Error Rate of MIMO OSTBC Systems over Mixed Nakagami-m/ Rice Fading Channels

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***Abstract*—We study the performance of multiple-input multiple-output orthogonal space-time block coded systems over mixed Nakagami-m/Rice fading channels. Novel closed-form expression for the exact average bit error rate (ABER) of Gray coded rectangular quadrature amplitude modulation is obtained. This expression include already published formulae for other fading channels as special cases. We further derive simple expression for the asymptotic ABER, the diversity order, and the coding gain, which give useful insights for the system performance at high signal-to-noise ratio values. Extensive numerical and computer simulation results are presented to validate the accuracy of the proposed analysis.**

***Index Terms*—Orthogonal space-time block coding, multiple-input multiple-output, Nakagami-m, Rice, fading, bit error rate, quadrature amplitude modulation.**

I. Introduction

Orthogonal space-time block code (OSTBC) is an efficient technology to support high-data rate, bandwidth efficiency and communication reliability, envisioned under the fifth generation (5G) wireless standards [1]–[3]. OSTBC integrated with multiple-input multiple-output (MIMO) systems possesses the potential to overcome the performance degrading effects of fading in wireless communications. Several classical fading models such as Rayleigh, Nakagami-m, Hoyt, Rice, etc. have been proposed to characterize various possible wireless propagation channels. However, usually in the open literature of wireless communication systems, the signal paths between a transmitter and receiver are assumed to be identically distributed. This is named in literature as *symmetric fading*. Furthermore, a more practical fading model, which can accommodate various wireless propagation scenarios is termed as *mixed fading* [4]. According to this model the signal paths follow different distribution. For example, in mixed fading model, one path could be dominated by line-of-sight (LoS) Rician statistics, while the other could be under severe or moderate scattering (Nakagami-m) phenomena. Note that mixed fading includes symmetric fading scenario as special case, while one can also view mixed fading as generalization of the independent non-identically distributed (i.n.d) symmetric fading channels. For example, i.n.d. symmetric Rice fading channels include mixed Rayleigh/Rice fading by choosing appropriate values for the Rice factor, K. It is important to mention that i.n.d. symmetric Rice fading channels do not include mixed Nakagam-m/Rice fading channels as special cases. On the other hand, mixed Nakagami-m/Rice fading analysis includes symmetric Rayleigh fading, symmetric Nakagami-m and symmetric Rice fading as special cases. It should be mentioned that mixed fading modeling is suitable to model practical urban micro-cell and indoor wireless scenarios [4], [5]. Recently [6], the small-scale fading statistics obtained from a 28 GHz outdoor measurement campaign suggest that Rician fading is more suited than Rayleigh even in non-line-of-sight environments.

Among various modulation schemes, the bandwidth efficient rectangular quadrature amplitude modulation (RQAM) schemes can be a promising solution to various bandwidth-intense immersive media services. The RQAM accommodates square QAM (SQAM), QPSK, and BPSK as special cases [7]. Thus, it may be of interest to analyze the performance of the generalized RQAM schemes for MIMO OSTBC systems over mixed Nakagami-m/Rice fading channels.

A. Prior Related Work

Several works on the performance of MIMO OSTBC systems are available in literature [3], [8]–[20]. Recently, the performance of OSTBC transmission in large MIMO systems was investigated in [3]. In [8], the error performance for the MIMO OSTBC system in Rayleigh fading channels was analyzed through Monte Carlo simulations. In [9], the symbol error rate (SER) performance for MIMO OSTBC systems employing generalized receive antenna selection in Nakagami-m fading channels was studied. In [10], the capacity of MIMO OSTBC systems over correlated Weibull fading channels was presented. In [11], exact SER expressions for MIMO OSTBC systems with M-ary phase-shift-keying (PSK) and SQAM signals are derived for flat Rayleigh fading channels. In [12], the authors derive closed-form expressions for the average bit error rate (ABER) of MIMO OSTBC systems with M-ary pulse amplitude modulation (PAM) and SQAM schemes over Nakagami-m fading channels for integer values of m. Furthermore, the BER performance of MIMO OSTBC systems over correlated Nakagami-m fading was presented in [13]. In [14], SER expressions for MIMO OSTBC systems were presented with PSK/QAM modulations over Rayleigh, Rician, and Nakagami-m fading channels. In [15], closed-form expressions for the ABER for Gray-coded M-ary one and two-dimensional amplitude for modulations were derived for MIMO OSTBC systems, employing transmit antenna selection. In [16], the BER performance for MIMO OSTBC systems was studied over correlated Rayleigh fading channels while in [17], the authors investigated the SER and the BER performance, assuming antenna selection over keyhole fading channels. In [18], the performance of pre-coded differential orthogonal space-time modulation over correlated Rician MIMO channels was presented. The exact performance analysis of maximal ratio combining/OSTBC was investigated in [19], assuming Nakagami-m and Rice fading channels and the error/outage performance of MIMO OSTBC systems over Rice fading channels in shadowing environments was analyzed in [20].

