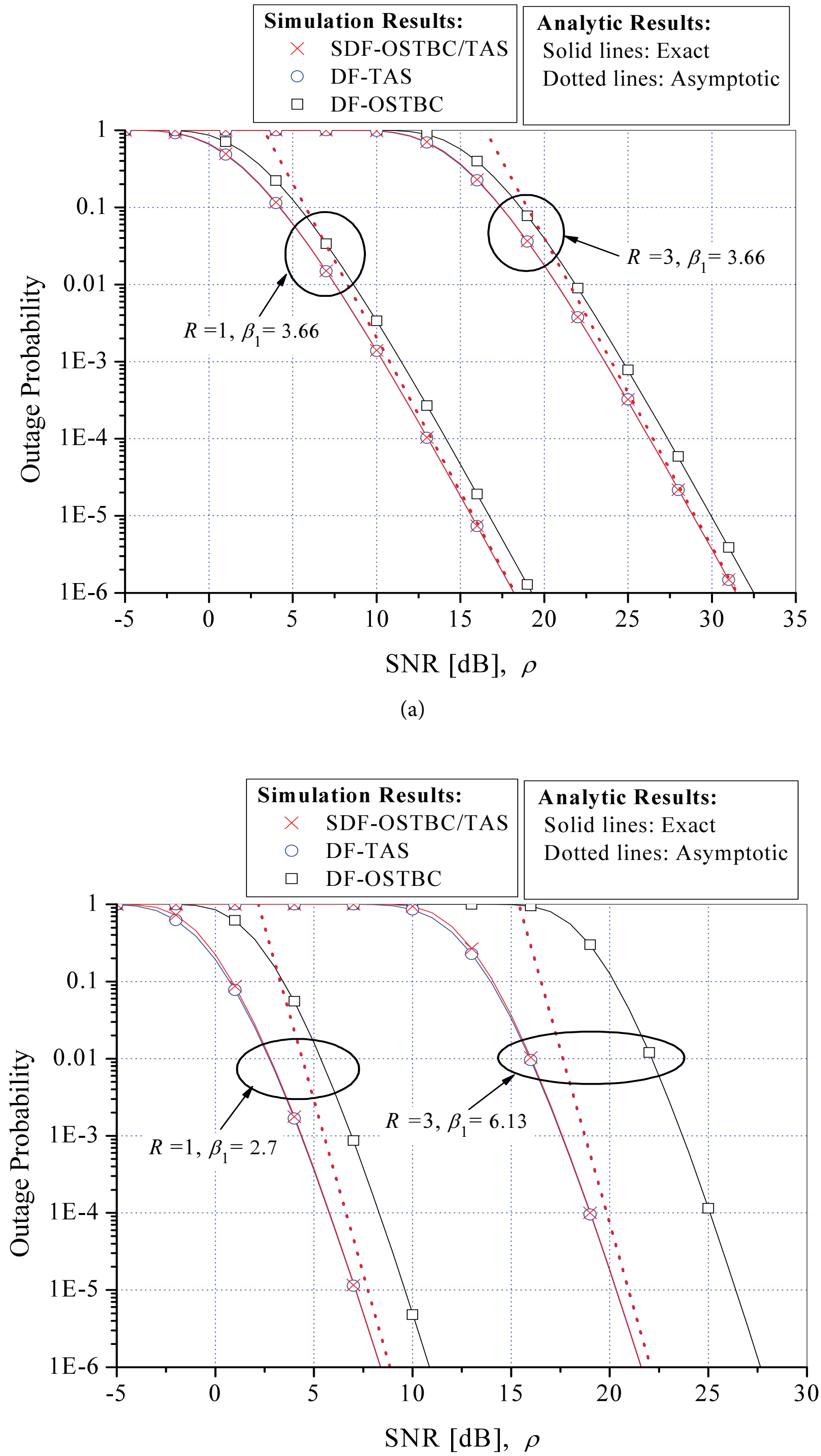
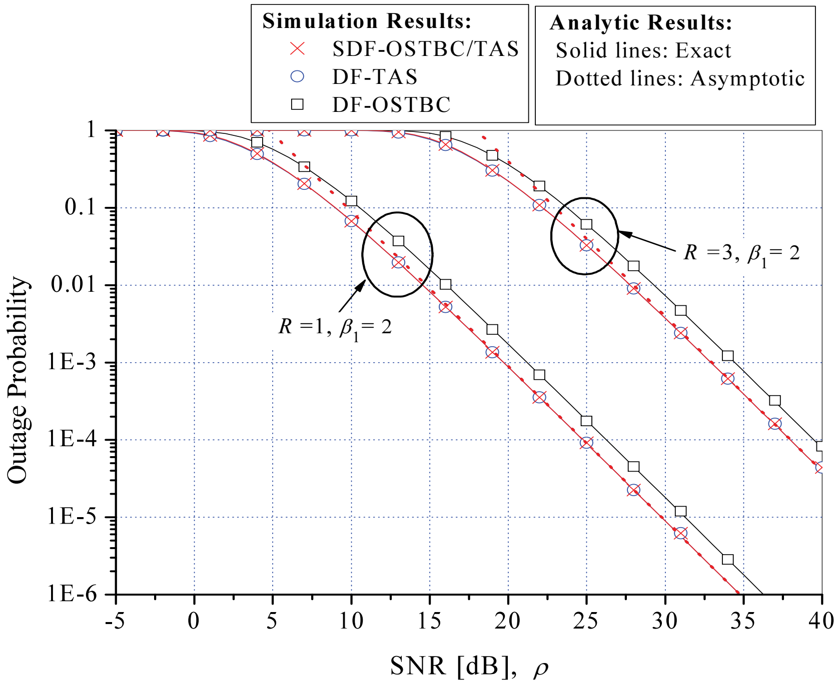
