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RESEARCH ARTICLE

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Analysis of maximal-ratio of transmitting/receiving antenna selection with perfect and partial channel information

Abstract To improve system performance and reduce the complexity and cost of receiver hardware, we investigated a new multiple-input multiple-output (MIMO) scheme combining maximal-ratio transmitting and receiver antenna selection (MRT/RAS). In this scheme, a single receiving antenna, which maximizes the signal-to-noise ratio (SNR) at the receiver, is selected for demodulation. The closed-form outage probability and the bit error rate (BER) of the MRT/RAS system are both presented. The simulation demonstrates that the MRT/RAS scheme can achieve a full diversity order as if all the receiving antennas were used. It is shown that the MRT/RAS scheme outperforms some more complex space-time codes of the same spectral efficiency. The analytical results are verified by simulation. In the end, we also analyze the MRT/RAS system based on partial channel information.

Keywords multi-input multi-output (MIMO), antenna selection, maximal-ratio transmitting, diversity

1 Introduction

Recent research has demonstrated that the multi-input multi-output (MIMO) scheme can significantly increase system capability and improve overall performance [1–3]. MIMO channels can be exploited to improve system performance through diversity techniques such as relative delay [4], spreading codes [5] and space-time (ST) coding [6,7], none of which requires or uses information about the current channel state. However, if the channel state information (CSI) is available in the transmitter, potentially increased performance can be obtained with an adaptive transmitter diversity scheme, i.e., the maximum ratio transmission (MRT) [8–11]. The MRT leaves the mobile receiver unchanged, in contrast to other transmission diversity schemes. On the other hand, a conventional multiple-antenna system requires the number of radio frequency (RF) chains to be equal to the total number of antennas. This will obviously result in system hardware complexity and considerably increase cost and power consumption, especially for mobile receivers. Therefore, a new MIMO scheme to improve system performance and reduce receiver hardware complexity and cost is timely desirable. However, in Refs. [12,13] only the maximum ratio combination (MRC) was targeted, while in Ref. [14], Thoen S et al. proposed a method that combined the transmitting-SC/receiving-MRC (SC/MRC). The method had two disadvantages. First, with transmitting antenna selection, it utilized array gain inadequately to improve system performance despite achieving a full diversity order gain. Second, with the receiver MRC, the receiver's RF chains do not decrease directly.

Here, we investigate a new downlink MIMO scheme combining the MRT and the receiver antenna selection combination (SC) [15]. A single receiving antenna, which maximizes the received signal-to-noise ratio (SNR), is selected for demodulation [16,17], hereinafter referred to as the maximal-ratio transmitting and receiver antenna selection combination (MRT/RAS) scheme. This paper studies both the closed-form analytical results and the numerical comparisons. The outage probability and the bit error rate (BER), which represent indicative performance, are first derived. The average SNR gain of the MRT/RAS is then quantified and compared with those of other schemes such as space-time block coding (STBC), SC/MRC, and MIMO MRC. Extensive simulation results are presented to validate the analysis and show that the MRT/RAS scheme is suitable for downlink communications in cellular radio systems. Finally, based on the mean feedback model, we analyze the impact of outdated CSI for the MRT/RAS system.

We mainly focus on the error performance of the MRT/RAS scheme instead of capacity studies. The remainder of the paper is organized as follows. The system model is

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introduced in Sect. 2. The performance analysis of the MRT/RAS is presented in Sect. 3, followed by the simulation results and discussion in Sect. 4. Finally, we present conclusions in Sect. 5.

2 System model

We consider an MRT/RAS system equipped with T transmitting and R receiving antennas in flat Rayleigh fading channels, as illustrated in Fig. 1. Let $\boldsymbol{H}$ denote the $R \times T$ channel matrix. Its entries are the corresponding path gain coefficients, which are modeled as samples of complex Gaussian random variables with a zero mean and variance of 0.5 per dimension. An $1 \times T$ vector $\boldsymbol{h}_i$, which is a row of $\boldsymbol{H}$, is used to denote the channel between the T transmitting antenna and the ith receiving antenna.