B. Contribution and Outline

The main contributions of this paper are as follows:

- We present novel closed-form expression for the exact ABER of MIMO OSTBC systems with Gray coded RQAM over mixed Nakagami-m/Rice fading channels.
- Simple closed-form expression is derived for the asymptotic ABER, which can be used to determine the diversity order and the coding gain.

To the best of our knowledge, closed-form expressions for the ABER of MIMO OSTBC systems with Gray coded RQAM over mixed Nakagami-m/Rice fading channels are not available in literature.

The rest of the paper is organized as follows. Section II contains system and channel model, the exact ABER, asymptotic ABER, the diversity order and coding gain are derived in Section III. In Section IV, numerical and simulation results with discussion are given. The paper is concluded in Section V.

II. System and Channel Model

A MIMO OSTBC system is considered as shown in Fig. 1, with $\mathcal{K}_t$ transmit and $\mathcal{K}_r$ receive antennas operating over independent mixed Nakagami-m/Rice fading channels. The message symbols $z_1, z_2, \ldots, z_W$, chosen from an M-ary QAM constellation, are encoded through an OSTBC defined by a $\mathcal{K}_t \times \mathcal{P}$ column orthogonal matrix $\mathcal{G}$, which is generated by linearly combining the symbols and their conjugates, and W is total message symbols transmitted over $\mathcal{P}$ symbol durations. The transmission model is [1]

$$\mathbf{Y} = \mathbf{H}\mathcal{G} + \mathbf{N}, \tag{1}$$

where the channel matrix $\mathbf{H}$ is defined as

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \ldots & h_{1,\mathcal{K}_t} \\ h_{2,1} & h_{2,2} & \ldots & h_{2,\mathcal{K}_t} \\ \vdots & \vdots & \vdots & \vdots \\ h_{\mathcal{K}_r,1} & h_{\mathcal{K}_r,2} & \ldots & h_{\mathcal{K}_r,\mathcal{K}_t} \end{bmatrix},$$

where $h_{i,j}$ is the channel gain between the i-th receive and the j-th transmit antennas, $\mathbf{Y}$ is a $\mathcal{K}_r \times \mathcal{P}$ matrix whose entries are the received signal through the $\mathcal{K}_r$ receiving antennas over $\mathcal{P}$ symbol durations, and $\mathbf{N}$ is a $\mathcal{K}_r \times \mathcal{P}$ matrix, where its elements are independent identically distributed (i.i.d.)

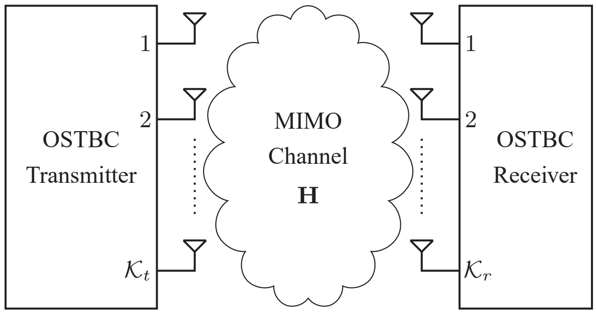

Fig. 1. System model

complex Gaussian random variables (RVs), with a one-sided power spectral density $\mathcal{N}_0$. We also assume that $|h_{i,j}|$ is modeled either Nakagami-m or Rice RV. The rate R of the OSTBC is defined as $R = W/\mathcal{P}$, while the instantaneous output signal-to-noise ratio (SNR) per symbol for maximum likelihood decoding with perfect channel state information is given by [1]

