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Simplified relay antenna selection with source beamforming for MIMO two-way relaying networks

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Abstract A simplified relay antenna selection with source beamforming (RAS-BF) scheme is advocated for multiple-input multiple-output (MIMO) two-way relaying networks (TWRNs) employing amplify-and-forward (AF) protocol, which does not require channel estimation at the relay node and the optimal relay antenna can be simply determined by comparing the minimum received pilot signaling powers pertaining to each antenna. The theoretical analysis of system outage probability and average symbol error rate (SER) shows that full diversity order can also be achieved by the simplified scheme. Simulation results are provided to verify our theoretical results and further illustrate that the simplified scheme outperforms the outage-optimal counterpart in the presence of channel state information (CSI) imperfections.

Keywords two-way relaying, relay antenna selection, beamforming, amplify-and-forward, diversity

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1 Introduction

In the future mobile communication systems, the demands for high-rate transmission and service quality are growing. As a low-cost and effective way to cope with these challenges, relay technology has been widely investigated to improve the transmission efficiency, restrain the interference between adjacent cells and expand the network coverage [1]. In contrast to one-way relaying, two-way relaying brings performance gains on spectral efficiency in relay systems [2]. Therefore, two-way relaying has become an extensively concerned research field in recent years, which can find broad applications in wireless cellular network, satellite communication, device-to-device communication and vehicular communication [3–5].

Integrating multiple-input multiple-output (MIMO) technology into two-way relaying networks (TWRNs) [6] with amplify-and-forward (AF) protocol has gained wide attention owing to the significant benefits in transmission reliability and efficiency [7, 8]. On the other hand, as AF relays usually advocate cost-effective design [9], some research efforts have been devoted to simplify the relay design while maintaining the system performance. An attractive solution is the relay antenna selection with source beamforming (RAS-BF) scheme minimizing the system outage probability [10, 11], which can not

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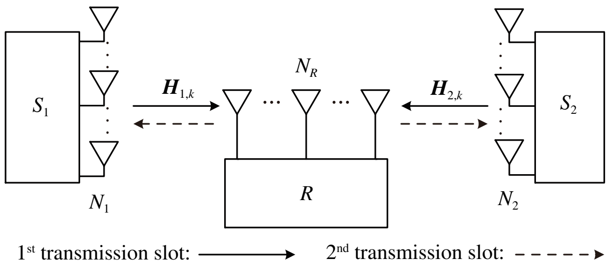

Figure 1 A MIMO two-way relaying network.

only achieve the maximum diversity order, but also alleviate the burden of configuring multiple radio frequency (RF) chains on the AF relays. However, the implementation of RAS-BF scheme requires the relay to monitor the instantaneous channel state information (CSI) and compute the received signal-to-noise ratio (SNR) associated with each antenna, increasing the energy consumption and complexity of relay devices, which may limit its application in energy-constrained wireless relay networks.

Motivated by the above consideration, this paper presents a simplified RAS-BF scheme for MIMO TWRNs, which promises low complexity and high real-time capability. Furthermore, the system outage probability and average symbol error rate (SER) performance of the proposed scheme are investigated over generalized and versatile Nakagami-m fading channels. Theoretical and simulation results corroborate our scheme.

Notations: $x \sim G(m,n)$ represents a variable follows gamma distribution with parameter m and n, $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\dagger}$ denote transpose and complex conjugate transpose respectively. $\|\cdot\|_{\mathrm{F}}$ means the Frobenius norm, I_N is the identity matrix with order N, and $\Pr\{\cdot\}$ denotes probability.

2 System model

We consider a half-duplex MIMO TWRN, as shown in Figure 1, where two sources S_1 and S_2 communicate with each other via a relay R and the number of antenna on each node is denoted by N_1, N_2 and N_R, respectively. It is assumed that R operates in AF strategy and is limited to one RF chain due to the hardware complexity constraint.

With the RAS-BF scheme, transmit and receive beamforming are employed at the two source nodes, while antenna selection is performed at the relay node to reduce its implementation complexity. In the 1st transmission slot, S_1 and S_2 transmit simultaneously to R utilizing maximal-ratio transmission (MRT). The signal received at the kth antenna of R, $k \in S_{\text{ant}} = \{1, 2, \ldots, N_R\}$, can be expressed as

$$y_{R_k} = \sqrt{P_1}\boldsymbol{H}_{1,k}\boldsymbol{w}_{1,k}x_1 + \sqrt{P_2}\boldsymbol{H}_{2,k}\boldsymbol{w}_{2,k}x_2 + n_{R_k}, \tag{1}$$