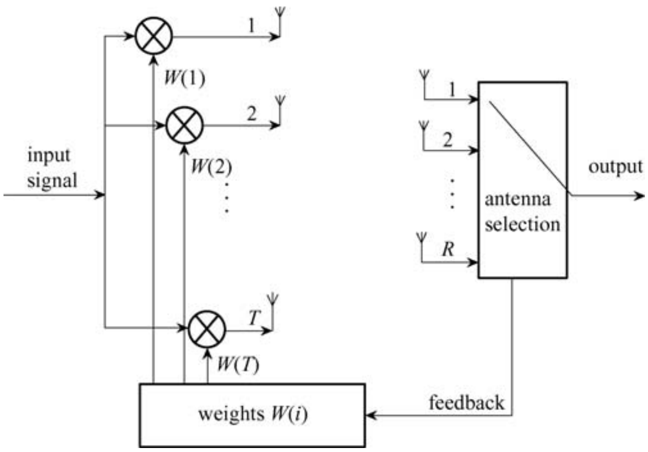

Fig. 1 An (R,T) MRT/RAS system

Let γ_i denote the received SNR of the ith receiving antenna, then the system output SNR γ_o is determined by

$$\gamma_o = \max_{1 \leqslant i \leqslant R} \{\gamma_1, \dots, \gamma_i, \dots, \gamma_R\}. \tag{1}$$

The antenna that maximizes the received SNR is selected for demodulation [16,17]. At any time slot t, the signal $\boldsymbol{s}$ is transmitted with the transmitting weights, and the received signal $\boldsymbol{r}_i$ at the ith receiving antenna can be expressed as

$$\boldsymbol{r}_i = \boldsymbol{h}_i \boldsymbol{W}_i \boldsymbol{s} + \boldsymbol{n}_i, \tag{2}$$

where $\boldsymbol{n}_i$ is plural white Gaussian noise with 0 mean and σ^2 variance of the ith receiving antenna, and $\boldsymbol{W}_i = (w(1), w(2), \dots, w(T))^{\mathrm{T}}$ denotes the corresponding transmitting weights.

Based on the random matrix theory [18], we obtain the statistics of the MIMO system's output SNR through the cumulative distribution function (CDF) of the largest eigenvalue [19,20]. We then apply these results to analyze the exact performance of MRT/RAS over the Rayleigh fading channels. It is well known that the maximal output SNR of the MIMO MRC system (joint MRC weights at both mobile receiver and base station (BS), also known as beamforming systems) is given by Refs. [18,20]:

$$\gamma_{\max} = \frac{P_s}{\sigma^2} \Lambda_{\max} = \bar{\gamma} \Lambda_{\max}, \tag{3}$$

where $\bar{\gamma} = P_s / \sigma^2$ denotes the average SNR per branch, and $\Lambda_{\max}$ denotes the largest eigenvalue of the matrix $\boldsymbol{H}^{\mathrm{H}} \boldsymbol{H}$. The probability density function (PDF) $f_{\Lambda_{\max}}(u)$ and the CDF $F_{\Lambda_{\max}}(u)$ of $\Lambda_{\max}$ are then given by (let $t = \max\{R, T\}$, $r = \min\{R, T\}$) [19]

$$f_{\Lambda_{\max}}(u) = \frac{1}{\left[\prod_{i=1}^{r} (r-i)!(t-i)!\right]} \frac{\mathrm{d}}{\mathrm{d}u} \det(\boldsymbol{S}(u)), \tag{4}$$

$$F_{\Lambda_{\max}}(u) = \frac{\det(\boldsymbol{S}(u))}{\left[\prod_{i=1}^{r} (r-i)!(t-i)!\right]}, \tag{5}$$

where $\boldsymbol{S}(u)$ is an $r \times r$ Hankel matrix, the kth row and the lth column of $\boldsymbol{S}(u)$ is

$$(\boldsymbol{S}(u))_{k,l} = S_{k,l}(u) = \Gamma(t - r + k + l - 1, u)$$

and the incomplete Gamma function $\Gamma(k+1, u)$ has the represention:

$$\Gamma(k+1, u) = \int_0^u x^k \exp(-x) \mathrm{d}x = k! \left[1 - \mathrm{e}^{-u} \sum_{m=0}^{k} \frac{u^m}{m!}\right], \quad k = 0, 1, 2, \dots, \quad u > 0.$$