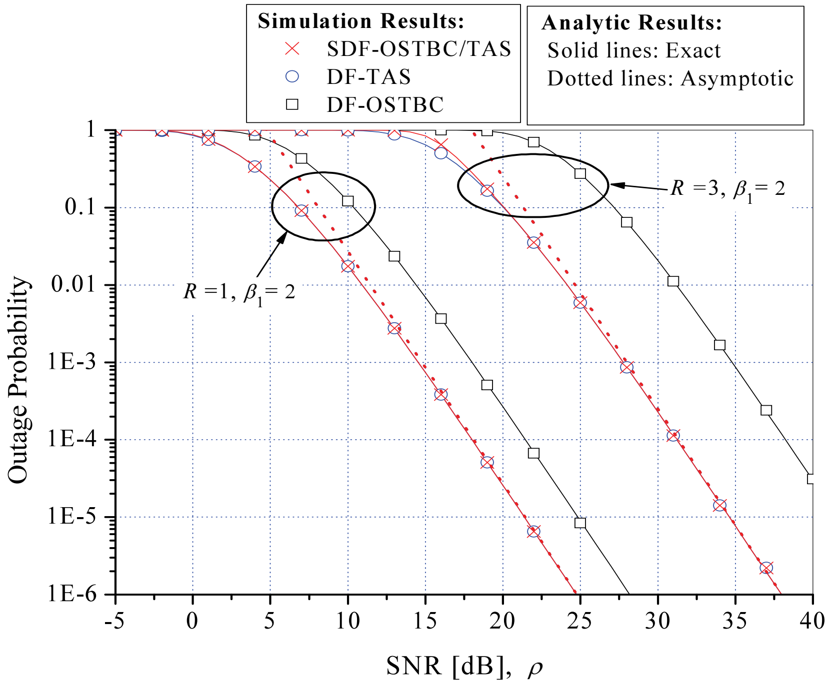


