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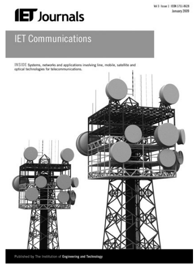

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Performance analysis for multiple-input multiple-output-maximum ratio transmission systems with channel estimation error, feedback delay and co-channel interference

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Abstract: In this study, the authors analyse the impact of channel estimation error (CEE), feedback delay (FD), and co-channel interference (CCI) on the performance of multiple-input multiple-output (MIMO) systems deploying maximum ratio transmission (MRT). In particular, the authors derive closed-form expressions for the ergodic capacity and the symbol error rate (SER) as well as the outage probability (OP). In addition, to reveal the effect of CEE, FD and CCI on the MIMO-MRT system, the authors adopt more simplified and tractable formulas in terms of asymptotic expressions for the ergodic capacity, SER and OP. The analysis shows that the system performance is degraded considerably under imperfect transmission conditions such as CEE, FD and CCI. However, the authors can compensate part of this degradation by deploying MRT transmission with a large number of antennas at the transmitter and receiver. Finally, the selected examples exhibit consistency between analytical results and Monte Carlo simulations.

1 Introduction

Recently, diversity combining techniques, because of their ability to resist fading, have been used extensively to improve the performance of wireless and mobile communication systems [1]. Together with orthogonal space-time block coding (OSTBC) transmission in [2], maximum ratio transmission (MRT) mentioned in [3] is another prominent space-time processing technique. This technique provides transmit diversity for multiple-input multiple-output (MIMO) systems when the channel state information (CSI) is available at both the transmitter and the receiver. To quantify the performance of such diversity combining techniques, an exact performance analysis for maximum ratio combining (MRC) and OSTBC over generalised fading channels has been presented in [4]. Moreover, when perfect CSI is not available in practice, the works of [5, 6] have investigated the effect of channel estimation error (CEE) on the ergodic capacity, the average symbol error rate (SER) and the outage probability (OP) of MIMO-MRT systems. Furthermore, the effect of feedback delay (FD) has been considered in [7]. Besides CEE and FD, co-channel interference (CCI) also significantly degrades the performance of MIMO systems as mentioned in [8]. Later on, in [9, 10], exact expressions for OP and SER of the scheme in [8] have been derived by considering both CCI and CEE at the receiver. So far, the authors of [11] have investigated the performance of a MIMO-MRT system under both CEE and FD.

In this paper, we extend our work reported in [12] by analysing the effect of CEE at the receiver, FD at the transmitter and CCI on the ergodic capacity, SER and OP of the MIMO system deploying MRT transmission. In particular, we derive closed-form expressions for the OP and SER as well as the ergodic capacity. It should be mentioned that we first derive an exact expression for ergodic capacity rather than only an approximation for it as in [12] and other literatures. Furthermore, to gain insights into the system performance, we also derive asymptotic expressions for the OP, SER and ergodic capacity in the high-signal-to-noise ratio (SNR) regime.

Notation: This paper will use the following notations. Bold upper case letters and bold lower case letters denote matrix and vector, respectively. Superscript † indicates the transpose conjugate operator and $\|\cdot\|_F$ stands for the Frobenius norm of a vector or matrix. Then, $f_X(\cdot)$ and $F_X(\cdot)$ represent the probability density function (PDF) and the cumulative distribution function (CDF) of a random variable (RV) X, respectively. Next, a complex Gaussian distribution with mean μ and variance σ^2 is expressed by $\mathcal{CN}(\mu, \sigma^2)$ and $E\{\cdot\}$ denotes the expectation operator. Furthermore, we define $\Gamma(n)$ as the gamma function [13, eq. (8.310.1)] and $\Gamma(n, x)$ as the incomplete gamma function [13, eq. (8.350.2)]. Additionally, $\Psi(a, b; x)$ is the confluent hypergeometric function [13, eq. (9.221.4)] and $G_{ij}^{mn}\left(a \middle| \begin{matrix} b, & c \\ d, & e \end{matrix}\right)$ is the Meijer's G-function in [13, eq. (7.813.1)]. Next, $\Phi(\cdot)$ stands for the moment generating function (MGF) of an RV X and $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind defined in [13, eq. (7.441.1)]. Finally, $C_b^a = b!/(a!(b-a)!)$ denotes the binomial coefficient.

2 System and channel model

We consider a MIMO system with N_1 antennas at transmitter T and N_2 antennas at receiver R. To maximise the signal-to-interference plus noise ratio (SINR), MRT is deployed by multiplying the transmit signal s_t with an $N_1 \times 1$ transmit beam-steering vector $\boldsymbol{v}_t$. We denote $\boldsymbol{H}_t$ as an $N_2 \times N_1$ Rayleigh fading matrix at the time instant t and $\boldsymbol{r}_t$ is an $N_2 \times 1$ received vector. Moreover, $\boldsymbol{n}_t$ denotes an $N_2 \times 1$ additive white Gaussian noise (AWGN) vector at R whose elements are independent and identical distributed (i.i.d.) complex Gaussian RVs denoted as $\mathcal{CN}(0, N_0)$. Consequently, the received signal at R can be given as

$$\boldsymbol{r}_t = \boldsymbol{H}_t \boldsymbol{v}_t s_t + \boldsymbol{n}_t \tag{1}$$