where x_i, $i \in \{1, 2\}$, denotes the unit-energy signal transmitted by S_i, and P_i represents the corresponding transmit power. $\boldsymbol{H}_{i,k} = [h_{i,1,k}, h_{i,2,k}, \ldots, h_{i,N_i,k}] \in C^{1\times N_i}$ represents the channel vector between S_i and the kth antenna of R, and the elements in $\boldsymbol{H}_{i,k}$ are assumed to be statistically independent with $m_{i,l,k}$ and $\Omega_{i,l,k}$, $l \in \{1, 2, \ldots, N_i\}$, denote their shape parameter and scale parameter, respectively. n_{R_k} stands for additive white Gaussian noise (AWGN) with zero mean and variance N_0. Furthermore, $\boldsymbol{w}_{i,k} \in C^{N_i\times 1}$ is the MRT beamforming vector at S_i and given by $\boldsymbol{w}_{i,k} = \boldsymbol{H}^{\dagger}_{i,k}/\|\boldsymbol{H}_{i,k}\|_F$. In the 2$^{\text{nd}}$ transmission slot, the kth antenna of R broadcasts the received signal y_{R_k} after scaling it by the factor G_{R_k}. Assuming the channel between S_i and R is reciprocal and using maximal-ratio combining (MRC) to process the received signal from each antenna, the resultant signal at S_i can be given by

$$z_i = \boldsymbol{w}^{\mathrm{T}}_{i,k}\left(\boldsymbol{H}^{\mathrm{T}}_{i,k}G_{R_k}y_{R_k} + \boldsymbol{n}_i\right), \tag{2}$$

where $G_{R_k} = \sqrt{P_R/(P_1\|\boldsymbol{H}_{1,k}\|^2_F + P_2\|\boldsymbol{H}_{2,k}\|^2_F + N_0)}$, P_R is the transmit power of the relay R and $\boldsymbol{n}_i \in C^{N_i\times 1}$ represents the AWGN vector with mean power $I_{N_i}N_0$ at S_i.

Plugging (1) into (2) and after the self-interference cancellation, the received SNR of the link $S_i \to R \to S_j$ can be derived as

$$\Gamma_{ikj} = \frac{\gamma_i \gamma_R \left\| \boldsymbol{H}_{i,k} \right\|_F^2 \left\| \boldsymbol{H}_{j,k} \right\|_F^2}{(\gamma_j + \gamma_R) \left\| \boldsymbol{H}_{j,k} \right\|_F^2 + \gamma_i \left\| \boldsymbol{H}_{i,k} \right\|_F^2 + 1}, \quad (i,j) \in \{(1,2), (2,1)\}, \tag{3}$$

where $\gamma_1 = P_1/N_0$, $\gamma_2 = P_2/N_0$, $\gamma_R = P_R/N_0$ and the resultant relay-assisted unidirectional data rate can be expressed as $R_{ikj} = \frac{1}{2}\log_2(1 + \Gamma_{ikj})$. Then the outage-optimal selection criterion [10] is to select the relay antenna k^* that maximizes the minimum received SNR at the two sources, which is mathematically presented as

$$k^* = \arg \max_{k \in S_{\rm ant}} \{\min\{\Gamma_{1k2}, \Gamma_{2k1}\}\}. \tag{4}$$

Regarding the implementation of the optimal scheme, it can be seen from (3) and (4) that the relay node is first required to estimate the channel $\boldsymbol{H}_{i,k}$ from source i to its kth antenna so that the equivalent channel gain $\left\| \boldsymbol{H}_{i,k} \right\|_F$ can be obtained. As the estimation of $\boldsymbol{H}_{1,k}$ and $\boldsymbol{H}_{2,k}$ requires N_1 and N_2 time slots respectively, a total of $(N_1 + N_2)N_R$ time slots are required to complete the channel estimation, which can then be used to compute the E2E SNR pertaining to each antenna. Due to the fact that the calculation of the instantaneous SNR requires continuous CSI monitoring from the two sources and channel estimation leads to an increase in the overhead of hardware and energy, it may hinder the usefulness of RAS-BF in practical energy-constrained relay network.

Simplified RAS-BF scheme. It is observed from (3) that Γ_{ikj} can be upper bounded by

$$\Gamma_{ikj} = \frac{\gamma_i \left\| \boldsymbol{H}_{i,k} \right\|_F^2}{\frac{\gamma_j \left\| \boldsymbol{H}_{j,k} \right\|_F^2 + \gamma_i \left\| \boldsymbol{H}_{i,k} \right\|_F^2 + 1}{\gamma_R \left\| \boldsymbol{H}_{j,k} \right\|_F^2} + 1} \leqslant \gamma_i \left\| \boldsymbol{H}_{i,k} \right\|_F^2, \quad (i,j) \in \{(1,2), (2,1)\}. \tag{5}$$

If Γ_{ikj} is replaced by the proposed upper bound in (5), then the 'best' relay antenna k^* turns out to be

$$\begin{aligned} k^* &= \arg \max_{k \in S_{\rm ant}} \left\{ \min \left\{ \gamma_1 \left\| \boldsymbol{H}_{1,k} \right\|_F^2, \gamma_2 \left\| \boldsymbol{H}_{2,k} \right\|_F^2 \right\} \right\} \\ &= \arg \max_{k \in S_{\rm ant}} \left\{ \min \left\{ P_1 \left\| \boldsymbol{H}_{1,k} \right\|_F^2, P_2 \left\| \boldsymbol{H}_{2,k} \right\|_F^2 \right\} \right\} \\ &= \arg \max_{k \in S_{\rm ant}} \left\{ \min \left\{ \underbrace{P_1 \left\| \boldsymbol{H}_{1,k} \right\|_F^2 + N_0}_{P_{R,1k}}, \underbrace{P_2 \left\| \boldsymbol{H}_{2,k} \right\|_F^2 + N_0}_{P_{R,2k}} \right\} \right\} \\ &= \arg \max_{k \in S_{\rm ant}} \{\min\{P_{R,1k}, P_{R,2k}\}\}, \end{aligned} \tag{6}$$