Fig. 2. Outage probability of SDF-OSTBC/TAS, DF-TAS, and DF-OSTBC for $\beta_2 = 1$: (a) when $n_1^t = n_1^r = n_2^t = n_2^r = 2$; (b) when $n_1^t = n_1^r = n_2^t = n_2^r = 3$.



(a)



(b)

Fig. 3. Outage probability of SDF-OSTBC/TAS, DF-TAS, and DF-OSTBC for $\beta_2 = 1$: (a) when $n_1^t = n_1^r = n_2^t = 2$ and $n_2^r = 1$; (b) when $n_1^t = n_1^r = n_2^t = 3$ and $n_2^r = 1$.

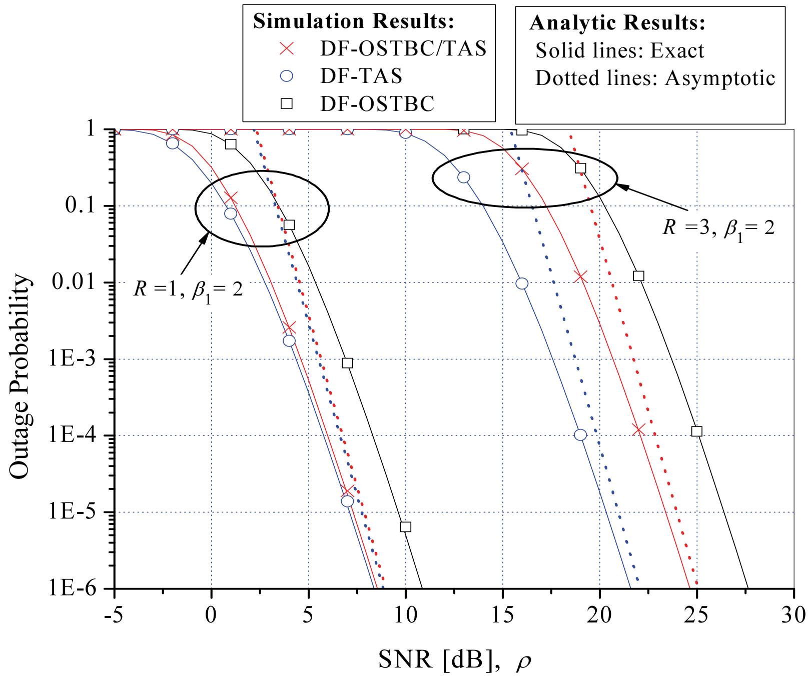


Fig. 4. Outage probability of DF-OSTBC/TAS, DF-TAS, and DF-OSTBC for $\beta_2 = 1$ when $n_1^t = n_1^r = n_2^t = n_2^r = 3$.

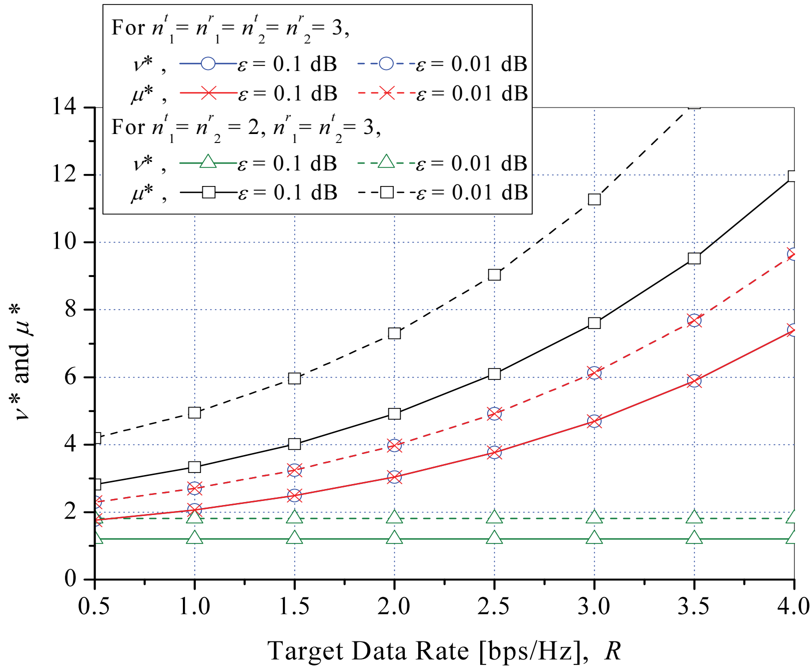


Fig. 5. ν^* and μ^* for ϵ [dB] = 0.1 dB, 0.01 dB when $n_1^t = n_1^r = n_2^t = n_2^r = 3$, and $n_1^t = n_2^r = 2$, $n_1^r = n_2^t = 3$.

5. Impacts of Correlated Channels and Feedback Delay

In this section, we investigate the impacts of spatial correlation in MIMO channels for each hop as well as feedback delay for TAS on the outage probability of SDF-OSTBC/TAS, respectively.