However, under more realistic conditions, we should consider the presence of CCI as mentioned in [9, 10] when investigating the performance of MIMO-MRT systems. In this case, the received signal vector in (1) can be expressed as

$$\tilde{\boldsymbol{r}}_t = \boldsymbol{H}_t \boldsymbol{v}_t s_t + \sqrt{P_I}\boldsymbol{H}_I \boldsymbol{s}_I + \boldsymbol{n}_t \tag{2}$$

where P_I is the average received power of the N_3 interferers. Here, $\boldsymbol{H}_I$ is the $N_2 \times N_3$ channel matrix of N_3 interferers whose elements are i.i.d. complex Gaussian RVs, $\mathcal{CN}(0, 1)$. Further, $\boldsymbol{s}_I$ is the $N_3 \times 1$ transmit symbol vector of N_3 interferers; all CCI symbols are assumed to be i.i.d. with unit power. For implementing MRT transmission, $\boldsymbol{H}_t$ needs to be perfectly measured at R and then sent back to T through a feedback channel. However, in practice, R estimates $\boldsymbol{H}_t$ with a certain amount of error and obtains only an approximation, namely $\tilde{\boldsymbol{H}}_t$. To account for CEE, we introduce $\boldsymbol{E}_t$ as a CEE matrix whose elements are i.i.d. complex Gaussian RVs, $\mathcal{CN}(0, \sigma_e^2)$, for example $\boldsymbol{H}_t = \tilde{\boldsymbol{H}}_t + \boldsymbol{E}_t$ where parameter σ_e^2 represents the variance of CEE. Then R sends $\tilde{\boldsymbol{H}}_t$ back to T. Owing to FD, T obtains a τ-delayed version of the estimated channel matrix $\tilde{\boldsymbol{H}}_t$, namely $\tilde{\boldsymbol{H}}_{t-\tau}$. It is noted that $\boldsymbol{H}_t$ is uncorrelated with $\boldsymbol{E}_t$; but $\tilde{\boldsymbol{H}}_t$ and $\tilde{\boldsymbol{H}}_{t-\tau}$ depend on $\boldsymbol{E}_t$ and all elements of $\tilde{\boldsymbol{H}}_t$ and $\tilde{\boldsymbol{H}}_{t-\tau}$ are i.i.d. complex Gaussian RVs, $\mathcal{CN}\left(0, \left(1-\sigma_e^2\right)\right)$. In case of perfect channel estimation, $\sigma_e^2 = 0$ and in case of completely random estimation error, $\sigma_e^2 = 1$. Considering the effect of FD, we use $\boldsymbol{G}_t$ as an error matrix induced by FD whose elements are i.i.d. complex Gaussian RVs, $\mathcal{CN}\left(0, \left(1-\sigma_e^2\right)\left(1-\rho^2\right)\right)$. Here, ρ is the channel correlation coefficient which presents the FD. As in [14], for the Clarke's fading spectrum, ρ can be obtained as

$$\rho = J_0\left(2\pi f_d \tau\right) \tag{3}$$

where f_d is the Doppler frequency and τ is the FD. The relationship between $\boldsymbol{H}_t$ and $\tilde{\boldsymbol{H}}_{t-\tau}$ is given in [12] as

$$\boldsymbol{H}_t = \rho\tilde{\boldsymbol{H}}_{t-\tau} + \boldsymbol{E}_t + \boldsymbol{G}_t \tag{4}$$

For this imperfect condition, the beam-steering vector, $\boldsymbol{v}_t$, at R is chosen to be the eigenvector $\tilde{\boldsymbol{u}}_t$ corresponding to the largest eigenvalue of the Wishart matrix $\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}$. At R, the received signal from the N_2 antennas is combined by applying the MRC technique, multiplying the received signal with a $1 \times N_2$ weighting vector $\tilde{\boldsymbol{W}}_t = \tilde{\boldsymbol{u}}_t^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}$. Hence, the received signal of the MIMO-MRT system takes into account CEE at R, FD from R to T and CCIs from interferers, and can be expressed as

$$\begin{aligned}\tilde{s}_t = {} & \rho\tilde{\boldsymbol{u}}_t^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}\tilde{\boldsymbol{u}}_t s_t + \tilde{\boldsymbol{u}}_t^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}\boldsymbol{E}_t\tilde{\boldsymbol{u}}_t s_t + \tilde{\boldsymbol{u}}_t^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}\boldsymbol{G}_t\tilde{\boldsymbol{u}}_t s_t \\ & + \tilde{\boldsymbol{u}}_t^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}\sqrt{P_I}\boldsymbol{H}_I\boldsymbol{s}_I + \tilde{\boldsymbol{u}}_t^{\dagger}\tilde{\boldsymbol{H}}_{t-\tau}^{\dagger}\boldsymbol{n}_t\end{aligned} \tag{5}$$