where $P_{R,1k}$ and $P_{R,2k}$ are used to denote the received pilot powers separately from the two sources at the kth antenna of R, and they can be easily obtained by averaging over the square of the received signal's modulus. This finding is interesting in that the optimal relay antenna selection in (4) is now transformed to the comparison among the minimum of $P_{R,1k}$ and $P_{R,2k}$, which is superior to the traditional counterpart as follows:

(1) Most importantly, the proposed scheme relieves the relay node from the burden of channel estimation in the antenna selection process, which leads to reduced implementation complexity and energy consumption. In view of the time overhead of the proposed scheme's implementation, as each antenna at the relay needs one time slot to broadcast and each source occupies one time slot to transmit pilot signaling, the total number of required time slots reduces to $3N_R$, which is independent to the number of source antennas. In contrast, the time overhead of the optimal scheme increases fast as the number of source antennas increases.

(2) In practical MIMO TWRNs, it is well known that CSIs can not be perfectly obtained both in the relay and source nodes due to feedback delay and channel estimation error, which will lead to severe performance degradation. Since the proposed scheme in (6) does not need to calculate the received

SNRs Γ_{1k2} and Γ_{2k1} in (3), where the negative impacts of CSI imperfections may be magnified in the multiplication and division operations, it is expected to provide better robustness than the traditional counterpart, as verified by the simulation results later.

Despite the above advantages, it is unknown whether the proposed scheme is capable of acquiring comparable performance as the optimal one, e.g., could the full-diversity property be maintained? To offer useful insights into practical MIMO TWRN design, it is necessary to analyze and discuss the proposed scheme mathematically. Thus, we present the derivation of two important performance metrics, i.e., outage probability and average SER, in the section below.

3 Performance analysis

3.1 Outage probability

In this part, the performance of the proposed scheme is investigated by deriving the closed-form expression for the system outage probability. In practice, a TWRN is referred to be in outage if either source's data rate falls below the required threshold $R_{\rm th}$, and the system outage probability $P_{\rm out}$ can be mathematically written as

$$P_{\rm out} = \Pr\left\{\Gamma_E < \gamma_{\rm th}\right\}, \tag{7}$$

where $\gamma_{\rm th} = 2^{2R_{\rm th}} - 1$, and $\Gamma_E = \min\left\{\Gamma_{1k^*2}, \Gamma_{2k^*1}\right\}$ represents the minimum of the received SNRs. By applying the well-known bound $\frac{xy}{x+y} \leqslant \min\left\{x, y\right\}$ [12] to Γ_{1k^*2} and Γ_{2k^*1} and after some necessary mathematics manipulations, we can obtain

$$\min\left\{\Gamma_{1k^*2}, \Gamma_{2k^*1}\right\} < \gamma_R \min\left\{\frac{\gamma_1\left\|\boldsymbol{H}_{1,k^*}\right\|_F^2}{\gamma_2+\gamma_R}, \frac{\gamma_2\left\|\boldsymbol{H}_{2,k^*}\right\|_F^2}{\gamma_1+\gamma_R}\right\}. \tag{8}$$

Let $\gamma = P/N_0$ be the system SNR and $P_n = \alpha_n P$, where P and α_n ($n \in \{1, 2, R\}$ and $\sum_n \alpha_n = 1$) represent the overall transmit power and the corresponding power allocation factors respectively, then the system outage probability can be lower bounded as

$$\begin{aligned}
P_{\rm out} &> \Pr\left\{\gamma_R \min\left\{\frac{\gamma_1\left\|\boldsymbol{H}_{1,k^*}\right\|_F^2}{\gamma_2+\gamma_R}, \frac{\gamma_2\left\|\boldsymbol{H}_{2,k^*}\right\|_F^2}{\gamma_1+\gamma_R}\right\} < \gamma_{\rm th}\right\} \\
&> \Pr\left\{\min\left\{\gamma_1\left\|\boldsymbol{H}_{1,k^*}\right\|_F^2, \gamma_2\left\|\boldsymbol{H}_{2,k^*}\right\|_F^2\right\} < \frac{\gamma_{\rm th}\gamma_o}{\gamma_R}\right\} \\
&= \prod_{k=1}^{N_R} \Pr\left\{\min\left\{\gamma_1\left\|\boldsymbol{H}_{1,k}\right\|_F^2, \gamma_2\left\|\boldsymbol{H}_{2,k}\right\|_F^2\right\} < \frac{\gamma_{\rm th}\gamma_o}{\gamma_R}\right\} \\
&= \prod_{k=1}^{N_R}\left[1 - \Pr\left\{\left\|\boldsymbol{H}_{1,k}\right\|_F^2 > \frac{\omega_1\gamma_{\rm th}}{\gamma}\right\}\Pr\left\{\left\|\boldsymbol{H}_{2,k}\right\|_F^2 > \frac{\omega_2\gamma_{\rm th}}{\gamma}\right\}\right] = P_{\rm out}^{\rm lb},
\end{aligned} \tag{9}$$

where $\gamma_o \triangleq \gamma_R + \min\left\{\gamma_1, \gamma_2\right\}$, $\omega_1 = \frac{\gamma_o}{\alpha_1\gamma_R}$, and $\omega_2 = \frac{\gamma_o}{\alpha_2\gamma_R}$.