The first and second hop channel matrices with spatial correlation are modeled by [15].

$$\mathbf{H}_k^c = \mathbf{W}_{r,k}^{1/2}\mathbf{H}_k\mathbf{W}_{t,k}^{1/2} \quad \text{for } k = 1, 2, \tag{18}$$

where $\mathbf{H}_k^c$ denotes the spatially correlated channel matrix for the k-th hop, and $\mathbf{W}_{t,k}^{1/2}$ and $\mathbf{W}_{r,k}^{1/2}$ are $n_k^t \times n_k^t$ and $n_k^r \times n_k^r$ correlation matrices for the transmitter and the receiver at hop k, respectively. In this paper, we assume that $\mathbf{W}_{t,k}$=$\mathbf{W}_{r,k}$ for $k = 1,2$, their diagonal elements are 1, and their off-diagonal elements are α_k for $k = 1,2$, where α_k ranges between 0 and 1. The MIMO channels are uncorrelated when $\alpha_k = 0$, but the channels become highly correlated as α_k becomes close to 1.

Fig. 6(a) and (b) show the outage performances for highly correlated channels when $n_1^t = n_1^r = n_2^t = n_2^r = 2, 3$, respectively, where the simulation results for SDF-OSTBC/TAS, DF-TAS, and DF-OSTBC are obtained by using $\mathbf{H}_k^c$ in (18). In Fig. 6(a), $\beta_1 = 3.66$ for R = 1, 3 is used for SDF-OSTBC/TAS as in Fig. 2(a). Fig. 6(a) indicates that SDF-OSTBC/TAS has the same performance as DF-TAS and the better performance than DF-OSTBC when the channels for each hop are highly correlated even though the performance of SDF-OSTBC/TAS is slightly worse than that of DF-TAS when only the channels for the first hop are highly correlated, i.e., $\alpha_1 = 0.8$ and $\alpha_2 = 0$. In Fig. 6(b), $\beta_1 = 2.7, 6.13$ for R = 1, 3 are respectively used for SDF-OSTBC/TAS as in Fig. 2(b). Fig. 6(b) demonstrates that SDF-OSTBC/TAS achieves the similar performance to DF-TAS and much better performance than DF-OSTBC when the channels for both hops are highly correlated, i.e., $\alpha_1 = \alpha_2 = 0.8$. However, the outage performance of SDF-OSTBC/TAS becomes severely degraded as SNR increases when only the channels for the first hop are highly correlated, i.e., $\alpha_1 = 0.8$ and $\alpha_2 = 0$. In comparing the results in Fig. 6(a) and (b), it is observed that the severe performance degradation of SDF-OSTBC can occur with an increase in the number of antennas when only the channels for the first hop are highly correlated.

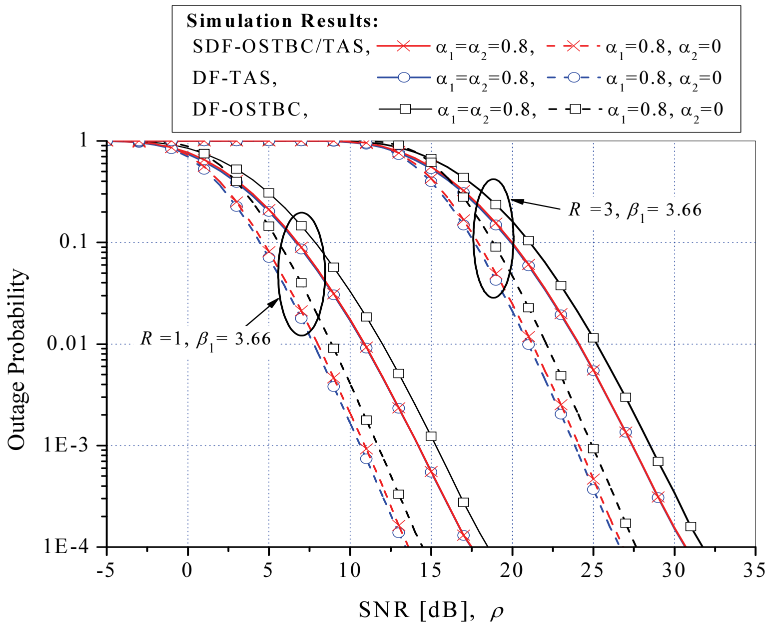
Fig. 7 shows the outage performances for the channels with low correlation when $n_1^t = n_1^r = n_2^t = n_2^r = 3$, where the simulation results are obtained by using $\mathbf{H}_k^c$ in (18), and the same values of β_1 as Fig. 6(b) are used for SDF-OSTBC/TAS. The figure illustrates that SDF-OSTBC/TAS achieves extremely similar performance to DF-TAS for high SNR even when only the channels for the first hop are correlated, i.e., $\alpha_1 = 0.3$ and $\alpha_2 = 0$.

