Outage Probability and Symbol Error Rate Analysis of MIMO-MRC with Estimation Error, Feedback Delay and Co-Channel Interference

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Abstract: — This correspondence propose the outage probability and symbol error rate (SER) performance of multiple-input multiple-output (MIMO) maximum ratio combining (MRC) in the existence of co-channel interferences (CCIs) with channel estimation error (CEE) and feedback delay (FD). In general, we derive the exact closed-form expressions for the statistical properties of the signal-to-noise-plus-interference ratio (SINR), the outage probability of the SINR and SER of M-ary constellation. Our outcome indicates that the system performance enhances with the increment of number of transceiver antenna, however deteriorates with the harshness of CEE, FD and CCIs.

Key words— Channel estimation error (CEE), co-channel interference (CCI), maximum ratio combining (MRC), multiple-input multiple-output (MIMO) systems, outage probability, symbol error rate (SER).

1 Introduction

WIRELESS multiple-input multiple-output (MIMO) system have drawn lot of research interest due to their potential to alleviate the performance reduction of channel impairments such as multipath fading and co-channel interference (CCI) via diversity and provide high capacity along with reliability of the system [1]-[8]. Based on the channel state information (CSI), MIMO maximal ratio combining (MRC) scheme maximize the receiver signal-to-noise (SNR) by driving the transmit power along the optimal eigen mode of the MIMO channel, was introduced in [2], [3]. By considering the impact of channel estimation error (CEE) in the absence of CCIs, a MIMO-MRC system was first introduced in [4]. Performance analyses of MIMO-MRC systems in the existence of CCIs with perfect channel estimation were explored in [5]–[6]. In [7], authors evaluated the outage probability performance of MIMO-MRC systems in the existence of CEE and CCIs, however the result derived in [7] was in the form of infinite sums of the Whittaker's hypergeometric function. All the research work mention above was studied in the absence of feedback delay (FD). Recently, authors derived the performance of MIMO systems with CEE and FD under Ricean fading channels in the absence of CCIs in [8].

In this paper, we examine the outage probability and SER for MIMO-MRC systems in the existence of CCIs with CEE and FD. Our outcomes provide a framework of finite sums, permitting for effortless investigation of MIMO-MRC systems with respect to infinite sums Whittaker's hypergeometric function [7].

Notation: Matrices and vectors are expressed by bold symbols. $E(.), (.)^T and\, (.)^H$ stand for expectation, transpose and complex conjugate transpose.

2 System and Channel Model

Considering a MIMO MRC system employing N_t transmit and N_r receive antennas in the existence of L independent CCIs. Then, the $N_r \times 1$ signal vector $\boldsymbol{y}$ received at the N_r antennas can be expressed as

$$\boldsymbol{y} = \sqrt{P_0}\boldsymbol{H}_t\boldsymbol{w}_t s_t + \sqrt{\boldsymbol{P}_I}\boldsymbol{H}_I\boldsymbol{w}_t s_I + \boldsymbol{v} \tag{1}$$

where s_t is the transmitted signal with average received power P_0 of the desired user, $\boldsymbol{v} \in C^{N_r\times 1}$ is a receiver noise vector and are modeled as $\boldsymbol{v}\sim\mathcal{CN}(0, \sigma_n^2 I_{N_r})$, $s_I \in C^{L\times 1}$ is the transmitted signal vector of the CCIs and $\boldsymbol{P_I} = diag(P_{I,1}, P_{I,2}, \dots, P_{I,L})$ is the average received power of the i^{th} CCIs where $i = 1,2,\dots,L$. Let $N_r \times N_t$ channel matrix $\boldsymbol{H}_t\, and\, N_r \times L$ channel matrix of the L interferers $\boldsymbol{H}_I$ are independent and identically-distributed (i.i.d.) complex Gaussian random variables (CGRVs) with zero mean and unit variance and also assume that the channel matrices $\boldsymbol{H}_t\, and\, \boldsymbol{H}_I$ and noise vector $\boldsymbol{v}$ are uncorrelated of each other. In (1) $\boldsymbol{w}_t$ represents $N_t \times 1$ unit energy weight vector at the transmitter, i.e., $\|\boldsymbol{w}_t\|^2 = 1$. In practice, transmit weighting factor $\boldsymbol{w}_t$ is calculated at the receiver and forwarded to the transmitter via a feedback channel. The CEE at the