For simplifying the mathematical analysis, it is supposed that the entries in $\boldsymbol{H}_{i,k}$ are independent and identically Nakagami-m distributed variables, i.e. $m_{i,l,k} = m_{i,k}$ and $\Omega_{i,l,k} = \Omega_{i,k}$, $l \in \left\{1, 2, \ldots, N_i\right\}$. It is shown in [10,13] that $\left\|\boldsymbol{H}_{i,k}\right\|_F^2 \sim G\left(N_i m_{i,k}, \Omega_{i,k}/m_{i,k}\right)$ and its cumulative distribution function (CDF) can be expressed as

$$F_{\left\|\boldsymbol{H}_{i,k}\right\|_F^2}(x) = 1 - \frac{\Gamma\left(N_i m_{i,k}, \frac{m_{i,k}x}{\Omega_{i,k}}\right)}{\Gamma\left(N_i m_{i,k}\right)}, \tag{10}$$

where $\Gamma(\cdot,\cdot)$ denotes the upper incomplete gamma function [14, Eq. (8.350.2)]. By inserting (10) into (9), a closed-form approximation of $P_{\rm out}^{\rm lb}$ can be given by

$$P_{\rm out}^{\rm lb} = \prod_{k=1}^{N_{\rm R}}\left[1 - \frac{\Gamma\left(N_1 m_{1,k}, \frac{m_{1,k}\omega_1\gamma_{\rm th}}{\Omega_{1,k}\gamma}\right)}{\Gamma(N_1 m_{1,k})}\frac{\Gamma\left(N_2 m_{2,k}, \frac{m_{2,k}\omega_2\gamma_{\rm th}}{\Omega_{2,k}\gamma}\right)}{\Gamma(N_2 m_{2,k})}\right]. \tag{11}$$

High SNR approximation. In order to gain some insights into the proposed scheme, we turn to derive a high-SNR approximation of the lower bound in (11). Based on [14, Eqs. (8.356.3), (8.351.2) and (9.210.1)], we can get the following expression that $\Gamma(\alpha, x) \to \Gamma(\alpha) - \frac{x^\alpha}{\alpha}$ as $x \to 0$. By applying this approximation in the high SNR regime, $P_{\text{out}}^{\text{lb}}$ can be asymptotically expressed as

$$P_{\text{out}}^{\text{lb}} \simeq \prod_{k=1}^{N_R} \left[\frac{(m_{1,k}\omega_1\gamma_{\text{th}})^{N_1 m_{1,k}}}{N_1 m_{1,k}\Gamma(N_1 m_{1,k})(\gamma\Omega_{1,k})^{N_1 m_{1,k}}} + \frac{(m_{2,k}\omega_2\gamma_{\text{th}})^{N_2 m_{2,k}}}{N_2 m_{2,k}\Gamma(N_2 m_{2,k})(\gamma\Omega_{2,k})^{N_2 m_{2,k}}} \right]. \tag{12}$$

It can be easily obtained from (12) that

$$P_{\text{out}}^{\text{lb}} \simeq \prod_{k=1}^{N_R} \left[\Theta_k \gamma^{-\min\{N_1 m_{1,k}, N_2 m_{2,k}\}} \right] = \left(\prod_{k=1}^{N_{\text{R}}} \Theta_k \right) \gamma^{-\sum_{k=1}^{N_R} \min\{N_1 m_{1,k}, N_2 m_{2,k}\}}, \tag{13}$$

where

$$\Theta_k = \begin{cases} \frac{(m_{1,k}\omega_1\gamma_{\text{th}})^{N_1 m_{1,k}}}{N_1 m_{1,k}\Gamma(N_1 m_{1,k})\Omega_{1,k}^{N_1 m_{1,k}}}, & N_1 m_{1,k} < N_2 m_{2,k}, \\ \frac{(m_{1,k}\omega_1\gamma_{\text{th}})^{N_1 m_{1,k}}}{N_1 m_{1,k}\Gamma(N_1 m_{1,k})\Omega_{1,k}^{N_1 m_{1,k}}} + \frac{(m_{2,k}\omega_2\gamma_{\text{th}})^{N_2 m_{2,k}}}{N_2 m_{2,k}\Gamma(N_2 m_{2,k})\Omega_{2,k}^{N_2 m_{2,k}}}, & N_1 m_{1,k} = N_2 m_{2,k}, \\ \frac{(m_{2,k}\omega_2\gamma_{\text{th}})^{N_2 m_{2,k}}}{N_2 m_{2,k}\Gamma(N_2 m_{2,k})\Omega_{2,k}^{N_2 m_{2,k}}}, & N_1 m_{1,k} > N_2 m_{2,k}. \end{cases} \tag{14}$$