The first and second hop channel matrices with feedback delay are modeled by [17,18].

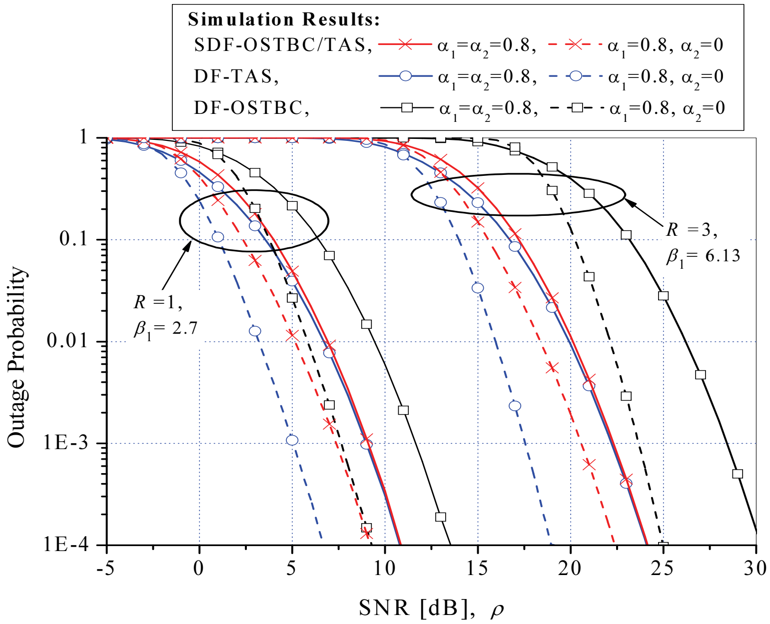
$$\mathbf{H}_k^f = \sigma_d\mathbf{H}_k + \sqrt{1-\sigma_d^2}\mathbf{U}_k \quad \text{for } k = 1, 2, \tag{19}$$

where $\mathbf{H}_k^f$ denotes the current channel matrix, $\mathbf{H}_k$ is the previous channel matrix, and $\mathbf{U}_k$ represents independent complex Gaussian random matrix whose elements are independent and identically distributed with mean zero and variance β_k. Furthermore, σ_d denotes the temporal correlation coefficient between the previous and current channels, and it is modeled by $\sigma_d = J_0(2\pi f_d \tau)$, where $J_0(\cdot)$ is a Bessel function of the first kind of zero order, f_d is the maximum Doppler frequency, and τ is a feedback delay time [19]. σ_d ranges between 0 and 1, $\sigma_d = 1$ means no feedback delay, and a decrease in σ_d means an increase in the feedback delay time. It is noted that the feedback delay is considered only for TAS since OSTBC requires no channel information at the transmitter. The simulation results in

Figs. 8 and 9 are obtained by assuming that the previous channel matrix $\mathbf{H}_k$ is used for TAS, but the current channel matrix $\mathbf{H}_k^f$ in (19) is used for data transmission after TAS. To focus on the impact of the feedback delay on the outage performance of SDF-OSTBC/TAS, the MIMO channels with no spatial correlation are assumed for simulations.



(a)



(b)

Fig. 6. Outage probability of SDF-OSTBC/TAS for $\beta_2 = 1$ in MIMO channels with high correlation: (a) when $n_1^t = n_1^r = n_2^t = n_2^r = 2$; (b) when $n_1^t = n_1^r = n_2^t = n_2^r = 3$.