By applying Eqs. (3)–(5), we can get the PDF and CDF of the maximal output SNR of MIMO systems:

$$f_{\gamma_{\max}}(u) = \frac{1}{\bar{\gamma}} f_{\Lambda_{\max}}\left(\frac{u}{\bar{\gamma}}\right), \tag{6}$$

$$F_{\gamma_{\max}}(u) = F_{\Lambda_{\max}}\left(\frac{u}{\bar{\gamma}}\right). \tag{7}$$

Obviously, assuming $t = T$ and $r = 1$, we can obtain the closed-form PDF and CDF of output SNR of the $1 \times T$ MRT system with Eqs. (6) and (7), in a way similar to that in Ref. [18]. Note that all matrices in Eqs. (6) and (7) are reduced to scalar quantities:

$$f_\gamma(u) = \frac{1}{\bar{\gamma}(T-1)!} \left(\frac{1}{\bar{\gamma}} u\right)^{T-1} \exp\left(-\frac{1}{\bar{\gamma}} u\right), \tag{8}$$

$$F_\gamma(u) = 1 - \exp\left(-\frac{1}{\bar{\gamma}} u\right) \sum_{m=0}^{T-1} \frac{\left(\frac{1}{\bar{\gamma}} u\right)^m}{m!}, \tag{9}$$

which agrees with the result in Ref. [10].

Since we assume reception of different mobile antennas are mutually independent events, then the received SNR γ_i are independent and uniform distribution random variables. Based on order statistics theory [21], we get the PDF and CDF of output SNR γ_o of MRT/RAS system with Eqs. (1), (8) and (9):

$$f_{\gamma_o}(u) = Rf_{\gamma}(u)\left[F_{\gamma}(u)\right]^{R-1} = \frac{Ru^{T-1}}{\bar{\gamma}^T(T-1)!}\exp\left(-\frac{1}{\bar{\gamma}}u\right) \times \left[1-\exp\left(-\frac{1}{\bar{\gamma}}u\right)\sum_{m=0}^{T-1}\frac{\left(\frac{1}{\bar{\gamma}}u\right)^m}{m!}\right]^{R-1}, \quad (10)$$

$$F_{\gamma_o}(u) = \left(F_{\gamma}(u)\right)^R = \left[1-\exp\left(-\frac{1}{\bar{\gamma}}u\right)\sum_{m=0}^{T-1}\frac{\left(\frac{1}{\bar{\gamma}}u\right)^m}{m!}\right]^R. \quad (11)$$

3 Performance analysis

In this section, we carry out a thorough and exact analysis for MRT/RAS over a fading channel, applying the statistic features of the MRT/RAS system's output SNR. We mainly focus on the outage probability, BER and SNR gain.

3.1 Outage probability

Outage probability, P_{out}, is an important performance measurement for wireless communication systems. It is defined as the probability that the received SNR falls below a threshold value, denoted by γ_{th}. For the MRT/RAS system, the channel outage probability can be calculated by evaluating the CDF of the output SNR at the threshold γ_{th}, i.e., $P_{\text{out}} = F_{\gamma_o}(\gamma_{\text{th}})$. Using Eq. (11), the outage probability is given by

$$P_{\text{out}} = F_{\gamma_o}(\gamma_{\text{th}}) = \left[1-\exp\left(-\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)\sum_{m=0}^{T-1}\frac{\left(\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)^m}{m!}\right]^R. \quad (12)$$

When $R = 1$, i.e., for the typical MRT system, Eq. (12) can be then simplified as

$$P_{\text{out}} = 1-\exp\left(-\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)\sum_{m=0}^{T-1}\frac{\left(\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)^m}{m!}, \quad (13)$$

which agrees with the results in Refs. [9,10].

When $R = 2$, the receiver will choose the receiving antenna with the larger received SNR, and the outage probability can be obtained from Eq. (12):

$$P_{\text{out}} = \left[1-\exp\left(-\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)\sum_{m=0}^{T-1}\frac{\left(\frac{\gamma_{\text{th}}}{\bar{\gamma}}\right)^m}{m!}\right]^2. \quad (14)$$