Then for the proposed scheme, the diversity gain G_{d} and coding gain G_{c}, which are important parameters to characterize the system performance, can be respectively given by

$$G_{\text{d}} = \sum_{k=1}^{N_R} \min\{N_1 m_{1,k}, N_2 m_{2,k}\}, \quad G_{\text{c}} = \left(\prod_{k=1}^{N_R} \Theta_k \right)^{-1/G_{\text{d}}}. \tag{15}$$

It is worth mentioning that when $m_{1,k} = m_1$ and $m_{2,k} = m_2$, the resultant diversity gain agrees with that of the optimal scheme [10], which highlights the usefulness of our proposed scheme.

3.2 Average SER

The average SER is also an important performance metric to evaluate TWRNs. For the proposed scheme, the mathematical expression of average SER can be given by [15–17]

$$P_{\text{SER}} = aE_{\Gamma_E}\left[Q\left(\sqrt{b\Gamma_E} \right) \right], \tag{16}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \mathrm{e}^{-\frac{y^2}{2}} \mathrm{d}y$, the parameters a and b depend on the modulation methods. Specifically, $a = 4(1 - \frac{1}{\sqrt{M}})$, $b = \frac{3}{M-1}$ for MQAM, $a = 2$, $b = 2\sin^2(\frac{\pi}{M})$ for MPSK ($M \geqslant 4$), and $a = 1$, $b = 1$ for BPSK. Through integrating (16) partially, the average SER can be rewritten as

$$P_{\text{SER}} = \frac{a\sqrt{b}}{2\sqrt{\pi}} \int_0^\infty \frac{\mathrm{e}^{-bz}}{\sqrt{z}} F_{\Gamma_E}(z) \mathrm{d}z, \tag{17}$$

where $F_{\Gamma_E}(z)$ denotes the CDF of Γ_E.

Obviously, $P_{\text{out}} = \Pr\{\Gamma_E < \gamma_{\text{th}}\} = F_{\Gamma_E}(\gamma_{\text{th}})$. Replacing γ_{th} by z in (12), the lower bound of $F_{\Gamma_E}(z)$ can be asymptotically expressed as

$$F_{\Gamma_E}^{\text{lb}}(z) \simeq \prod_{k=1}^{N_R} \left[\frac{(m_{1,k}\omega_1 z)^{N_1 m_{1,k}}}{N_1 m_{1,k}\Gamma(N_1 m_{1,k})(\gamma\Omega_{1,k})^{N_1 m_{1,k}}} + \frac{(m_{2,k}\omega_2 z)^{N_2 m_{2,k}}}{N_2 m_{2,k}\Gamma(N_2 m_{2,k})(\gamma\Omega_{2,k})^{N_2 m_{2,k}}} \right], \tag{18}$$

which can be further represented as

$$F_{\Gamma_E}^{\mathrm{lb}}(z) \simeq \prod_{k=1}^{N_R}\left[\Psi_k\left(\frac{z}{\gamma}\right)^{\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}}\right] = \left(\prod_{k=1}^{N_R}\Psi_k\right)\left(\frac{z}{\gamma}\right)^{\sum\limits_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}}, \tag{19}$$

where

$$\Psi_k = \begin{cases} \dfrac{(m_{1,k}w_1)^{N_1m_{1,k}}}{N_1m_{1,k}\Gamma(N_1m_{1,k})(\Omega_{1,k})^{N_1m_{1,k}}}, & N_1m_{1,k} < N_2m_{2,k}, \\ \dfrac{(m_{1,k}w_1)^{N_1m_{1,k}}}{N_1m_{1,k}\Gamma(N_1m_{1,k})(\Omega_{1,k})^{N_1m_{1,k}}} + \dfrac{(m_{2,k}w_2)^{N_2m_{2,k}}}{N_2m_{2,k}\Gamma(N_2m_{2,k})(\Omega_{2,k})^{N_2m_{2,k}}}, & N_1m_{1,k} = N_2m_{2,k}, \\ \dfrac{(m_{2,k}w_2)^{N_2m_{2,k}}}{N_2m_{2,k}\Gamma(N_2m_{2,k})(\Omega_{2,k})^{N_2m_{2,k}}}, & N_1m_{1,k} > N_2m_{2,k}. \end{cases} \tag{20}$$