$$\gamma = \frac{\rho^2 \omega_0 \lambda_{max}}{\sum_{i=1}^{L} \frac{\omega_i}{\lambda_{max}} \left\| \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{H}_{I,i} \right\|^2 + \sum_{k=1}^{N_t} \frac{\rho^2 \sigma_e^2 \omega_0}{\lambda_{max}} \left\| \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{F}_{t,k} \right\|^2 + \sigma_e^2 \omega_0 + 1} \quad (4)$$

receiver and FD between receiver and transmitter is consistently present. Hence, with the existence of CEE, the true channel matrix $\boldsymbol{H}_t$ changes to be $\hat{\boldsymbol{H}}_t$ by an estimation error $\boldsymbol{E}_t = [e_{ij}]_{N_r \times N_t}$ whose elements are i.i.d. CGRVs with zero-mean and variance σ_e^2. In this correspondence, we consider feedback channel of delay τ, thus we model $\boldsymbol{H}_t$ as [8]

$$\boldsymbol{H}_t = \rho \hat{\boldsymbol{H}}_{t-\tau} + \boldsymbol{E}_t + \boldsymbol{F}_t \quad (2)$$

where $\rho = \frac{E\{[\hat{\boldsymbol{H}}_t]_{ij}[\hat{\boldsymbol{H}}_{t-\tau}^H]_{ij}\}}{\sqrt{1-\sigma_e^2}}$, $\hat{\boldsymbol{H}}_{t-\tau}$ is the estimated channel matrix delayed by τ time occurrence whose elements are i.i.d. $\mathcal{CN}\left(0, (1-\sigma_e^2)\right)$. Finally $\boldsymbol{F}_t = \hat{\boldsymbol{H}}_t - \rho \hat{\boldsymbol{H}}_{t-\tau}$ is the CEE matrix incurred by the delay, consist of i.i.d $\mathcal{CN}\left((1-\rho^2)(1-\sigma_e^2)\right)$. At the transmitter if the weighting vector $\boldsymbol{w}_t = \hat{\boldsymbol{u}}_t$ is picked in order to maximize the receiver SNR, the weighting vector $\boldsymbol{w}_r$ at the receiver is selected to $\boldsymbol{w}_r = \hat{\boldsymbol{H}}_{t-\tau} \hat{\boldsymbol{u}}_t$ where eigenvector $\hat{\boldsymbol{u}}_t$ corresponding to the highest eigen value λ_{max} of the Wishart matrix $\hat{\boldsymbol{H}}_{t-\tau} \hat{\boldsymbol{H}}_{t-\tau}^H$. Then the output signal at the receiver combiner can be written as

$$\begin{aligned} \tilde{\boldsymbol{y}} &= \boldsymbol{w}_r^H \boldsymbol{y} \\ &= \rho \sqrt{P_0} \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \hat{\boldsymbol{H}}_{t-\tau} \hat{\boldsymbol{u}}_t s_t + \sigma_e \sqrt{P_0} \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{E}_t \hat{\boldsymbol{u}}_t s_t \\ &\quad + \rho \sigma_e \sqrt{P_0} \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{F}_t \hat{\boldsymbol{u}}_t s_t + \sqrt{\boldsymbol{P}_I} \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{H}_I s_I \\ &\quad + \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{v} \end{aligned} \quad (3)$$

The output signal-to-interference-plus-noise ratio (SINR) γ of the MIMO-MRC system in the existence of CCIs with CEE and FD can be written as in (4), at the top of the page. In (4), $\boldsymbol{H}_{I,i}$ means i^{th} column of the matrix $\boldsymbol{H}_I$, $\boldsymbol{F}_{t,k}$ means k^{th} column of the matrix $\boldsymbol{F}_t$, $\omega_0 = P_0/\sigma_n^2$ and $\omega_i = P_i/\sigma_n^2$. Therefore, the SINR in (4) can be expressed as the ratio of two independent random variables and given by