$$\gamma_o = \frac{\bar{\gamma}_b}{R\mathcal{K}_t}||\mathbf{H}||_F^2, \tag{2}$$

where $\bar{\gamma}_b = E_b/\mathcal{N}_0$ is the average SNR per bit per receive antenna, E_b represents the total transmitted energy, $||\mathbf{H}||_F$ denotes the Frobenius norm of the matrix $\mathbf{H}$[1], and $\mathbf{h}_l = [h_{l,1} h_{l,2} \ldots h_{l,\mathcal{K}_t}]$; $l = 1, 2, \ldots \mathcal{K}_r$ denotes the l-th row of the matrix $\mathbf{H}$. The moment generating function (MGF) of a RV γ_i is defined as $\mathbb{M}_{\gamma_i}(s) = \mathbb{E}[\exp(-s\gamma_i)]$, where $\mathbb{E}[\cdot]$ denotes statistical averaging operator. If $|h_{i,j}|$ follows Nakagami-m distribution, then the MGF of $\gamma_m = \frac{\bar{\gamma}_b}{R\mathcal{K}_t}|h_{i,j}|^2$, can be expressed as [7]

$$\mathbb{M}_{\gamma_m}(s) = \left(1 + \frac{s\bar{\gamma}_b\Omega_m}{mR\mathcal{K}_t}\right)^{-m}, \tag{3}$$

where $m \geq 0.5$ denotes the Nakagami fading parameter and $\Omega_m = \mathbb{E}[|h_{i,j}|^2]$ is the average power. If $|h_{i,j}|$ follows Rice distribution, then the MGF of $\gamma_k = \frac{\bar{\gamma}_b}{R\mathcal{K}_t}|h_{i,j}|^2$, can be written as [7]

$$\mathbb{M}_{\gamma_k}(s) = \exp\left(-\frac{sK\bar{\gamma}_b\Omega_k}{(1+K)R\mathcal{K}_t + s\bar{\gamma}_b\Omega_k}\right) \times \left(1 + \frac{s\bar{\gamma}_b\Omega_k}{(1+K)R\mathcal{K}_t}\right)^{-1}, \tag{4}$$

where K is the Rician factor K, which represents the ratio of the power of the specular component to the average power of the scattered component and $\Omega_k = \mathbb{E}[|h_{i,j}|^2]$ is the average power of Rice faded link.

[1]The Frobenius norm of a $m \times n$ matrix can be computed as $||\mathbf{H}||_F = \sqrt{\sum_{l=1}^{m}\sum_{k=1}^{n}|h_{l,k}|^2}$.

III. Performance Analysis

In an AWGN channel, the conditional BER for $M_I \times M_J$ Gray coded RQAM constellations is given by [21]

$$P(e|\gamma_o) = \beta\Bigg[\sum_{u=1}^{\log_2 M_I}\sum_{p=0}^{(1-2^{-u})M_I-1} \mathcal{Z}(p,u,M_I)\, Q\big((2p+1)\rho\sqrt{\gamma_0}\big) + \sum_{v=1}^{\log_2 M_J}\sum_{q=0}^{(1-2^{-v})M_J-1} \mathcal{Z}(q,v,M_J)\, Q\big(2q+1)\rho\sqrt{\gamma_0}\big)\Bigg], \quad (5)$$

where $\beta = 1/\log_2(M_I M_J)$, $\rho^2 = 6/(\beta(M_I^2 + M_J^2 - 2))$, $\mathcal{Z}(a,b,c) = (2(-1)^{\lfloor \frac{2^{b-1}a}{c}\rfloor}/c)\left(2^{b-1}\left(\lfloor(2^{b-1}a/c)+0.5\rfloor\right)\right)$, $\lfloor\cdot\rfloor$ denotes the floor function, M_I and M_J are the number of in-phase and quadrature phase constellation points, respectively, and the Gaussian Q-function is defined as [7]

$$Q(y) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-\frac{y^2}{2\sin^2(\psi)}\right) d\psi; \qquad y \geq 0 \quad (6)$$