By substituting (19) into (17) and with the aid of [14, Eq. (3.381.4)], the lower bound of average SER $P_{\mathrm{SER}}^{\mathrm{lb}}$ can be derived as

$$\begin{aligned} P_{\mathrm{SER}}^{\mathrm{lb}} &= \frac{a\sqrt{b}}{2\sqrt{\pi}}\int_0^\infty \frac{\mathrm{e}^{-bz}}{\sqrt{z}}\left(\prod_{k=1}^{N_\mathrm{R}}\Psi_k\right)\left(\frac{z}{\gamma}\right)^{\sum\limits_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}}\mathrm{d}z \\ &= \frac{a\sqrt{b}}{2\sqrt{\pi}}\left(\prod_{k=1}^{N_\mathrm{R}}\Psi_k\right)\gamma^{-\sum\limits_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}}\int_0^\infty \mathrm{e}^{-bz}z^{\sum\limits_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}-\frac{1}{2}}\mathrm{d}z \\ &= \frac{a\sqrt{b}}{2\sqrt{\pi}}\left(\prod_{k=1}^{N_\mathrm{R}}\Psi_k\right)\frac{\Gamma\left(\sum_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}+\frac{1}{2}\right)}{b^{\sum\limits_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}+\frac{1}{2}}}\gamma^{-\sum\limits_{k=1}^{N_R}\min\{N_1\mathrm{m}_{1,k},N_2\mathrm{m}_{2,k}\}}. \end{aligned} \tag{21}$$

It is obvious from (21) that the diversity gain $G_\mathrm{d} = \sum_{k=1}^{N_R}\min\{N_1m_{1,k}, N_2m_{2,k}\}$, which is consistent with the outage analysis.

4 Simulation results

In this part, representative simulations are presented to justify the proposed scheme and the corresponding theoretical analysis. Without loss of generality, we normalize the distance between S_1 and S_2 to 1 and use d_{2R} to represent the normalized distance between S_2 and R. The path loss exponent is 3, which leads to $\Omega_{2,k} = \Omega_2 = d_{2R}^{-3}$ and $\Omega_{1,k} = \Omega_1 = (1-d_{2R})^{-3}$. Furthermore, we assume $m_{1,k} = m_1$=0.5 and $m_{2,k} = m_2$=1.5, the power allocation factors $\{\alpha_1, \alpha_2, \alpha_R\}$ are randomly set as $\{5/12, 1/3, 1/4\}$, and the data rate threshold $R_{\mathrm{th}} = 1$ bit·s^{-1}·Hz^{-1}.

4.1 Comparison with the optimal scheme

Figure 2 presents the system outage probability of RAS-BF versus SNR for fixed relay location d_{2R}=0.5 with various antenna configurations. It can be observed that our proposed scheme achieves nearly the same performance as the optimal counterpart and the derived lower bound is proved to be tight at the high SNR region. In order to further validate the effectiveness of this bound, we define relative approximation error as follows:

$$\mu = \frac{|\text{lower bound} - \text{simulation result}|}{\text{simulation result}}. \tag{22}$$

Figure 3 shows the relative approximation error of RAS-BF versus SNR with various antenna configurations. Although the relative approximation error is relatively large in the low SNR regime, the accuracy of the lower bound improves as the SNR increases and it gradually approaches to zero. It is worth mentioning that the relative large approximation error observed in the low SNR regime is mainly

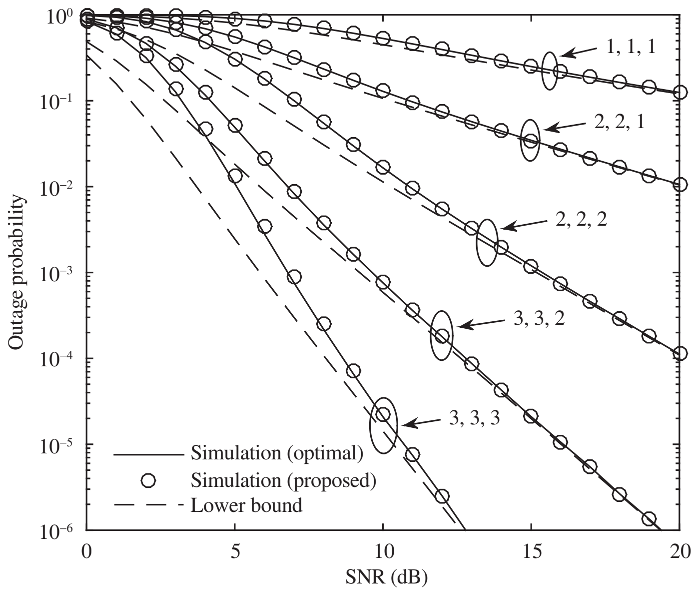

Figure 2 Outage probability of RAS-BF against SNR for various antenna configurations $\{N_1,\ N_2,\ N_R\}$ and d_{2R}=0.5.

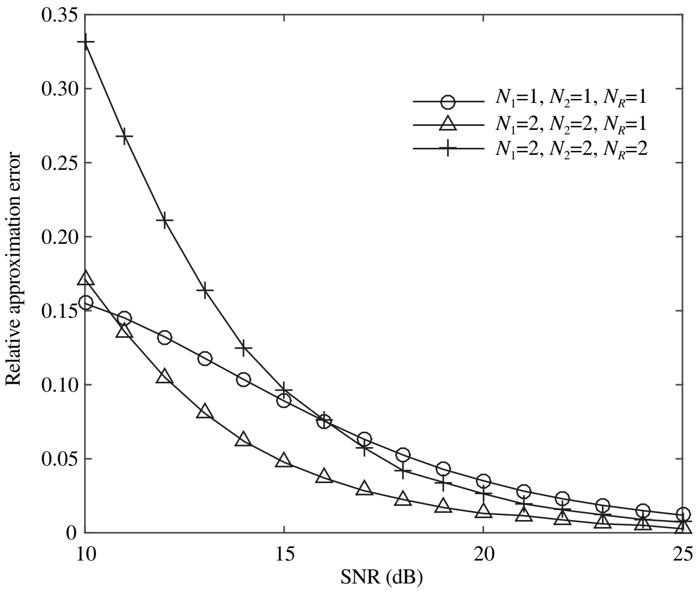

Figure 3 Relative approximation error of the proposed scheme versus SNR for various antenna configurations $\{N_1,\ N_2,\ N_R\}$ and d_{2R}=0.5.