$$\gamma = \frac{\lambda}{z+1} \quad (5)$$

where $\lambda = \xi \lambda_{max}$, $z = x + y$,
$x = \sum_{i=1}^{L} \frac{\beta_i}{\lambda_{max}} \left\| \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{H}_{I,i} \right\|^2$,
$y = \sum_{k=1}^{N_t} \frac{\delta_0}{\lambda_{max}} \left\| \hat{\boldsymbol{u}}_t^H \hat{\boldsymbol{H}}_{t-\tau}^H \boldsymbol{F}_{t,k} \right\|^2$ in which
$\xi = \frac{\rho^2 \omega_0}{\sigma_e^2 \omega_0 + 1}$, $\beta_i = \frac{\omega_i}{\sigma_e^2 \omega_0 + 1}$ and $\delta_0 = \frac{\rho^2 \sigma_e^2 \omega_0}{\sigma_e^2 \omega_0 + 1}$.

3 Evaluation of the pdf of output SINR

Based on [5], x and y follow gamma distribution, thus pdf of x and y can be written as

$$f_x(x) = \frac{x^{L-1} e^{-x}}{\Gamma(L)} \quad (6)$$

and

$$f_y(y) = \frac{y^{N_t-1} e^{-y}}{\Gamma(N_t)} \quad (7)$$

Then, the pdf of $z = x + y$ can be written as

$$f_z(z) = \sum_{i=1}^{2} \sum_{j=1}^{\mu_i} \eta_{ij} \frac{z^{j-1} e^{-v_i z}}{\Gamma(j)} \quad (8)$$

where

$$\eta_{ij} = \prod_{g=1}^{2} \frac{v_g^{\mu_g}}{(\mu_i - j)!} \frac{d^{\mu_i - j} \left[\prod_{g=1, g\neq i}^{2} \left(s + v_g\right)^{-\mu_i} \right]}{ds^{\mu_i - j}} \Bigg|_{s=v_i} \quad (9)$$

Proof of (9), *see Appendix A.*

The probability density function (pdf) of highest eigen value λ of the matrix $\hat{\boldsymbol{H}}_t^{\boldsymbol{H}} \hat{\boldsymbol{H}}_t$ in (5) is given by [3]

$$f_\lambda(\lambda) = \sum_{k=1}^{m} \sum_{l=n-m}^{(n+m-2k)k} \frac{q_{kl}}{\Gamma(l+1)} \left(\frac{k}{\xi}\right)^{l+1} \lambda^l e^{-\frac{k}{\xi}\lambda} \quad (10)$$

where $m = min(N_T, N_R)$ and $n = max(N_T, N_R)$ and coefficient q_{kl} have been defined in [3]. Using (8) and (10), the distribution of (5) can be computed as

$$f_\gamma(\gamma) = \int_0^\infty (z+1) f_\lambda\big(\gamma(z+1)\big) f_z(z) dz \quad (11)$$

$$= \sum_{i=1}^{2} \sum_{j=1}^{\mu_i} \sum_{k=1}^{m} \sum_{l=n-m}^{(n+m-2k)k} \sum_{r=0}^{l+1} \frac{\eta_{ij} q_{kl}}{\Gamma(j)\Gamma(l+1)} \times \frac{\Gamma(r+j)}{v_i^{r+j}} \left(\frac{k}{\xi}\right)^{l+1} \binom{l+1}{r} \frac{\gamma^l e^{-\frac{k}{\xi}\gamma}}{\left(1 + \frac{k\gamma}{\xi v_i}\right)^{r+j}} \quad (12)$$

The pdf in (12) can be evaluated by using binomial expansion as a finite sum $(a+x)^n = \sum_{k=0}^{n} \binom{n}{k} x^k a^{n-k}$ and the integral $\int_0^\infty s^{n-1} e^{-\mu s} ds = \mu^{-n} \Gamma(n)$.

4 Performance Analysis

4.1) Outage Probability

The nonergodic capacity of MIMO-MRC systems can be written as [3]

$$C = log_2(1+\gamma) \quad (13)$$

The outage probability may be defined as the probability that the random variable C drops under particular SINR threshold γ_{th}, hence the outage probability is given by

$P_{out}(\gamma_{th}) = Pr(C < \gamma_{th}) = \int_0^{\chi} f_\gamma(\gamma)\, d\gamma$, where $\chi = 2^{\gamma_{th}} - 1$.