The ABER can be obtained by averaging the conditional BER in (5) over the probability density function of γ_0. Thus, using (6) and after some manipulations, $P(e)$

$$P(e) = \beta\Bigg[\sum_{u=1}^{\log_2 M_I}\sum_{p=0}^{(1-2^{-u})M_I-1} \mathcal{Z}(p,u,M_I)\, \mathcal{C}\big(p,\rho\big) + \sum_{v=1}^{\log_2 M_J}\sum_{q=0}^{(1-2^{-v})M_J-1} \mathcal{Z}(q,v,M_J)\, \mathcal{C}\big(q,\rho\big)\Bigg], \quad (7)$$

where

$$\mathcal{C}\big(z,\rho\big) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \mathbb{M}_{\gamma_0}\left(\frac{(2z+1)^2\rho^2}{2\sin^2(\psi)}\right) d\psi. \quad (8)$$

Next, in order to obtain a closed-form solution for the ABER, we solve the integral $\mathcal{C}\big(z,\rho\big)$ for mixed Nakagami-m/Rice fading channels.

A. Exact ABER

If the entries of the $\mathcal{K}_{r_1}$ rows are i.i.d. Nakagami-m RVs and the remaining $\mathcal{K}_{r_2} = \mathcal{K}_r - \mathcal{K}_{r_1}$ rows are i.i.d. Rice RVs, then the MGF of γ_o can be readily obtained as

$$\begin{aligned}\mathbb{M}_{\gamma_o}(s)) &= \Big(\mathbb{M}_{\gamma_k}(s)\Big)^{\mathcal{K}_{r_2}\mathcal{K}_t}\Big(\mathbb{M}_{\gamma_m}(s)\Big)^{\mathcal{K}_{r_1}\mathcal{K}_t} \\ &= \exp\left(-\frac{sK\bar{\gamma}_b\Omega_k\mathcal{K}_{r_2}\mathcal{K}_t}{(1+K)R\mathcal{K}_t + s\bar{\gamma}_b\Omega_k}\right) \\ &\times \left(1+\frac{s\bar{\gamma}_b\Omega_k}{(1+K)R\mathcal{K}_t}\right)^{-\mathcal{K}_{r_2}\mathcal{K}_t} \\ &\times \left(1+\frac{s\bar{\gamma}_b\Omega_m}{mR\mathcal{K}_t}\right)^{-m\mathcal{K}_{r_1}\mathcal{K}_t}. \end{aligned} \quad (9)$$

Lemma 1. *A closed-form solution for the integral $\mathcal{C}\big(z,\rho\big)$, when mixed Nakagami-$m$/Rice fading is assumed, is given by*

$$\begin{aligned}&\mathcal{C}\big(z,\rho\big) \\ &= \frac{(2z+1)\rho\sqrt{\bar{\gamma}_b\Omega_k}(m\Omega_k)^{m\mathcal{K}_{r_1}\mathcal{K}_t}\exp(-K\mathcal{K}_{r_2}\mathcal{K}_t)}{\sqrt{8\pi(1+K)R\mathcal{K}_t}((1+K)\Omega_m)^{m\mathcal{K}_{r_1}\mathcal{K}_t}\lambda^{-\nu_2-0.5}} \\ &\times \frac{\Gamma(\nu_2+0.5)}{\Gamma(\nu_2+1)}\Phi_1^{(3)}\big(\nu_2+0.5, 1, m\mathcal{K}_{r_1}\mathcal{K}_t; \nu+1; \lambda, \\ &\lambda - \lambda m\Omega_k/\left((1+K)\Omega_m\right), \lambda K\mathcal{K}_{r_2}\mathcal{K}_t\big),\end{aligned} \quad (10)$$

where $\nu_2 = (m\mathcal{K}_{r_1} + \mathcal{K}_{r_2})\mathcal{K}_t$, and $\Phi_1^{(3)}(\cdot)$ denotes the three variable confluent Lauricella's hypergeometric function, defined as [22]