due to the upper bound of the received SNRs, as introduced in (8), which results in a smaller integral region to derive the lower bound of the system outage probability. In summary, this lower bound can be safely used to characterize the performance of the proposed scheme and the exact outage performance will be left for the future work.

In Figure 4, we fix SNR=15 dB and present the outage performance versus relay location d_{2R} for various antenna configurations. It can be observed that the proposed scheme achieves almost the same performance as the optimal counterpart when d_{2R} changes. Therefore, the effectiveness of the proposed scheme is verified under different relay location scenarios and the relay nodes can be deployed in an outage-optimal manner to improve the system performance.

Figure 5 presents the average SER of RAS-BF against SNR for different relay antenna number N_R. We assume N_1=2, N_2=2, d_{2R}=0.5 and adopt 16QAM modulation method. It can be found that the average SER of the proposed scheme matches well with the optimal scheme and increasing the antennas

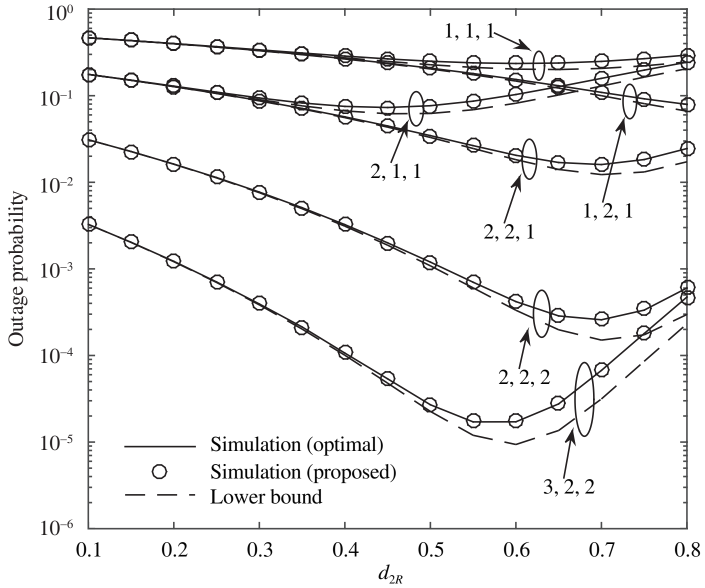

Figure 4 Outage probability against d_{2R} for various antenna configurations $\{N_1, N_2, N_R\}$ and SNR=15 dB.

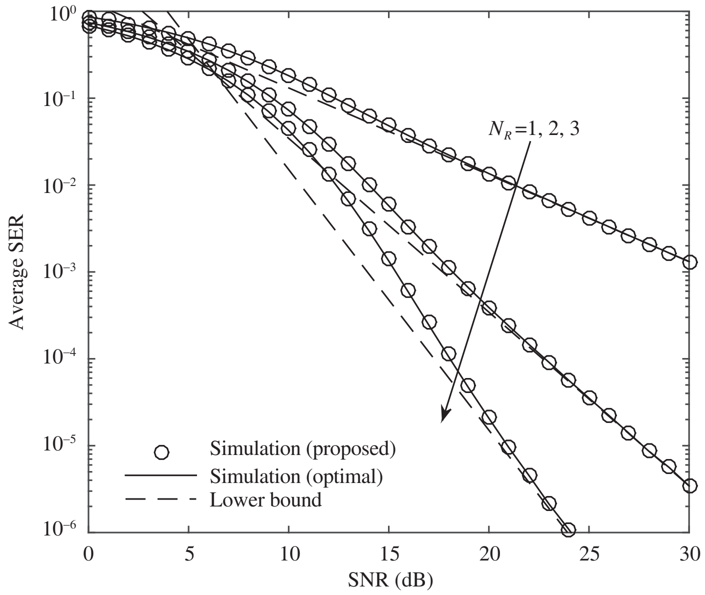

Figure 5 Average SER of RAS-BF against SNR for different relay antenna number N_R, with N_1=2, N_2=2 and d_{2R}=0.5.

at the relay will greatly lower the average SER. Moreover, the derived lower bound is in line with the simulation results in the high SNR regime, which also confirms our analytical results.