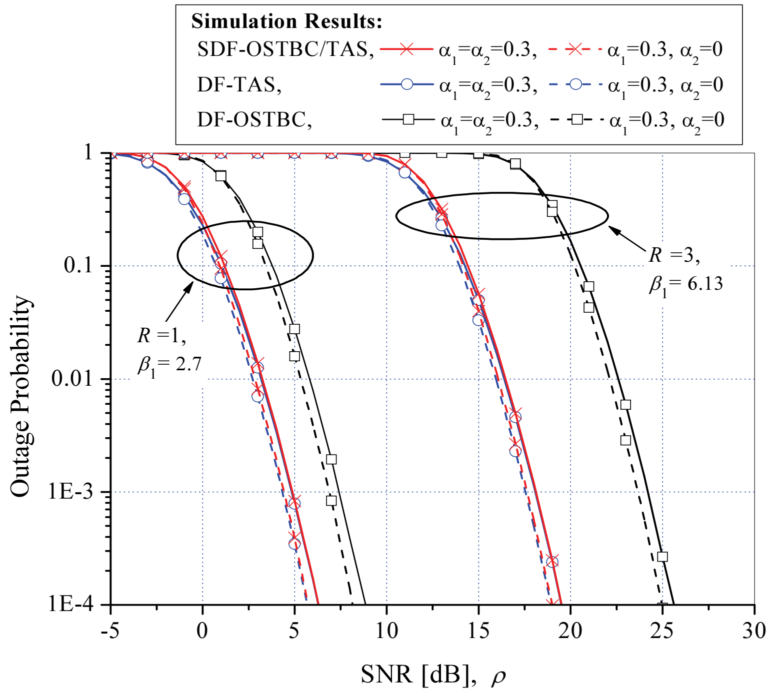
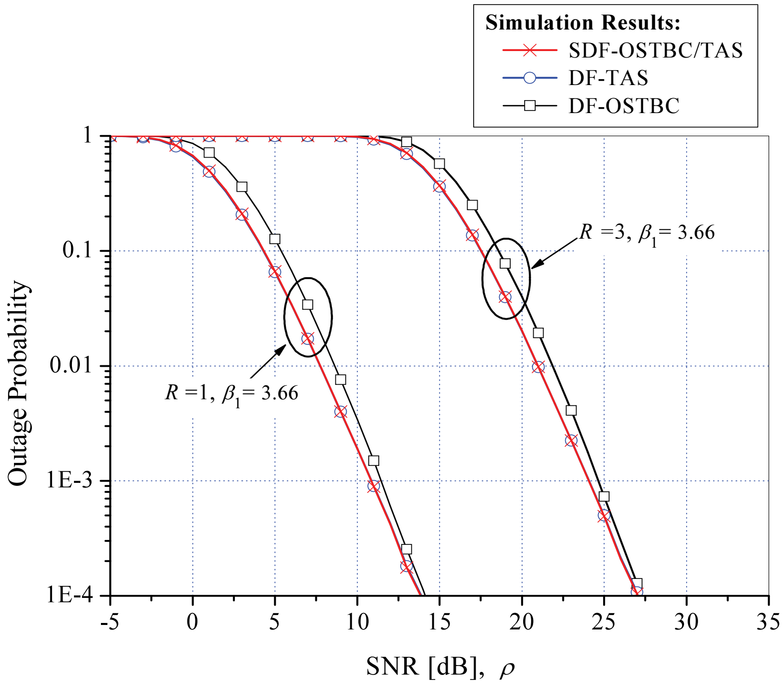