$$\begin{aligned}&\Phi_1^{(3)}(m,p_1,p_2;q;s_1,s_2,s_3) = \frac{\Gamma(q)}{\Gamma(m)\Gamma(q-m)}\int_0^1 v^{m-1} \\ &\times (1-v)^{q-m-1}\prod_{i=1}^{2}(1-v\,s_i)^{-p_i}\exp(v\,s_3)dv; \\ &\quad \mathrm{Re}(m) > 0,\ \mathrm{Re}(q-m) > 0 \\ &= \sum_{l_1,l_2,l_3=0}^{\infty}\frac{(m)_{l_1+l_2+l_3}(p_1)_{l_1}(p_2)_{l_2}\,s_1^{l_1}s_2^{l_2}s_3^{l_3}}{(q)_{l_1+l_2+l_3}\Gamma(l_1+1)\Gamma(l_2+1)\Gamma(l_3+1)}; \\ &\quad |s_1| < 1, |s_2| < 1\end{aligned} \quad (11)$$

Since $|\lambda| < 1$ and $|\lambda - \lambda m\Omega_k/\left((1+K)\Omega_m\right)| < 1$, it implies that the convergence condition of $\Phi_1^{(3)}(\cdot)$ is satisfied.

Proof:: Putting (9) in (8), using two successive substitutions $t = \frac{2K(1+K)R\mathcal{K}_{r_2}\mathcal{K}_t^2\sin^2(\psi)}{2(1+K)R\mathcal{K}_t\sin^2(\psi)+(2z+1)^2\rho^2\bar{\gamma}_b\Omega_k}$ and $v = \left(\frac{2(1+K)R\mathcal{K}_t+(2z+1)^2\rho^2\bar{\gamma}_b\Omega_k}{2K(1+K)R\mathcal{K}_{r_2}K_t^2}\right)t$, and the definition of $\Phi_1^{(3)}(\cdot)$, (10) can be obtained. ∎

B. Asymptotic ABER

The asymptotic ABER of a MIMO OSTBC system with Gray coded RQAM can be given as

$$P_\infty(e) \approx \beta\Bigg[\sum_{u=1}^{\log_2 M_I}\sum_{p=0}^{(1-2^{-u})M_I-1} \mathcal{Z}(p,u,M_I)\, \mathcal{C}_\infty\big(p,\rho\big) + \sum_{v=1}^{\log_2 M_J}\sum_{q=0}^{(1-2^{-v})M_J-1} \mathcal{Z}(q,v,M_J)\, \mathcal{C}_\infty\big(q,\rho\big)\Bigg], \quad (12)$$

where

$$\mathcal{C}_\infty\big(z,\rho\big) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \mathbb{M}_\infty\left(\frac{(2z+1)^2\rho^2}{2\sin^2(\psi)}\right) d\psi. \quad (13)$$

Further, we present solutions for the integral $\mathcal{C}_\infty\big(z,\rho\big)$ for mixed Nakagami-m/Rice fading channels.

At high SNR, the MGF $\mathbb{M}_{\gamma_o}(s)$ in (9) can be approximated as

$$\begin{aligned}\mathbb{M}_\infty(s) &= \lim_{\bar{\gamma}_b\to\infty}\mathbb{M}_{\gamma_o}(s) \\ &\approx \left(\frac{s\bar{\gamma}_b}{R\mathcal{K}_t}\right)^{-(m\mathcal{K}_{r_1}+\mathcal{K}_{r_2})\mathcal{K}_t}\left(\frac{\Omega_m}{m}\right)^{-m\mathcal{K}_{r_1}\mathcal{K}_t} \\ &\times \left(\frac{\Omega_k}{1+K}\right)^{-\mathcal{K}_{r_2}\mathcal{K}_t}\exp(-K\mathcal{K}_{r_2}\mathcal{K}_t).\end{aligned} \quad (14)$$