As mentioned in [12], the instantaneous SINR of the considered system is given by

$$\gamma_D = \frac{\gamma_1}{aX + bY + c} = \frac{\gamma_1}{\gamma_2 + c} \tag{6}$$

where a, b, c, respectively, are given by

$$a = \frac{1-\rho^2}{\rho^2} \tag{7}$$

$$b = \frac{P_I}{P_s\rho^2\left(1-\sigma_e^2\right)} \tag{8}$$

$$c = \frac{\sigma_e^2 + \left(1/\left(P_s/N_0\right)\right)}{\rho^2\left(1-\sigma_e^2\right)} \tag{9}$$

Here, X, Y are gamma RVs with parameter sets (N_1, 1) and (N_3, 1), respectively. Moreover, γ_1 is the maximum eigenvalue of a standard Wishart matrix and its PDF is derived in [12, eq. (21)] as

$$f_{\gamma_1}(\gamma_1) = K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k} d_{k,l}\gamma^l \exp(-k\gamma) \tag{10}$$

where $M = \min(N_1, N_2)$, $N = \max(N_1, N_2)$, $K^{-1} = \prod_{i=1}^{M}(N-1)!(i-1)!$ and $d_{k,l}$ is a weighting coefficient obtained numerically using the algorithm proposed in [15]. Finally, $\gamma_2 = aX + bY$ is an RV which captures the effect of CEE, FD as well as CCI. As reported in [12, eq. (24)], the PDF of γ_2 can be derived as

$$f_{\gamma_2}(\gamma_2) = \sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}\gamma_2^{q-1}\exp\left(-\alpha_p\gamma_2\right)}{(q-1)!} \tag{11}$$

where

$$\alpha_1 = \frac{\rho^2}{\left(1-\rho^2\right)}; \quad m_1 = N_1 \tag{12}$$

$$\alpha_2 = \frac{P_S\rho^2\left(1-\sigma_e^2\right)}{P_I}; \quad m_2 = N_3 \tag{13}$$

$$\beta_{pq} = \prod_{i=1}^{2}\frac{\alpha_i^{m_i}}{(m_p-q)!}\left.\frac{d^{\left(m_p-q\right)}\left[\prod_{i=1, i\neq p}^{2}\left(s+\alpha_i\right)^{-m_i}\right]}{d^{\left(m_p-q\right)}s}\right|_{s=\alpha_p} \tag{14}$$

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3 Exact performance analysis

In this section, we present the performance analysis of the MIMO-MRT system. In particular, we derive closed-form expressions for the ergodic capacity, SER and OP of the system. As mentioned in [12, eq. (32)] and [12, eq. (36)], the CDF and PDF of the instantaneous SINR, γ_D are, respectively, given by (see (15) and (16))

$$f_{\gamma_D}(\gamma) = K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k} d_{k,l}\sum_{j=0}^{l+1} C_j^{l+1} c^{l+1-j} \times \sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}(j+q-1)!}{(q-1)!}\frac{\gamma^j \exp(-kc\gamma)}{(k\gamma+\alpha_p)^{j+q}} \quad (16)$$

3.1 Exact expression for ergodic capacity

The ergodic capacity expressed in bits/s/Hz is defined in terms of the instantaneous SINR γ_D as

$$C = E\{\log_2(1+\gamma_D)\} \quad (17)$$

From (6), we rewrite the expression for the ergodic capacity as

$$C = \frac{1}{\ln 2}\left(E\{\ln(\gamma_S + c)\} - E\{\ln(\gamma_2 + c)\}\right) \quad (18)$$

where $\gamma_S = \gamma_1 + \gamma_2$. In order to calculate the first summand in (18), that is $E\{\ln(\gamma_S + c)\}$, we need to calculate $f_{\gamma_S}(\gamma_S)$. To obtain an expression for $f_{\gamma_S}(\gamma_S)$, we first calculate the MGF $\Phi_{\gamma_1}(\gamma_1)$ and $\Phi_{\gamma_2}(\gamma_2)$ of γ_1 and γ_2, respectively. Then, we attain the MGF of γ_S as $\Phi_{\gamma_S}(\gamma_s) = \Phi_{\gamma_1}(\gamma_1)\Phi_{\gamma_2}(\gamma_2)$. Next, we apply partial fraction given in [13, eq. (2.102)] to expand $\Phi_{\gamma_S}(\gamma_s)$. Finally, using the table of Laplace transform pairs in [13, eq. (17.13.7)] to inverse transform the expanded expression of $\Phi_{\gamma_S}(\gamma_s)$, we obtain the PDF of γ_S as

$$f_{\gamma_S}(\gamma_s) = K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k} d_{k,l}\, l! \sum_{p=1}^{2}\sum_{q=1}^{m_p}\beta_{pq}\sum_{u=1}^{2}\sum_{r=1}^{n_u} g_{ur} \times \frac{\gamma_s^{r-1}\exp(-\chi_u\gamma_s)}{(r-1)!} \quad (19)$$

where

$$\begin{aligned} &n_1 = q,\ n_2 = l+1 \\ &\chi_1 = \alpha_p,\ \chi_2 = k \\ &g_{ur} = \prod_{i=1}^{2}\frac{1}{(n_u - r)!}\left.\frac{d^{(n_u-r)}\prod_{i=1, i\neq u}^{2}(s+\chi_i)^{-n_i}}{ds^{(n_u-r)}}\right|_{s=\chi_u} \end{aligned} \quad (20)$$