3.2 Bit error rate (BER)

For wireless communication systems employing diversity reception, the average BER can be calculated by averaging the corresponding BER in the additive white Gaussian noise (AWGN) channel over the PDF of the output SNR, i.e., [22]

$$P = \int_0^{\infty} P_{\text{b}}(E|\gamma_o = x)f_{\gamma_o}(x)\text{d}x, \quad (15)$$

where $P_{\text{b}}(E|\gamma_o = x)$ denotes the BER of the modulation scheme of interest in the AWGN channel with SNR $\gamma_o = x$. For example, for the special case of incoherent DPSK, $P_{\text{b}}(E|\gamma_o = x) = \text{e}^{-x}/2$; and $P_{\text{b}}(E|\gamma_o = x) = Q(2x)$ for BPSK/QPSK, where $Q(\cdot)$ is the Gaussian Q-function [22]. After applying Eq. (11), it can be shown that the average BER of incoherent DPSK with MRT/RAS is given by

$$P_{R\times T} = \frac{R}{2(\bar{\gamma})^T(T-1)!}\int_0^{\infty} x^{T-1}\text{e}^{-(x+x/\bar{\gamma})} \times \left[1-\text{e}^{-x/\bar{\gamma}}\sum_{m=0}^{T-1}\frac{\left(\frac{x}{\bar{\gamma}}\right)^m}{m!}\right]^{R-1}\text{d}x. \quad (16)$$

When $R = 1$, i.e., for the typical MRT system, Eq. (16) can be simplified as

$$P_{1\times T} = \frac{1}{2}(1+\bar{\gamma})^{-T}, \quad (17)$$

which also agrees with the result in Ref. [10].

When $R = 2$, the average BER can be obtained from Eq. (16)

$$P_{2\times T} = \frac{1}{(\bar{\gamma})^T(T-1)!}\int_0^{\infty} x^{T-1}\text{e}^{-(x+x/\bar{\gamma})} \times \left[1-\text{e}^{-x/\bar{\gamma}}\sum_{m=0}^{T-1}\frac{\left(\frac{x}{\bar{\gamma}}\right)^m}{m!}\right]\text{d}x. \quad (18)$$

When $T = 1$, Eq. (16) can be tranformed into:

$$P_{R\times 1} = \frac{R}{2\bar{\gamma}}\int_0^{\infty} \text{e}^{-(x+x/\bar{\gamma})}(1-\text{e}^{-x/\bar{\gamma}})^{R-1}\text{d}x, \quad (19)$$

which is the typical SC system's average BER expression [23]. The latter simulation results demonstrate that the MRT/RAS scheme can achieve a full diversity order and a good array gain.

3.3 Average SNR gain

The error performance is compared between the MRT/RAS scheme and the STBC, SC/MRC, and MIMO schemes in this section. Let the four schemes have the same total transmitted power. The average SNR gain ξ is defined as the ratio between the average output SNR, $E\{\gamma_o\}$ and $\bar{\gamma}$, where $E\{\cdot\}$ denotes the expected value.

The average SNR gain $\xi_{\mathrm{MRT/RAS}}$ of MRT/RAS system can then be given from Eq. (10) as follows:

$$\xi_{\mathrm{MRT/RAS}}=\frac{R}{(T-1)!}\int_0^{\infty}u^T\exp(-u)\times\left[1-\exp(-u)\sum_{m=0}^{T-1}\frac{(u)^m}{m!}\right]^{R-1}\mathrm{d}u. \tag{20}$$

The above integral expression can be evaluated by using

$$\xi_{\mathrm{MRT/RAS}}=\frac{R}{(T-1)!}\times\sum_{k=0}^{R-1}(-1)^k\binom{R-1}{k}\sum_{t=0}^{k(T-1)}\frac{\alpha_t(T,k)(T+t)!}{(t+1)^{T+t+1}}, \tag{21}$$

where $\alpha_t(T,k)$ denotes the coefficient of β^t, with $t=0,1,\ldots,k(T-1)$ used in the following expression

$$\left(\sum_{i=0}^{T-1}\frac{\beta^i}{i!}\right)^k. \tag{22}$$

For a $R\times T$ STBC, the output SNR γ_o is given by Ref. [4]

$$\gamma_o=\frac{\bar{\gamma}}{T}\|H\|_F^2=\frac{\bar{\gamma}}{T}\sum_{i=1}^{T}\sum_{j=1}^{R}|h_{i,j}|^2, \tag{23}$$

from which we obtain its average SNR gain as

$$\xi_{\mathrm{STBC}}=E\left\{\frac{1}{T}\sum_{i=1}^{T}\sum_{j=1}^{R}|h_{i,j}|^2\right\}=R. \tag{24}$$