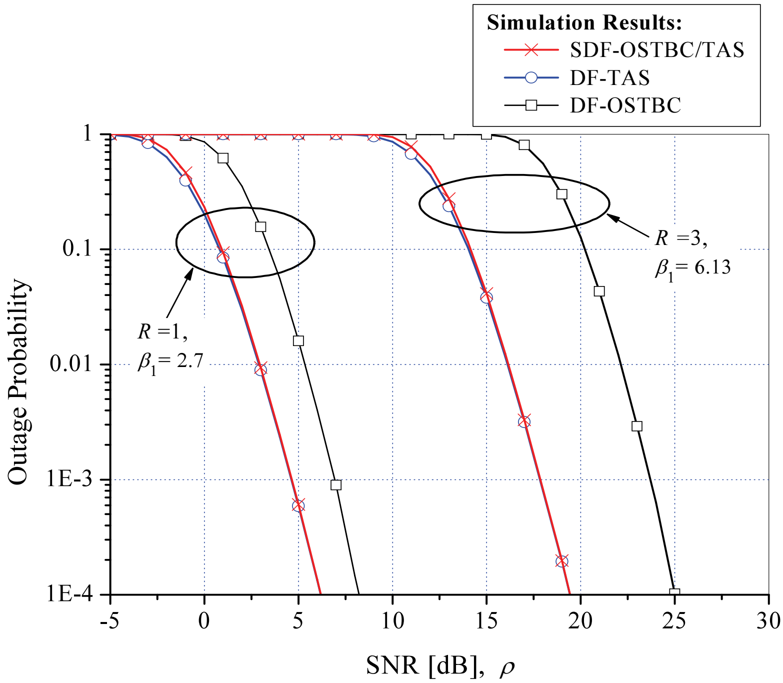
Fig. 7. Outage probability of SDF-OSTBC/TAS for $\beta_2 = 1$ in MIMO channels with low correlation when $n_1^t = n_1^r = n_2^t = n_2^r = 3$.

Fig. 8(a) and (b) show the outage performances of SDF-OSTBC/TAS and DF-TAS for $\sigma_d = 0.992$ in the presence of the feedback delay when $n_1^t = n_1^r = n_2^t = n_2^r = 2, 3$, respectively, where $\sigma_d = 0.992$ corresponds to τ = 3 ms, v_m =5 km/h, and $f_c = 2$ GHz. It is noted that $f_d = f_c v_m / v_c$, where f_c is a carrier frequency, v_m is a mobile speed, and v_c=3× 10^8 m/s. In Fig. 8(a), $\beta_1 = 3.66$ for R = 1, 3 is used for SDF-OSTBC/TAS as in Fig. 2(a). The figure indicates that SDF-OSTBC/TAS provides the same performance as DF-TAS, but the performance gap between SDF-OSTBC/TAS and DF-OSTBC diminishes as SNR rises. In Fig. 8(b), $\beta_1 = 2.7, 6.13$ for R = 1, 3 are respectively used for SDF-OSTBC/TAS as in Fig. 2(b). The results in Fig. 8(b) show the similar trend to those in Fig. 8(a). From Fig. 8(b), it is recognized that SDF-OSTBC/TAS still attains much better performance than DF-OSTBC for the short feedback delay time, i.e., τ = 3ms.

Fig. 9(a) and (b) show the outage performances of SDF-OSTBC/TAS and DF-TAS for $\sigma_d = 0.932$ in the presence of the feedback delay when $n_1^t = n_1^r = n_2^t = n_2^r = 2, 3$, respectively, where $\sigma_d = 0.932$ corresponds to τ = 9 ms, v_m =5 km/h, and $f_c = 2$ GHz. The results in Fig. 9(a) and (b) are obtained by using the same values of β_1 as Fig. 8(a) and (b) for SDF-OSTBC/TAS, respectively. In comparing the results in Fig. 9(a) and (b), it is observed that the impact of an increase in the feedback delay time on the outage performance of SDF-OSTBC/TAS becomes severer as the number of antennas decreases and SNR rises. In addition, an increase in the feedback delay time can induce a decrease in the diversity order, and thus the outage performance of SDF-OSTBC/TAS is considerably degraded for high SNR. However, SDF-OSTBC/TAS achieves better performance than DF-OSTBC in the low SNR regime even for an increase in the feedback delay time.