Lemma 2. *A closed-form solution for the integral $\mathcal{C}_\infty(z,\rho)$, when mixed Nakagami-$m$/Rice fading is assumed, is*

$$\mathcal{C}_\infty(z,\rho) = \frac{0.5}{\pi}\left(\frac{(2z+1)^2\rho^2\bar{\gamma}_b}{2R\mathcal{K}_t}\right)^{-(m\mathcal{K}_{r_1}+\mathcal{K}_{r_2})\mathcal{K}_t} \times \left(\frac{\Omega_m}{m}\right)^{-m\mathcal{K}_{r_1}\mathcal{K}_t}\left(\frac{\Omega_k}{1+K}\right)^{-\mathcal{K}_{r_2}\mathcal{K}_t}\exp(-K\mathcal{K}_{r_2}\mathcal{K}_t) \times \mathcal{B}\left(0.5,(m\mathcal{K}_{r_1}+\mathcal{K}_{r_2})\mathcal{K}_t+0.5\right), \tag{15}$$

where $\mathcal{B}(a,b)=\int_0^1 x^{a-1}(1-x)^{b-1}dx$ denotes Beta function.

Proof:: Putting (14) in (13), using substitution $v=\cos^2(\psi)$ and the definition of Beta function $\mathcal{B}(\cdot)$, the expression in (15) can be obtained. ■

C. Diversity Order and Coding Gain

In the high SNR region, the ABER can be expressed as

$$P_\infty(e) = (G_c\bar{\gamma}_b)^{-G_d}, \tag{16}$$

where G_d and G_c denote the achieved diversity order and the coding gain of the system, respectively. From (15), the diversity order of the considered system is $G_d=(m\mathcal{K}_{r_1}+\mathcal{K}_{r_2})\mathcal{K}_t$, and the coding gain is

$$G_c = \left[\beta\left[\sum_{u=1}^{\log_2 M_I}\sum_{p=0}^{(1-2^{-u})M_I-1}\mathcal{Z}(p,u,M_I)\,\mathcal{D}_\infty(p,\rho) + \sum_{v=1}^{\log_2 M_J}\sum_{q=0}^{(1-2^{-v})M_J-1}\mathcal{Z}(q,v,M_J)\,\mathcal{D}_\infty(q,\rho)\right]\right]^{-\frac{1}{G_d}},$$

where

$$\mathcal{D}_\infty(z,\rho) = \frac{0.5}{\pi}\left(\frac{(2z+1)^2\rho^2}{2R\mathcal{K}_t}\right)^{-G_d}\left(\frac{\Omega_m}{m}\right)^{-m\mathcal{K}_{r_1}\mathcal{K}_t} \times \left(\frac{\Omega_k}{1+K}\right)^{-\mathcal{K}_{r_2}\mathcal{K}_t}\exp(-K\mathcal{K}_{r_2}\mathcal{K}_t)\mathcal{B}\left(0.5,G_d+0.5\right).$$

It should be noted here that the fading parameter K has no impact on the diversity order, while the coding gain is affected by the rate R of the OSTBC and the fading parameters, m and K.

IV. Numerical and Simulation Results

In this section, numerical results are presented to validate the mathematical analysis. In particular, in the numerical examples, we take the $\mathcal{G}_2$ [8] OSTBC as standard model with different modulation schemes. The Lauricella's hypergeometric function $\Phi_1^{(3)}(\cdot)$ can be efficiently computed using their finite integral representation by mathematical softwares such as the MATHEMATICA and MATLAB.

Figs. 2 and 3 present the ABER performance of 2 × 2-MIMO OSTBC system with Gray coded 4 × 4-QAM and 8-PAM schemes over mixed fading channels for $\mathcal{K}_{r_1}=\mathcal{K}_{r_2}=1$. It can be noticed that simulations match with the analytical results. Four cases of fading channels, namely $m=1,K=0$ (Rayleigh/Rayleigh), $m=0.5,K=1$ (One sided Gaussian/Rice), $m=2,K=1$ (Nakagami-m/Rice), and $m=3.5,K=4$ (Nakagami-m/Rice) are investigated. It can be seen that the achieved SNR gains are resulting from the increase in fading parameters, m and K. For example, an ABER of 10^{-4} for 4×4-QAM occurs at $\bar{\gamma}_b\approx15$ dB when $m=0.5,K=1$, $\bar{\gamma}_b\approx14$ dB when $m=1,K=0$, $\bar{\gamma}_b\approx12.5$ dB when $m=2,K=1$, and $\bar{\gamma}_b\approx11$ dB when $m=3.5,K=4$. Fig 4 illustrates the ABER performance of 3×2-MIMO OSTBC system with Gray coded 8×8-QAM over mixed fading channels for $\mathcal{K}_t=3,\mathcal{K}_{r_1}=\mathcal{K}_{r_2}=1$, and $\mathcal{G}_3$.