As per definition, we have

$$E\{\ln(\gamma_S + c)\} = \int_0^\infty \ln(\gamma_s + c) f_{\gamma_S}(\gamma_s)\,d\gamma_s \quad (21)$$

Substituting (19) into (21), we obtain

$$\begin{aligned} E\{\ln(\gamma_S + c)\} &= K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k} d_{k,l}\, l! \sum_{p=1}^{2}\sum_{q=1}^{m_p}\beta_{pq}\sum_{u=1}^{2}\sum_{r=1}^{n_u}\frac{g_{ur}}{(r-1)!} \\ &\times\left[\ln c\int_0^\infty \gamma_s^{r-1}\exp(-\chi_u\gamma_s)\,d\gamma_s + c^r \right. \\ &\left. \times\int_0^\infty \ln(1+v)v^{r-1}\exp(-c\chi_u v)\,dv\right] \end{aligned} \quad (22)$$

To simplify (22), we apply [13, eq. (3.352.3)] to calculate the first integral. For the second integral, we use [13, eq. (8.4.6)] to express $\ln(1+u)$ in terms of Meijer's G-function $\ln(1+u) = G_{22}^{12}\left(u\left|\begin{matrix}1, & 1\\ 1, & 0\end{matrix}\right.\right)$, and then apply [13, eq. (7.813.1)] to calculate the second integral. Finally, we obtain

$$\begin{aligned} E\{\ln(\gamma_S + c)\} &= K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k} d_{k,l}\, l! \sum_{p=1}^{2}\sum_{q=1}^{m_p}\beta_{pq}\sum_{u=1}^{2}\sum_{r=1}^{n_u}\frac{g_{ur}}{(r-1)!\chi_u^r} \\ &\times\left[\ln c\,\Gamma(r) + G_{32}^{13}\left(\frac{1}{c\chi_u}\left|\begin{matrix}1-r, 1, 1\\ 1, 0\end{matrix}\right.\right)\right] \end{aligned} \quad (23)$$

Similarly, the second term in (18) is defined as

$$E\{\ln(\gamma_2 + c)\} = \int_0^\infty \ln(\gamma_2 + c) f_{\gamma_2}(\gamma_2)\,d\gamma_2 \quad (24)$$

Substituting (11) into (24), after some algebraic manipulations and re-arranging terms, we yield

$$\begin{aligned} E\{\ln(\gamma_2 + c)\} &= \sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}}{(q-1)!}\left[\ln c\int_0^\infty \exp(-\alpha_p\gamma_2)\gamma_2^{q-1}\,d\gamma_2 \right. \\ &\left. + c^q\int_0^\infty \ln(1+v)v^{q-1}\exp(-c\alpha_p v)\,dv\right] \end{aligned} \quad (25)$$

To calculate (25), we first use [13, eq. (8.4.6)] to transform $\ln(1+v)$ into Meijer's function. Then, applying [13, eq. (3.352.3)] and [13, eq. (7.813.1)] to solve the first and the second integral, we obtain

$$\begin{aligned} E\{\ln(\gamma_2 + c)\} &= \sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}}{(q-1)!\alpha_p^q} \\ &\times\left[\ln c\,\Gamma(q) + G_{32}^{13}\left(\frac{1}{c\alpha_p}\left|\begin{matrix}1-q, 1, 1\\ 1, 0\end{matrix}\right.\right)\right] \end{aligned} \quad (26)$$

Substituting (23) and (26) into (18), we finally obtain a

$$F_{\gamma_D}(\gamma) = K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k}\frac{d_{k,l}\Gamma(l+1)}{k^{l+1}}\left[1 - \sum_{u=0}^{l}\frac{k^u}{u!}\sum_{v=0}^{u} C_v^u \sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}(v+q-1)!}{(q-1)!}\frac{\gamma^u\exp(-kc\gamma)}{(k\gamma+\alpha_p)^{v+q}}\right] \quad (15)$$

closed-form expression for the ergodic capacity of the considered system as

$$C = \frac{1}{\ln 2}\Bigg[K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k} d_{k,l}\, l! \sum_{p=1}^{2}\sum_{q=1}^{m_p}\beta_{pq}\sum_{u=1}^{2}\sum_{r=1}^{n_u}\frac{g_{ur}}{\chi_u^r\Gamma(r)} \left(\ln c\,\Gamma(r) + G_{32}^{13}\left(\frac{1}{c\chi_u}\middle|\begin{matrix}1-r,1,1\\1,0\end{matrix}\right)\right) - \sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}}{\Gamma(q)\alpha_p^q}\left(\ln c\,\Gamma(q) + G_{32}^{13}\left(\frac{1}{c\alpha_p}\middle|\begin{matrix}1-q,1,1\\1,0\end{matrix}\right)\right)\Bigg] \quad (27)$$