$$P_{out}(\gamma_{th}) = \int_0^{\chi}\int_0^{\infty} (z+1)\, f_\lambda\big(\gamma(z+1)\big) f_z(z) dz\, d\gamma \quad (14)$$

$$= \sum_{i=1}^{2}\sum_{j=1}^{\mu_i}\sum_{k=1}^{m}\sum_{l=n-m}^{(n+m-2k)k} \frac{\eta_{ij} q_{kl}}{\Gamma(j)\Gamma(l+1)}$$
$$\int_0^{\chi}\int_0^{\infty} (1+z)^{l+1} z^{j-1} e^{-v_i z} \gamma^l e^{-\frac{k}{\xi}(z+1)\gamma} dz\, d\gamma \quad (15)$$

The integral $\int_0^s t^{n-1} e^{-t} dt = \psi(n,s)$ can be used to simplify (15), where $\psi(n,s)$ is incomplete gamma function and is defined as[9, (8.350.1)] $\psi(n,s) = \Gamma(n)\left[1 - e^{-s}\sum_{k=0}^{n}\binom{n}{k}\frac{s^k}{k!}\right]$. Hence interchanging the order of integration and utilizing the binomial expansion $(1+s)^n$ as a finite sum as well as integral $\int_0^{\infty} s^{v-1} e^{-\mu s}\, ds = \mu^{-v}\Gamma(v)$ [9, (3.351.3)], the closed-form expression of the outage probability is given as

$$P_{out}(\gamma_{th}) = \sum_{i=1}^{2}\sum_{j=1}^{\mu_i}\sum_{k=1}^{m}\sum_{l=n-m}^{(n+m-2k)k} \frac{\eta_{ij} q_{kl}}{{v_i}^j}$$
$$\times\left[1 - e^{-\frac{k}{\xi}\chi}\sum_{u=0}^{l}\sum_{r=0}^{u}\left(\frac{k\chi}{\xi}\right)^u \binom{r}{u}\frac{\Gamma(r+j)}{\Gamma(j)u!}\frac{1}{\left(\frac{k\chi}{\xi}+v_i\right)^{r+j}}\right] \quad (16)$$

4.2) Symbol Error Rate (SER)

The SER of MIMO MRC with CEE and FD in the existence of CCI over Rayleigh fading is computed by averaging the instantaneous SER $P_M(\gamma)$ over the pdf of γ.

$$P_e = \int_0^{\infty} P_M(\gamma)\, f_\gamma(\gamma) d\gamma \quad (17)$$

4.2.1 SER for M-PSK:

The $P_M(\gamma)$ of M-PSK is given as [10]-[11]

$$P_M(\gamma) = 2Q\left(\sqrt{2\gamma sin^2\frac{\pi}{M}}\right) - \frac{1}{\pi}\int_{\frac{\pi}{2}-\frac{\pi}{M}}^{\frac{\pi}{2}} e^{-\frac{\gamma sin^2\frac{\pi}{M}}{cos^2\theta}} d\theta \quad (18)$$

For high SNR and for high value of M the $P_M(\gamma)$ of M-PSK is approximated as

$$P_M(\gamma) \cong aQ\big(\sqrt{2b\gamma}\big) \quad (19)$$

where $a = 2, b = sin^2\frac{\pi}{M}$. Substituting (11) and (19) into (17), we get

$$P_e^{M-PSK} = \sum_{i=1}^{2}\sum_{j=1}^{\mu_i}\sum_{k=1}^{m}\sum_{l=n-m}^{(n+m-2k)k} \frac{a\eta_{ij} q_{kl}}{\Gamma(j){v_i}^j}\int_0^{\infty} z^{j-1} e^{-v_i z}$$
$$\times\,\mathcal{J}\left(2b, \frac{k}{\xi}(1+z), (l+1)\right) dz \quad (20)$$

where $\mathcal{J}(x,y,n) = (y^n/\Gamma(n))\int_0^{\infty} Q\left(\sqrt{xf}\right) e^{-yf} f^{n-1} df$, in which Q is defined as $Q(f) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} e^{-f^2/2sin^2\theta} d\theta$ [9]. Applying the identity [9] $\int_0^{\infty} x^{v-1} e^{-\mu x}\, dx = \mu^{-v}\Gamma(v)$, $\mathcal{J}(x,y,n)$ can be written as $\mathcal{J}(x,y,n) = \mathfrak{T}\left(\frac{\pi}{2}, \left(\frac{x}{2y}\right), n\right)$ where $\mathfrak{T}(\phi,c,n) = (1/\pi)\int_0^{\phi} (sin^2\theta/sin^2\theta + c)^n\, d\theta$ $for\ -\pi \le \phi \le \pi$. Utilizing the result in [11,(18)], for integer n the function $\mathfrak{T}(\phi,c,n)$ has closed form solution [12, (5A.24)]. Let a function $\mathcal{K}(p,q,\phi,m,n)$ is defined as