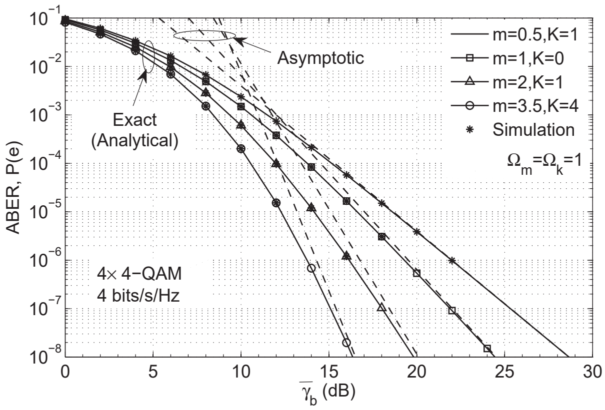

Fig. 2. ABER of 2×2-MIMO OSTBC system with 4×4-QAM over mixed Nakagami-m/Rice fading channels.

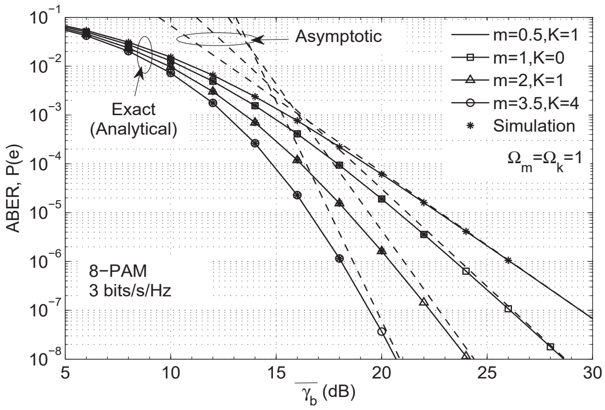

Fig. 3. ABER of 2×2-MIMO OSTBC system with 8-PAM over mixed Nakagami-m/Rice fading channels.

The ABER performance of 2×2-MIMO OSTBC system with Gray coded 8×4-QAM scheme over mixed fading channels are shown in Fig. 5 with $m=1,K=1$ and $m=3.5,K=5$ for different values of $\{\Omega_m,\Omega_k\}$. As expected, the ABER performance improves with an increase in the ratio of $\frac{\Omega_k}{\Omega_m}$. For example, an ABER of 10^{-5} with $m=1,K=1$ occurs at $\bar{\gamma}_b\approx20.5$ dB when $\Omega_m=1,\Omega_k=0.5$, $\bar{\gamma}_b\approx20$ dB when $\Omega_m=1,\Omega_k=0.7$, and $\bar{\gamma}_b\approx19$ dB when $\Omega_m=\Omega_k=1$.

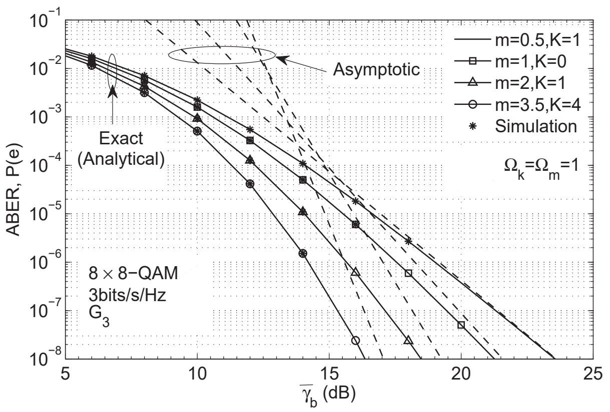

Fig. 4. ABER of 3×2-MIMO OSTBC system with 8×8-QAM over mixed Nakagami-m/Rice fading channels.