3.2 Exact expression for OP

OP, $P_{\rm out}$, is defined as the probability that the instantaneous SINR, γ_D, of the system falls below a specified threshold $\gamma_{\rm th}$. It is obtained by using the threshold $\gamma_{\rm th}$ as argument of the CDF given in (15) resulting in

$$P_{\rm out} = K\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k}\frac{d_{k,l}}{k^{l+1}} \times\left[\Gamma(l+1) - l!\sum_{u=0}^{l}\frac{k^u}{u!}\sum_{v=0}^{u}C_v^u c^{u-v} \times\sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}(v+q-1)!}{(q-1)!}\frac{\gamma_{\rm th}^u\exp(-kc\gamma_{\rm th})}{(k\gamma_{\rm th}+\alpha_p)^{v+q}}\right] \quad (28)$$

3.3 Exact expression for SER

As mentioned in [16], for many modulation formats, the SER can be expressed directly in terms of the CDF of the instantaneous SINR, $\gamma_{\rm D}$, as

$$P_E = \frac{a\sqrt{b}}{2\sqrt{\pi}}\int_0^\infty \frac{{\rm e}^{-b\gamma}}{\sqrt{\gamma}}F_{\gamma_{\rm D}}(\gamma)\,{\rm d}\gamma \quad (29)$$

where a, b are positive modulation parameters determined by modulation schemes. For M-ary phase shift keying, M-PSK, ($a = 2$, $b = \sin^2[\pi/M]$).

By substituting (15) into (29), the expression for SER is given by

$$P_E = \frac{Ka\sqrt{b}}{2\sqrt{\pi}}\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k}\frac{d_{k,l}\Gamma(l+1)}{k^{l+1}} \times\int_0^\infty\frac{\exp(-b\gamma)}{\sqrt{\gamma}}{\rm d}\gamma - \frac{Ka\sqrt{b}}{2\sqrt{\pi}}\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k}\frac{d_{k,l}l!}{k^{l+1}} \times\sum_{u=0}^{l}\frac{k^u}{u!}\sum_{v=0}^{u}C_v^u c^{u-v}\sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{pq}}{k^{v+q}}\frac{(v+q-1)!}{(q-1)!} \times\int_0^\infty\frac{\gamma^{u-\frac{1}{2}}\exp(-(kc+b)\gamma)}{\left(\gamma+(\alpha_p/k)\right)^{v+q}}{\rm d}y \quad (30)$$

Applying [13, eq. (3.361.28)] to calculate the first integral and [17, eq. (3.353)] to compute the second integral of (30), we finally obtain an exact expression for the SER as

$$P_E = K\frac{a}{2}\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k}\frac{d_{k,l}}{k^{l+1}}\Gamma(l+1) - K\frac{a\sqrt{b}}{2\sqrt{\pi}}\sum_{k=1}^{M}\sum_{l=N-M}^{(N+M-2k)k}\frac{d_{k,l}}{k^{l+\frac{3}{2}}}l!\sum_{u=0}^{l}\sum_{v=0}^{u}C_v^u\frac{c^{u-v}}{u!} \times\sum_{p=1}^{2}\sum_{q=1}^{m_p}\frac{\beta_{\rm pq}(v+q-1)!}{(q-1)!\alpha_p^{v+q-u-\frac{1}{2}}}\Gamma\left(u+\frac{1}{2}\right) \times\Psi\left(u+\frac{1}{2}, u+\frac{3}{2}-v-q; (kc+b)\frac{\alpha_p}{k}\right) \quad (31)$$

4 Asymptotic performance analysis in the high-SNR regime

In the previous section, closed-form expressions for the ergodic capacity, SER and OP were derived. Although these expressions are exact, they are too complicated to reveal any insight into the system performance. Therefore in this section, we adopt an asymptotic analysis for the system performance in the high-SNR regime. As in [18], a tight approximation for the PDF and CDF of the largest eigenvalue γ_1 of a standard Wishart matrix are given, respectively, as

$$f_{\gamma_1}(\gamma) = \frac{N_1N_2\prod_{k=0}^{M-1}k!}{\prod_{k=0}^{M-1}(N+k)!}\gamma^{N_1N_2-1} \quad (32)$$

$$F_{\gamma_1}(\gamma) = \frac{\prod_{k=0}^{M-1}k!}{\prod_{k=0}^{M-1}(N+k)!}\gamma^{N_1N_2} \quad (33)$$

Given any function $f_X(x)$, we always can expand it into a MacLaurin series as in [13, Eq. (0.318.2)]. As such, we also express the PDF of the instantaneous SINR, $\gamma_{\rm D}$ in terms of a MacLaurin series as

$$f_{\gamma_{\rm D}}(\gamma) = \sum_{n=0}^{\infty}\frac{\partial^n f_{\gamma_{\rm D}}(\gamma)}{\partial\gamma^n}\frac{\gamma^n}{n!} \quad (34)$$

Here, we obtain an asymptotic expression in the high-SNR regime for $f_{\gamma_{\rm D}}(\gamma)$ by considering only the first non-zero higher order derivative of $f_{\gamma_{\rm D}}(\gamma)$ at $\gamma = 0$. From (6), the nth order derivative of $f_{\gamma_{\rm D}}(\gamma)$ is given by

$$\frac{\partial^n f_{\gamma_{\rm D}}(\gamma)}{\partial\gamma^n} = \int_0^\infty(\gamma_2+c)^{n+1}\frac{\partial^n f_{\gamma_1}(\gamma)}{\partial\gamma^n}f_{\gamma_2}(\gamma_2)\,{\rm d}\gamma_2 \quad (35)$$