4.2 Impact of imperfect CSI

In most of the previous studies, it is assumed that the CSIs can be perfectly obtained both at the relay and the terminals, which is far from practice in real application. These CSI imperfections will result in severe performance degradation [18–20], and thereby the outage performance is used here as an example to illustrate the negative impacts of feedback delay and channel estimation error. Without loss of generality, the correlation coefficients of channels between the relay antenna selection instant and the data transmission instant and those between the real and estimated values are assumed be identical for all the links, which are denoted by $\rho_{\rm d}$ and $\rho_{\rm e}$, respectively.

The outage probability of RAS-BF is presented in Figure 6 when only feedback delay exists. Here

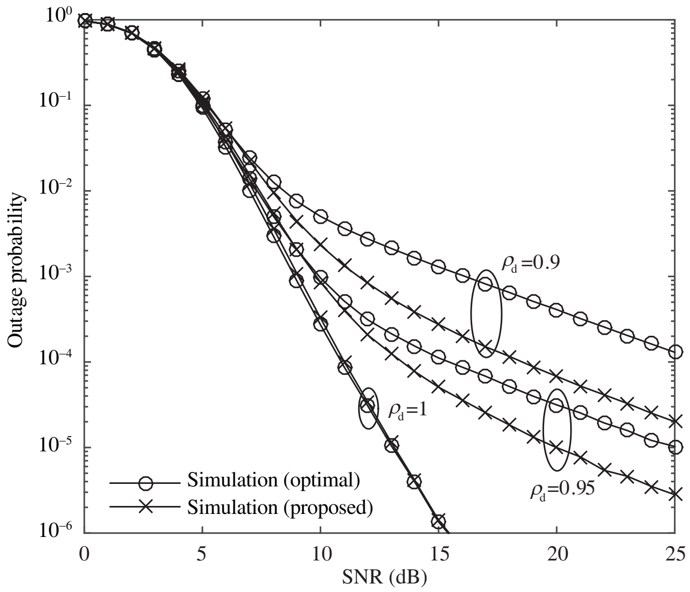

Figure 6 Outage probability of RAS-BF against SNR with the presence of feedback delay when N_1=2, N_2=2, N_R=4 and d_{2R}=0.5.

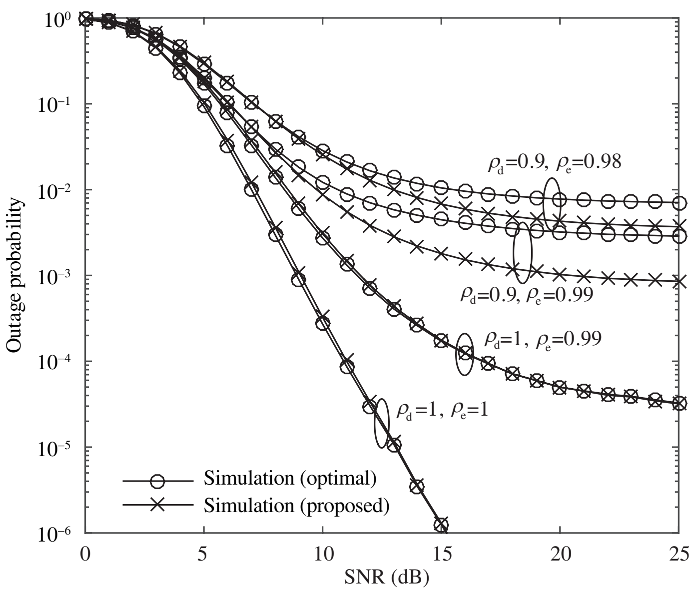

Figure 7 Outage probability of RAS-BF against SNR with the presence of both feedback delay and channel estimation error when N_1=2, N_2=2, N_R=4 and d_{2R}=0.5.

we assume $\rho_e = 1$, i.e., all the channel coefficients are perfectly estimated, and fix N_1=2, N_2=2, N_R=4, d_{2R}=0.5. It can be noticed that the slopes of the simulation curves when $\rho_d = 0.9$ and 0.95 are smaller than that when $\rho_d = 1$, which illustrates that feedback delay causes a loss of diversity order and degrades the system performance. Notably, our proposed scheme performs better than the optimal scheme with the existence of feedback delay.

In Figure 7, outage performance of RAS-BF against SNR is plotted for different CSI scenarios, where $(\rho_d, \rho_e) \in \{(1,1),(1,0.99),(0.9,0.99),(0.9,0.98)\}$. As is expected, channel estimation error causes an error floor and the diversity gain reduces to zero. It is also interesting to see that the proposed scheme outperforms the optimal one when both feedback delay and channel estimation error exist, which indicates that our design can provide more robustness to CSI imperfections in real application.

5 Conclusion

In this work, a novel RAS-BF scheme with low complexity is proposed and analyzed for MIMO TWRNs over Nakagami-m channel. We have investigated the performance of the proposed scheme by deriving tight lower bounds of system outage probability and average SER, from which the diversity gain is obtained. The analytical results show that this simplified scheme can also achieve full diversity order. Simulation results confirm the theoretical analysis and show that the simplified scheme is superior to the outage-optimal counterpart under CSI imperfections, rendering our proposed scheme an attractive solution for practical MIMO TWRNs.

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Conflict of interest The authors declare that they have no conflict of interest.

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