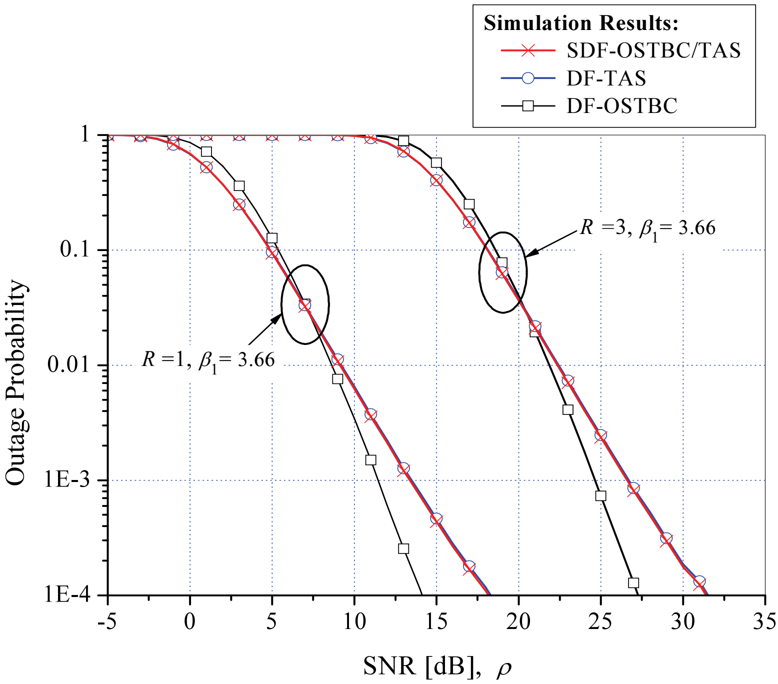


(a)

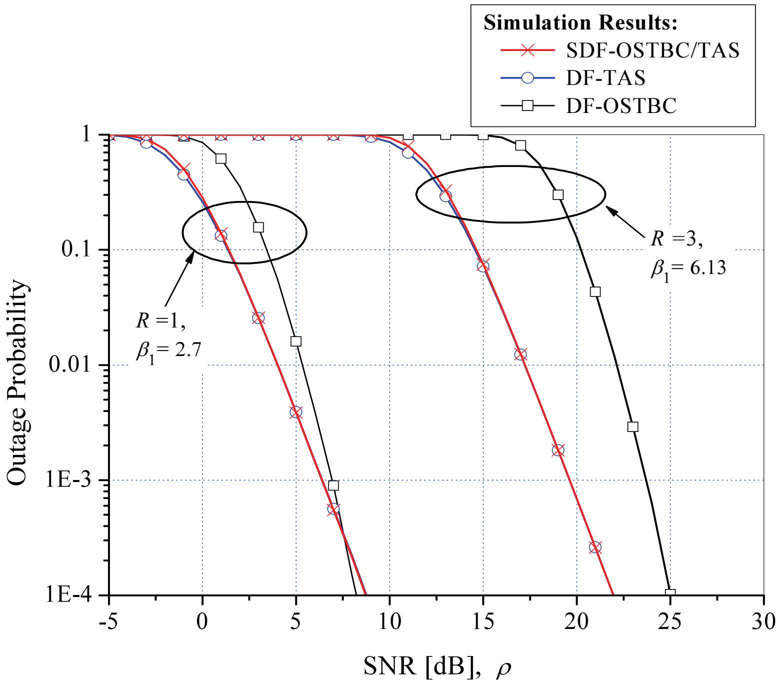


(b)

Fig. 8. Outage probability of SDF-OSTBC/TAS for $\beta_2 = 1$ and $\sigma_d = 0.992$ in the presence of feedback delay: (a) when $n_1^t = n_1^r = n_2^t = n_2^r = 2$; (b) when $n_1^t = n_1^r = n_2^t = n_2^r = 3$.



(a)



(b)

Fig. 9. Outage probability of SDF-OSTBC/TAS for $\beta_2 = 1$ and $\sigma_d = 0.932$ in the presence of feedback delay: (a) when $n_1^t = n_1^r = n_2^t = n_2^r = 2$; (b) when $n_1^t = n_1^r = n_2^t = n_2^r = 3$.

6. Conclusions

In this paper, we propose SDF-OSTBC/TAS to achieve an asymptotically identical performance to DF-TAS, while requiring lower feedback overhead. In SDF-OSTBC/TAS, the selection is completed using only information about the antenna configuration and average channel powers for the first and second hops. Because the antenna configuration is not changed, and the average channel powers vary slowly, the additional complexity required for the selection in SDF-OSTBC/TAS is negligible. Therefore, SDF-OSTBC/TAS can be used as a low-complexity alternative for DF-TAS when $n_1^t n_1^r \neq n_2^t n_2^r$ and $n_1^t n_1^r = n_2^t n_2^r$ with $\beta_1 \geq \nu^* \beta_2$ or $\beta_2 \geq \mu^* \beta_1$. Moreover, SDF-OSTBC/TAS can be effective in the presence of low spatial correlation for MIMO channels and short feedback delay for TAS.

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