$$\mathcal{K}(p,q,\phi,m,n) = \int_0^{\infty} z^{m-1}\, e^{-pz}\mathfrak{T}\left(\phi, \frac{q}{1+z}, n\right) dz \quad (21)$$

For $\phi = \frac{\pi}{2}$, the function $\mathfrak{T}\left(\frac{\pi}{2}, \frac{q}{1+z}, n\right)$ can be decomposed as

$$\mathfrak{T}\left(\frac{\pi}{2}, \frac{q}{1+z}, n\right) = \frac{1}{2} - \frac{\sqrt{q}}{2}\sum_{k=0}^{n-1}\sum_{l=0}^{k} W_{kl}\, z^l \left(\frac{1}{1+q+z}\right)^{k+\frac{1}{2}} \quad (22)$$

where $W_{kl} = \binom{2k}{k}\binom{k}{l}\left(\frac{1}{4}\right)^k$. Inserting (22) into (21), the function $\mathcal{K}(p,q,\phi,m,n)$ has a closed form expression as given below

$$\mathcal{K}(p,q,\phi,m,n) = \mathcal{K}_1 - \mathcal{K}_2 \quad (23)$$

where

$$\mathcal{K}_1 = \frac{\phi p^{-m}\Gamma(m)}{\pi} \quad (24)$$

$$\mathcal{K}_2 = \frac{\sqrt{q}}{2}\sum_{k=0}^{n-1}\sum_{l=0}^{k} W_{kl}\,(1+q)^{m+l-k-\frac{1}{2}}\Gamma(m+l)$$
$$\times\,\psi\left(m+l; m+l-k+\frac{1}{2}; p(1+q)\right) \quad (25)$$

where $\psi(a;b;c)$ is the confluent hypergeometric function defined by [9,(9.211.4)]. Utilizing (21) to (25), (20) can be evaluated as

$$P_e^{M-PSK} = \sum_{i=1}^{2}\sum_{j=1}^{\mu_i}\sum_{k=1}^{m}\sum_{l=n-m}^{(n+m-2k)k} \frac{a\eta_{ij} q_{kl}}{\Gamma(j){v_i}^j}$$
$$\times\,\mathcal{K}\left(\frac{1}{v_i}, \frac{b\xi}{k}, \frac{\pi}{2}, j, l+1\right)$$
$$= \sum_{i=1}^{2}\sum_{j=1}^{\mu_i}\sum_{k=1}^{m}\sum_{l=n-m}^{(n+m-2k)k} \frac{a\eta_{ij} q_{kl}}{2}\left[1 - \left(\frac{b\xi}{k}\right)^{\frac{1}{2}}\right.$$

$$\times \frac{1}{v_i{}^j} \sum_{u=0}^{l} \sum_{r=0}^{u} \binom{2u}{u} \binom{u}{r} \left(\frac{1}{4}\right)^r \times \frac{\Gamma(r+j)}{\Gamma(j)} \left(1+\frac{b\xi}{k}\right)^{j+r-u-\frac{1}{2}} \times \psi\left(j+r; j+r-u-\frac{1}{2}; \frac{1}{v_i}\left(1+\frac{b\xi}{k}\right)\right)\Bigg] \quad (26)$$