By substituting (11) and (32) into (35), we realise that the first non-zero order derivative of $f_{\gamma_{\rm D}}(\gamma)$ is achieved at $n = N_1N_2 - 1$. Utilising [13, eq. (3.351.3)] to solve the integral in (35), we obtain the first non-zero higher order derivative of $f_{\gamma_{\rm D}}(\gamma)$ at $\gamma = 0$ as

$$\left.\frac{\partial^{N_1N_2-1}f_{\gamma_{\rm D}}(\gamma)}{\partial\gamma^{N_1N_2-1}}\right|_{\gamma=0} = \frac{(N_1N_2)!\prod_{k=0}^{M-1}k!}{\prod_{k=0}^{M-1}(N+k)!}\sum_{p=1}^{2}\sum_{q=1}^{\theta_p}\frac{\beta_{pq}}{(q-1)}\times\sum_{i=0}^{N_1N_2}C_i^{N_1N_2}c^{N_1N_2-i}\Gamma(q+i)\alpha_p^{-(q+i)} \quad (36)$$

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With this outcome, an asymptotic expression for $f_{\gamma_D}(\gamma)$ is obtained as

$$f_{\gamma_D}(\gamma) = \frac{N_1 N_2 \prod_{k=0}^{M-1} k!}{\prod_{k=0}^{M-1}(N+k)!} \sum_{p=1}^{2} \sum_{q=1}^{\theta_p} \frac{\beta_{pq}}{(q-1)!} \times \sum_{i=0}^{N_1 N_2} C_i^{N_1 N_2} c^{N_1 N_2 - i} \Gamma(q+i) \alpha_p^{-(q+i)} \gamma^{N_1 N_2 - 1} \quad (37)$$

By integrating $f_{\gamma_D}(x)$ in (37) with respect to variable x over the interval $(0, \gamma)$, we finally obtain the asymptotic expression for the CDF of γ_D as

$$F_{\gamma_D}(\gamma) = \frac{\prod_{k=0}^{M-1} k!}{\prod_{k=0}^{M-1}(N+k)!} \sum_{p=1}^{2} \sum_{q=1}^{\theta_p} \frac{\beta_{pq}}{(q-1)!} \times \sum_{i=0}^{N_1 N_2} C_i^{N_1 N_2} c^{N_1 N_2 - i} \Gamma(q+i) \alpha_p^{-(q+i)} \gamma^{N_1 N_2} \quad (38)$$

4.1 Asymptotic expression for ergodic capacity

From the definition of ergodic capacity in (17), in the high-SNR regime, the expression for the ergodic capacity is given by

$$C \approx E\{\log_2(\gamma_D)\} = \frac{1}{\ln 2}\left[E\{\ln(\gamma_1)\} - E\{\ln(\gamma_2 + c)\}\right] \quad (39)$$

Using the expression for $f_{\gamma_1}(\gamma)$ given in (10) to calculate $E\{\ln(\gamma_1)\} = \int_0^\infty \ln(\gamma_1) f_{\gamma_1}(\gamma_1)\,d\gamma_1$, after some algebraic manipulations together with the help of [13, Eq. (4.352.1)] to solve the remaining integral, we obtain

$$E\{\ln(\gamma_1)\} = K \sum_{k=1}^{M} \sum_{l=N-M}^{(N+M-2k)k} \frac{d_{k,l}}{k^{l+1}} \Gamma(l+1)[\psi(l+1) - \ln k] \quad (40)$$

where $\psi(x)$ is the psi function defined in [13, eq. (8.360.1)] as $\psi(x) = d(\ln \Gamma(x))/dx$. Using (11) to calculate $E\{\ln(\gamma_2 + c)\}$, after some manipulations and changing variable $v = \gamma_2/c$, we can rewrite $E\{\ln(\gamma_2 + c)\}$ as

$$E\{\ln(\gamma_2 + c)\} = \sum_{p=1}^{2} \sum_{q=1}^{m_p} \frac{\beta_{pq}}{(q-1)!} \left[\ln c \int_0^\infty \gamma_2^{q-1} \exp(-\alpha_p \gamma_2)\,d\gamma_2 + c^p \int_0^\infty \ln(1+v) v^{q-1} \exp(-\alpha_p c v)\,dv\right] \quad (41)$$

To further calculate (41), first we apply [13, eq. (8.4.6)] to transform $\ln(1+v)$ into Meijer's function defined in [13, eq. (9.301)]. Next, we utilise [13, eq. (3.352.3)] and [13, eq. (7.813.1)] to solve the first and the second integral in (41). Finally, we obtain

$$E\{\ln(\gamma_2 + c)\} = \sum_{p=1}^{2} \sum_{q=1}^{m_p} \frac{\beta_{pq} \alpha_p^{-q}}{(q-1)!} \left[\ln c\, \Gamma(q) + G_{32}^{13}\left(\frac{1}{c\alpha_p} \middle| \begin{matrix} 1-q, 1, 1 \\ 1, 0 \end{matrix}\right)\right] \quad (42)$$