Using Eqs. (3), (4) and (6), we obtain the average SNR gain ξ_{MIMO} for a MIMO scheme with transmitting T and receiving R antennas as

$$\xi_{\mathrm{MIMO}}=\frac{1}{\left[\prod_{i=1}^{r}(r-i)!(t-i)!\right]}\int_0^{\infty}u\mathrm{d}[\det(\boldsymbol{S}(u))]. \tag{25}$$

From Ref. [14], the average SNR gain $\xi_{\mathrm{SC/MRC}}$ of the SC/MRC system is

$$\xi_{\mathrm{SC/MRC}}=\frac{T}{(R-1)!}\int_0^{\infty}u^R\exp(-u)\times\left[1-\exp(-u)\sum_{m=0}^{R-1}\frac{(u)^m}{m!}\right]^{T-1}\mathrm{d}u, \tag{26}$$

which can be also rewritten in a closed-form as in Eq. (20).

4 Simulation results

4.1 MRT/RAS system with perfect CSI

In this section, we illustrate the analytical and simulation performance for the MRT/RAS scheme in Rayleigh fading channels. We also simulate MIMO, STBC, and SC/MRC schemes for a comparison.

Letting $\bar{\gamma}=3$ dB, we obtain outage probabilities of 1×2, 2×2, and 2×4 MRT/RAS and MIMO schemes and the corresponding 400000 independent channel Monte-Carlo simulation results, as shown in Fig. 2. We can find that analytical curves match well with simulation curves, which indicates that the mathematical analysis is correct. We can see that the MRT/RAS's performance is less than the corresponding MIMO scheme by only about 1 dB. Figure 2 also shows that the slopes of MRT/RAS's outage probability curves are the same as those of MIMO schemes, which indicates that they have the same order diversity gain. These results are also confirmed in Fig. 3. When the number of receiving antenna is reduced to one in Fig. 2, the curve will be the MRT's outage probability.