4.2.2 SER for M-QAM:

The rectangular QAM is equal to two PAM signal on quadrature carrier. Therefore SEP of M-QAM can be computed as [10]

$$P_e^{M-QAM} = 1 - \left(1 - P_e^{\sqrt{M}-PAM}\right)^2 \quad (27)$$

The $P_e^{\sqrt{M}-PAM}$ can be obtained as

$$P_e^{\sqrt{M}-PAM} = \int_0^\infty P_{\sqrt{M}}(\gamma)\, f_\gamma(\gamma) d\gamma \quad (28)$$

where $P_{\sqrt{M}}(\gamma) = 2\left(1-\frac{1}{\sqrt{M}}\right) Q\left(\sqrt{2b\gamma}\right)$ in which $a = 2\left(1-\frac{1}{\sqrt{M}}\right)$ and $b = \frac{3}{2(M-1)}$. Substituting $P_{\sqrt{M}}(\gamma)$ and (11) into (17) and utilizing (21)-(25) we get

$$P_e^{\sqrt{M}-PAM} = \sum_{i=1}^{2} \sum_{j=1}^{\mu_i} \sum_{k=1}^{m} \sum_{l=n-m}^{(n+m-2k)k} \frac{a\eta_{ij} q_{kl}}{2} \Bigg[1 - \left(\frac{b\xi}{k}\right)^{\frac{1}{2}} \times \frac{1}{v_i{}^j} \sum_{u=0}^{l} \sum_{r=0}^{u} \binom{2u}{u} \binom{u}{r} \left(\frac{1}{4}\right)^r \times \frac{\Gamma(r+j)}{\Gamma(j)} \left(1+\frac{b\xi}{k}\right)^{j+r-u-\frac{1}{2}} \times \psi\left(j+r; j+r-u-\frac{1}{2}; \frac{1}{v_i}\left(1+\frac{b\xi}{k}\right)\right)\Bigg] \quad (29)$$

Hence inserting (29) into (27), we can achieve SER of M-QAM.

5 Numerical Results

This correspondence examines the analytical outage probability and SER performance of MIMO-MRC over uncorrelated Rayleigh fading channels. Fig. 1 illustrates the outage probability against average received SINR per branch with $L = 6, P_I = \sigma_n^2 = 1$, $P_0 = 5$, $\gamma_{th} = 10dB$, and $(a)(N_t, N_r) = (2, 2)$ $(b)(N_t, N_r) = (4, 4)$ configuration in case of perfect CEE and perfect FD $(\rho = 1, \sigma_e^2 = 0)$ and various imperfect cases $(\rho = 0.99, \sigma_e^2 = 0.01)$, $(\rho = 0.95, \sigma_e^2 = 0.15)$ and $(\rho = 0.90, \sigma_e^2 = 0.25)$. It can be observed that the outage performance improves in case of perfect CEE and FD and with increase of antenna configuration. Fig. 2 depicts the SER against average received SINR per branch with $L = 4, P_I = \sigma_n^2 = 1$, $P_0 = 5, \rho = 0.99$, $\sigma_e^2 = 0.01$ for different antenna configuration using 4-PSK constellation. It can be noticed that SER deteriorates on increasing the antenna configuration.

6. Conclusion

In this correspondence we have analyzed the performance of MIMO-MRC system in the existence of CCI with CEE and FD. We have evaluated outage probability and SER for M-ary constellation. It can be observed that the system performance enhances with the increment of number of transceiver antenna, however deteriorates with the harshness of CEE, FD and CCIs. The performance metrics were derived analytically and avoids the necessity of integration methods. Our outcome provide a framework of finite sums, permitting for effortless investigation of MIMO-MRC systems with respect to infinite sums Whittaker's hypergeometric function [7].