Substituting (40) and (42) into (39), we attain the asymptotic expression for the ergodic capacity as

$$C = \frac{K}{\ln 2} \sum_{k=1}^{M} \sum_{l=N-M}^{(N+M-2k)k} \frac{d_{k,l}}{k^{l+1}} \Gamma(l+1)[\psi(l+1) - \ln k] - \frac{1}{\ln 2} \sum_{p=1}^{2} \sum_{q=1}^{m_p} \frac{\beta_{pq}}{\alpha_p^q (q-1)!} \times \left[\ln c\, \Gamma(q) + G_{32}^{13}\left(\frac{1}{c\alpha_p} \middle| \begin{matrix} 1-q, 1, 1 \\ 1, 0 \end{matrix}\right)\right] \quad (43)$$

4.2 Asymptotic expression for OP

The asymptotic expression for the OP is easily obtained from (38) by setting $\gamma = \gamma_{th}$ as

$$P_{out} = \frac{\prod_{k=0}^{M-1} k!}{\prod_{k=0}^{M-1}(N+k)!} \sum_{p=1}^{2} \sum_{q=1}^{m_p} \frac{\beta_{pq}}{(q-1)!} \times \sum_{i=0}^{N_1 N_2} C_i^{N_1 N_2} c^{N_1 N_2 - i} \Gamma(q+i) \alpha_p^{-(q+i)} \gamma_{th}^{N_1 N_2} \quad (44)$$

4.3 Asymptotic expression for SER

By substituting (38) into (29) and utilising [13, eq. (3.381.4)] to compute the remaining integral, we derive an asymptotic expression for the SER as

$$P_E = \frac{a\Gamma(N_1 N_2 + (1/2))}{2\sqrt{\pi} b^{N_1 N_2}} \frac{\prod_{k=0}^{M-1} k!}{\prod_{k=0}^{M-1}(N+k)!} \sum_{p=1}^{2} \sum_{q=1}^{m_p} \frac{\beta_{pq}}{(q-1)!} \times \sum_{i=0}^{N_1 N_2} C_i^{N_1 N_2} c^{N_1 N_2 - i} \Gamma(q+i) \alpha_p^{-(q+i)} \quad (45)$$

5 Numerical results and discussion

In this section, we will illustrate how CEE, FD, CCI and the number of antennas at the transmitter and receiver effect the system performance. For this purpose, we should alternatively change CEE, FD, CCI, and the number of antennas at T and R to illustrate clearly the impact of each parameter on the system performance.

First, let us examine the ergodic capacity of the system in the following five cases:

- *Case 1:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.92, 3, 3, 2)$
- *Case 2:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.92, 3, 3, 4)$
- *Case 3:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.92, 2, 2, 2)$
- *Case 4:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.05, 0.92, 2, 2, 2)$
- *Case 5:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.85, 2, 2, 2)$

Fig. 1 depicts the ergodic capacity in bits/s/Hz against average SNR of the system. In Case 1 and Case 2, we illustrate the channel capacity with the same level of imperfect CSI, (σ_e^2, ρ^2), and the same number of transmit and receive antennas, (N_1, N_2), but having different number of interferers, N_3. Comparing Case 1 with Case 2, we can see the negative effect of the number of interferers on the ergodic capacity. Conversely, with the same imperfect channel conditions, $(N_3, \sigma_e^2, \rho^2)$, in Case 1 and Case 3, the ergodic capacity of the system increases in proportion to the number of antennas at the transmitter and receiver, (N_1, N_2). Moreover, as observed from Case 3 and Case 4, when the number of antennas, the number of interferers, and the FD, (ρ^2, N_1, N_2, N_3), are constant, the channel capacity reduces severely with a small increase in level of CEE. Finally, by keeping the values of $(\sigma_e^2, N_1, N_2, N_3)$ constant and only changing ρ^2 in Case 3 and Case 5, it is easy to realise that the more FD, τ, is, the lower ergodic capacity is achieved (if τ increases, the channel coefficient ρ will be decreased).

Next, we illustrate the OP in five scenarios

- *Case 6:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.96, 2, 2, 2)$
- *Case 7:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.05, 0.99, 2, 2, 2)$
- *Case 8:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.99, 2, 2, 2)$
- *Case 9:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.99, 3, 3, 6)$
- *Case 10:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.99, 3, 3, 2)$

and demonstrate the SER for quadrature phase shift keying (QPSK) in the following cases:

- *Case 11:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.1, 0.99, 1, 2, 2)$
- *Case 12:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.97, 1, 2, 2)$
- *Case 13:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.99, 1, 2, 2)$
- *Case 14:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.99, 2, 3, 6)$
- *Case 15:* $(\sigma_e^2, \rho^2, N_1, N_2, N_3) = (0.01, 0.99, 2, 3, 2)$

Figs. 2 and 3 plot the OP and SER against average SNR of the considered system, respectively. The threshold value for calculating the OP is selected as 3 dB and QPSK is chosen