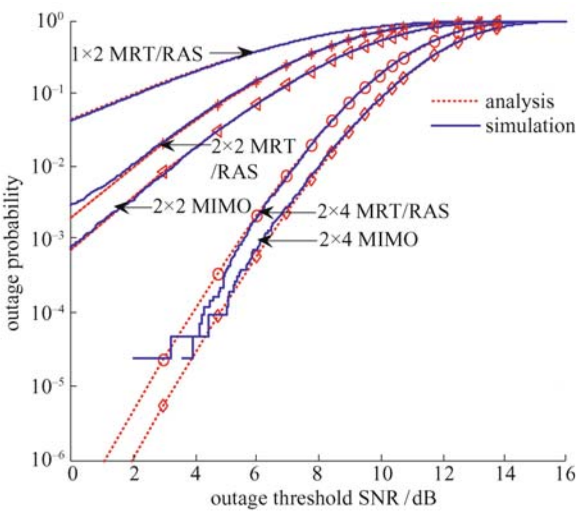

Fig. 2 Outage probability comparison

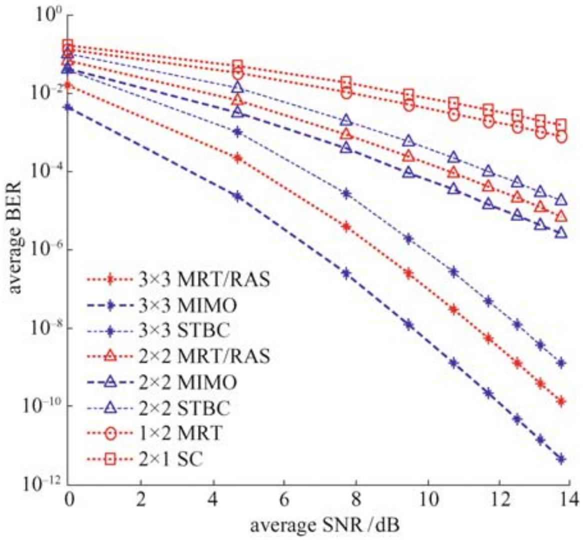

Fig. 3 BER comparison for different systems

We also simulate and compare the BER performances between the MRT/RAS scheme and the MIMO and STBC schemes, as shown in Fig. 3. First, we can find that MRT/RAS scheme has the same performance curve slope as the corresponding STBC and MIMO schemes. This shows that the MRT/RAS scheme can achieve the same full diversity gain as STBC and MIMO schemes in Ref. [24]. Second, it shows that 2×2, 3×3 MRT/RAS schemes are better than the corresponding STBC schemes with 0.7 dB and 1.2 dB respectively, when BER $= 10^{-5}$. These indicate that MRT/RAS can obtain a full diversity gain and a good array gain at the same time, compared with STBC. But 2×2, 3×3 MRT/RAS schemes are worse than the corresponding MIMO schemes with 1 dB, 1.8 dB respectively, when BER $= 10^{-5}$. This is because an MRT/RAS scheme deploys only one RF chain in mobile, preventing full use of the signal power from all of the receiving antennas. Obviously, when the number of antennas is relatively large, the whole system performance will be markedly improved. Therefore, a slight fall in performance is significant with the mobile receiver hardware complexity and cost decrease. It was also found that when the antenna configurations are 1×2, 2×1, the performance curves of the MRT/RAS scheme are those of the 1×2 MRT scheme and 2×1 SC scheme in Fig. 3, which agree with the analytical results of Eqs. (17) and (19).

We compare the average SNR gain between the MRT/RAS scheme and STBC, MIMO, and SC/MRC [14] schemes of the same diversity order in Fig. 4. When the diversity order is 8, we see that the 2×4 MRT/RAS, 2×4 STBC, 2×4 MIMO, and 2×4 SC/MRC have an average SNR gain of 5.094, 2, 6.188, 3.547, respectively. Therefore, the 2×4 MRT/RAS is 4.06 dB, 1.6 dB superior to the 2×4 STBC, SC/MRC, respectively. We can also find that as long as the number of transmitting antennas is larger than that of receiving antennas, which meets the requirements of current MIMO downlink transmission, the performance of the MRT/RAS scheme is superior to that of the SC/MRC scheme. In addtion, when the number of transmitting antennas becomes larger, the performance gain for MRT/RAS becomes better compared with the SC/MRC and STBC schemes.

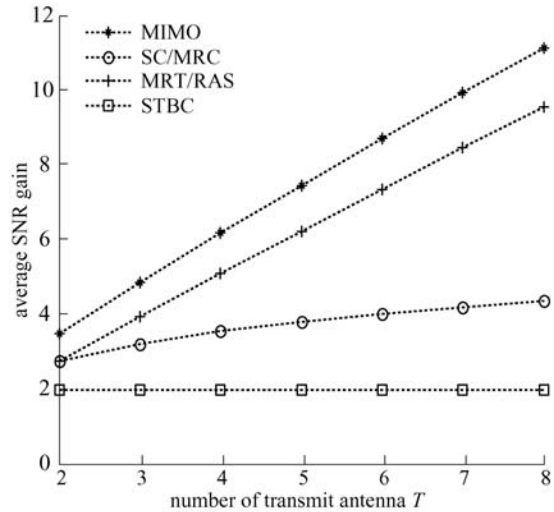

Fig. 4 Average SNR gain comparison (diversity order: $2T$)

4.2 MRT/RAS system based on partial CSI

Similar to the MIMO and SC/MRC schemes, MRT/RAS also requires a feedback link. In practice, perfect channel state information (CSI) is usually impossible to secure at the transmitter [25–27]. Thus, analyzing the MRT/RAS system based on partial channel information is significant.

Perfect channel estimation at the receiver (with infinite quantization resolution) and error-free feedback, which can be approximated by using the error-control coding and automatic repeat request (ARQ) protocol in the feedback channel, are commonly assumed in Refs. [28,29]. Therefore, we focus on the application scenario that the CSI error is caused by a delay or time variance.