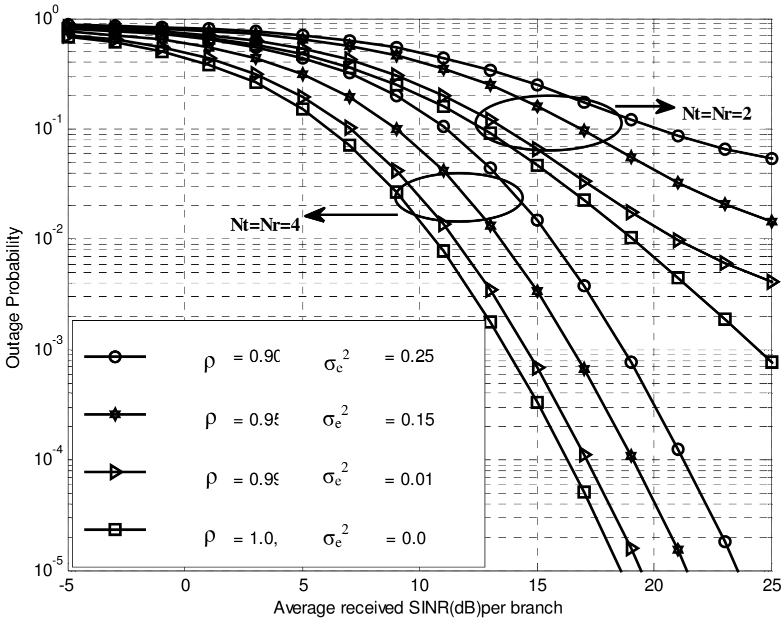

Fig. 1 Outage Probability of MIMO-MRC in the existence of CCIs against SINR for different antennas configurations $(a) N_t = N_r = 2$ and $(a) N_t = N_r = 4$ for perfect CEE and FD and imperfect CEEs and FDs.

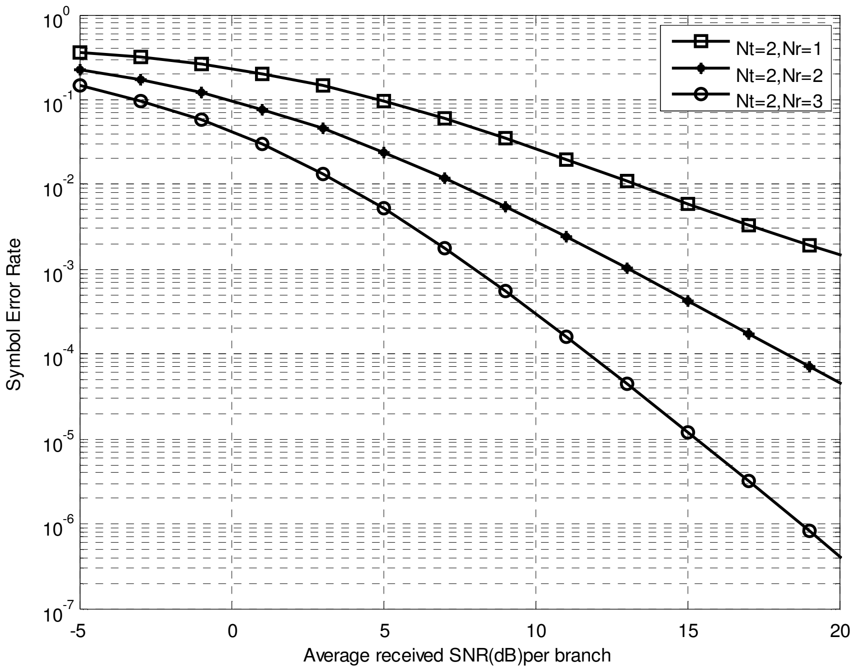

Fig. 2 SER of MIMO-MRC with CEE and FD in the existence of CCIs against SINR for different antennas configurations with $\rho = 0.99, \sigma_e^2 = 0.01$ using 4-PSK constellation

Appendix A

Let $x = x_1\ and\ y = x_2$, then from (6) & (7), the pdf of $x_1\ and\ x_2$ are evaluated as

$$f_{x_1}(x_1) = \frac{{x_1}^{L-1} e^{-x_1/c}}{c^L \Gamma(L)} \quad (30)$$

and

$$f_{x_2}(x_2) = \frac{{x_2}^{N_t-1} e^{-x_2/d}}{d^{N_t} \Gamma(N_t)} \quad (31)$$

Since $z = x_1 + x_2$ follow gamma distribution function, the pdf of z can be achieved by applying inverse Laplace transform of moment generating function (MGF) of z. From (17) & (18), the MGF of $x_1\ and\ x_2$ is given by

$$G_{x_1}(s) = {v_1}^{\mu_1}(s + v_1)^{-\mu_1} \quad (32)$$

$$G_{x_2}(s) = {v_2}^{\mu_2}(s + v_2)^{-\mu_2} \quad (33)$$

where $v_1 = \frac{1}{c}, \mu_1 = L, v_2 = \frac{1}{d}\ and\ \mu_2 = N_t$. Hence the MGF of z can be yield as

$$G_z(s) = \prod_{g=1}^{2} {v_g}^{\mu_g} \left(s + v_g\right)^{-\mu_g} \quad (34)$$

By using partial fraction and taking the inverse Laplace transform of $G_z(s)$, we can achieve the pdf of z in (8).

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