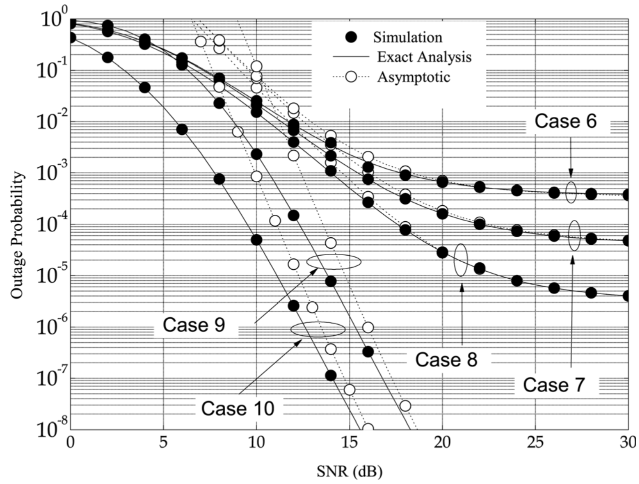

Fig. 2 *OP against average SNR with different parameters for CEE, FD, CCIs and various number of antennas at the transmitter and receiver*

to illustrated the SER. By comparing Case 6 with Case 8 and Case 12 with Case 13, having the same $(\sigma_e^2, N_1, N_2, N_3)$, we can observe the negative effect of the FD on the OP and SER. Furthermore, by fixing the four parameters (ρ^2, N_1, N_2, N_3) in Case 7 and Case 8 of Fig. 2; Case 11 and Case 13 of Fig. 3, we observe that the OP and SER degrade severely with the seriousness of CEE, σ_e^2. As we can see, with the same parameters $(\sigma_e^2, \rho^2, N_3)$ in Case 8 and Case 10 for the OP; Case 13 and Case 15 for the SER, when the number of antennas increases, the OP and SER decrease, respectively. Finally, we keep $(\sigma_e^2, \rho^2, N_1, N_2)$ constant and only change the number of CCIs, N_3, in Case 9 and Case 10 of Fig. 2; Case 14 and Case 15 of Fig. 3 which enable to examine the impact of the number of interferers on the OP and SER of the system. As expected, better OP and SER are achieved for the cases with a smaller number of N_3.

As a final point, from the above examples, we show a good agreement between the analytical results and the Monte Carlo simulations.

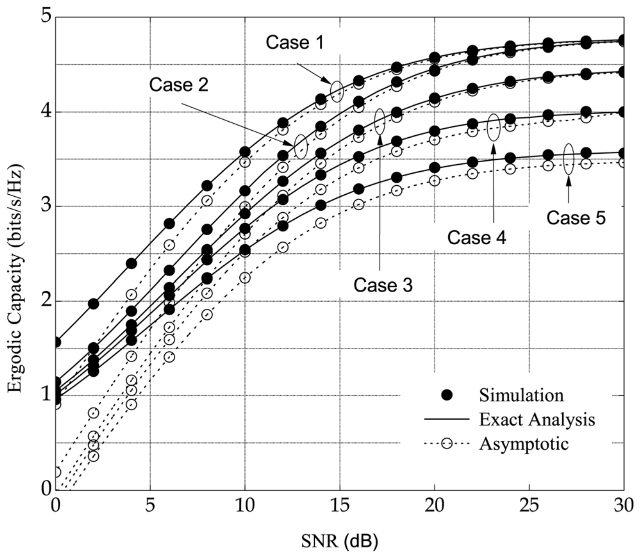

Fig. 1 *Ergodic capacity against average SNR with different parameters for CEE, FD, CCIs and various number of antennas at the transmitter and receiver*

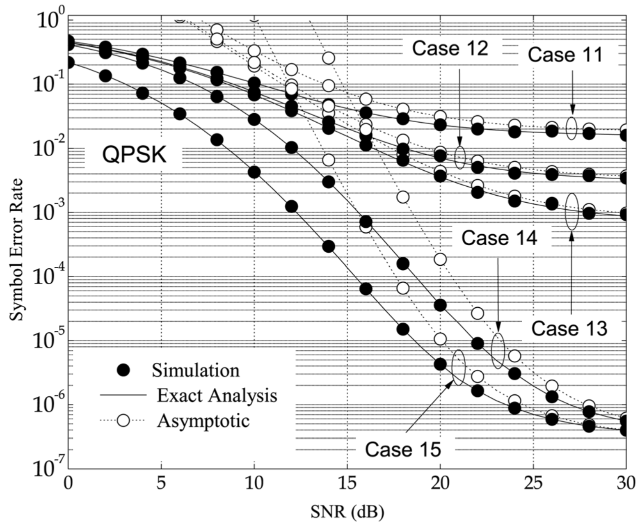

Fig. 3 *SER against average SNR with different parameters for CEE, FD, CCIs and various number of antennas at the transmitter and receiver*

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6 Conclusions

This paper investigated the performance of MIMO-MRT systems with CEE, FD and CCI. In particular, we derived closed-form expressions for the ergodic capacity, OP and SER of the considered system. Furthermore, we also analysed the asymptotic behaviour of the ergodic capacity, OP and SER in the high-SNR regime. Our analysis indicates that the system performance is improved significantly with the increase in the number of antennas at the transmitter and the receiver. However, the system performance is severely degraded when there exists interference, large FD and serious CEE. Given the promising results in this paper and the presented analytical framework of including CEEs, FD, and CCI, our future research shall also focus on dealing with other practical issues such as the overhead incurred by pilot signals.

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