Similar to Ref. [29], we focus on channel mean feedback, where spatial fading channels are modeled as Gaussian random variables with nonzero mean and white covariance conditioned on the feedback. The channel is modeled at the transmitter as $\boldsymbol{H} \sim \tilde{C}N\left(\bar{\boldsymbol{H}}, R\sigma_{\varepsilon}^{2} I_{T}\right)$, where $\bar{\boldsymbol{H}}$ is the conditional mean of $\boldsymbol{H}$ given feedback channel $\boldsymbol{H}_f$ and σ_{ε}^{2} can be interpreted as the variance of the estimation error. Matrix $\bar{\boldsymbol{H}}$, which is treated as deterministic, can be regarded as the channel estimation at the transmitter based on partial channel information. Considering $\boldsymbol{H}$ is just a delayed version of $\boldsymbol{H}_f$, their corresponding entries are all consistent with the Gaussian distribution defined earlier with the correlation coefficient $\rho = \mathrm{J}_0(2\pi f_{\mathrm{D}}\tau)$, where $\mathrm{J}_0(\cdot)$ is the zeroth-order Bessel function, f_{D} is the maximum Doppler shift, and τ is the feedback delay. Under this assumption, it can be drawn [29]

$$\bar{\boldsymbol{H}} = E\{\boldsymbol{H}|\boldsymbol{H}_f\} = \rho \boldsymbol{H}_f, \quad (27)$$

$$\sigma_\varepsilon^2 = \left(1 - |\rho|^2\right). \quad (28)$$

Then, similar to Refs. [29,30], Eq. (3) becomes

$$\gamma_{\max} = \bar{\gamma}\Lambda_{\max} = \bar{\gamma}\left(|\rho|^2 \lambda_{f,\max} + R\left(1 - |\rho|^2\right)\right). \quad (29)$$

$\lambda_{f,\max}$ denotes the maximum eigenvalue and corresponding eigenvector of the feedback channel matrix $(\boldsymbol{H}_f)^{\mathrm{H}}\boldsymbol{H}_f$.

Generally, we use the variable $\rho = \mathrm{J}_0(2\pi f_{\mathrm{D}}\tau)$ to describe the feedback quality, where the smaller the value of ρ, the worse the feedback quality. Letting $\bar{\gamma} = 3$ dB, we get outage probabilities of 2×2, 2×4 MRT/RAS schemes with different ρ ($\rho = 0.5$ and $\rho = 0.9$). For comparison, we also plot an outage probability curve with $\rho = 1$ (i.e., the transmitter has perfect CSI) as the benchmark, and the results are shown in Fig. 5. It is clear that the system performance decreases relatively fast as the feedback quality drops.

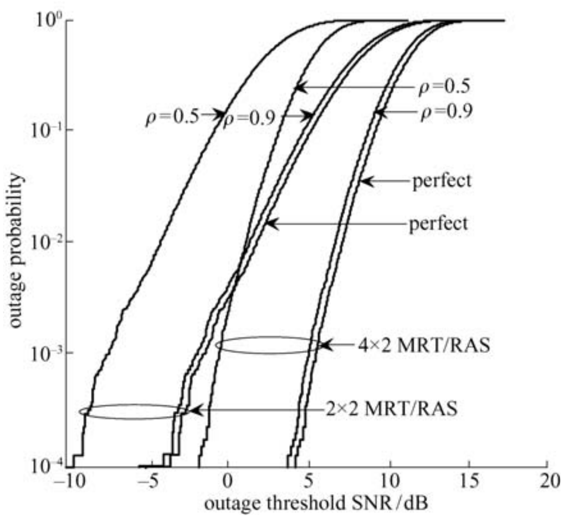

Fig. 5 Impact of delayed CSI

From Fig. 5, we can find that the delay constraint can be relaxed by using more transmitting antennas (or receiving antennas) — an interesting tradeoff between feedback quality and hardware complexity. The performance with $T = 4$, $R = 2$ and $\rho = 0.9$ ($f_{\mathrm{D}}\tau \approx 0.1$) is even 6 dB better than that of $T = 2$, $R = 2$ with perfect CSI. Another method which can effectively restrain the system performance's decline due to feedback delay is application to a multi-user circumstance. The channel gain and feedback quality of different users can be considered as independent random variables, and the overall system performance can be improved through user diversity. However, this is not included here.

5 Conclusions

In this paper, we investigated a new MIMO downlink transmission scheme, MRT/RAS. We analyzed it and obtained mathematical expressions of the performance, which may offer a theoretical guide for the practical application of the scheme. Analysis and simulation results show that MRT/RAS can improve system performance and reduce receiver hardware complexity and cost, compared with the conventional diversity scheme. It satisfies the mobile receiver's strict requirements on hardware complexity, cost and power consumption. Furthermore, an interesting tradeoff between feedback quality and hardware complexity can be obtained.

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