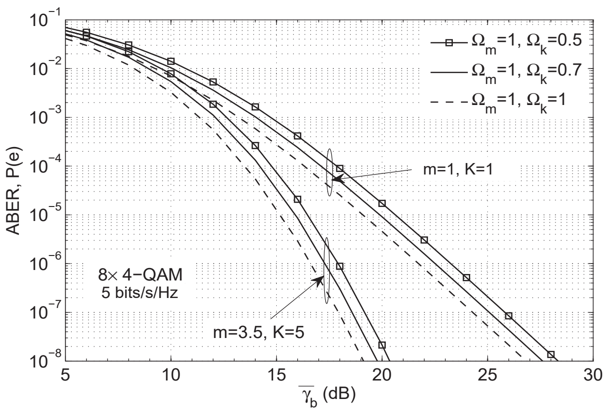

Fig. 5. ABER of 2×2-MIMO OSTBC system with 8×4-QAM over mixed Nakagami-m/Rice fading channels.

V. Conclusion

The error performance of MIMO OSTBC systems were analyzed over mixed Nakagami-m/Rice fading channels. Novel closed-form exact and asymptotic ABER expressions for Gray coded RQAM modulation were derived. The obtained results are general and can be efficiently used for antennas and various modulation schemes. Moreover, the ABER expressions include other fading channels addressed in the literature as special cases such as Rayleigh and Nakagami-m fading channels. As expected, the MIMO OSTBC system achieves diversity order $(m\mathcal{K}_{r_1} + \mathcal{K}_{r_2})\mathcal{K}_t$ over mixed Nakagami-m/Rice fading channels.

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References

[1] E. G. Larsson, and P. Stoica, *Space-Time Block Coding for Wireless Communications* Cambridge University Press, 2003.

[2] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 45, no. 5, pp. 1456-1467, Jul. 1999.

[3] M. K. Arti, "OSTBC transmission in large MIMO systems," *IEEE Commun. Lett.*, vol. 20, no. 11, pp. 2308-2311, Nov. 2016.

[4] P. Kyosti, et al., 'WINNER II interim channel models (IST-4-027756 WINNER II D1.1.1 V1.1), WINNER II' Munich, Germany, Tech. Rep. [Online]. Available: http://www.ist-winner.org/WINNER2-Deliverables/D1.1.1.pdf, Tech. Rep.

[5] M. D. Kim, H. K. Kwon, B. S. Park, J. J. Park, and H. K. Chung, "Wideband MIMO channel measurements in indoor hotspot scenario at 3.705GHz", *4th Int. Conf. Signal Process. Commun. Sys.*, Dec 2010, pp. 1-5.

[6] M. K. Samimi, G. R. MacCartney, S. Sun, and T. S. Rappaport, "28 GHz millimeter-wave ultrawideband small-scale fading models in wireless channels", in *Proc. VTC Spring*, May 2016, pp. 1-6.

[7] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels,* 2nd ed. New York: Wiley, 2005.

[8] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes for wireless communications: Performance results", *IEEE J. Select. Area Commun.*, vol. 17, no. 3, pp. 451-460, Mar. 1999.

[9] Y. G. Kim, N. C. Beaulieu, and W. K. Lee, "SEP performance using equivalence in Nakagami-m fading channels", *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3792-3795, May 2016.

[10] S. S. Chauhan, and S. Kumar, "Capacity of orthogonal space-time block codes in spatially correlated MIMO Weibull fading channel under various adaptive transmission techniques", *Telecommunication Systems*, vol. 62, no. 1, pp. 101-110, 2016.

[11] H. Shin, and J. H. Lee, "Exact symbol error probability of orthogonal space-time block codes", in *Proc. IEEE Globecom, Taipei, Taiwan*, Nov. 2002, pp. 1197-1201.

[12] A. Maaref, and S. Aissa, "Exact closed-form expression for the bit error rate of orthogonal STBC in Nakagami fading channels," in *Proc IEEE VTC-Fall*, Sep. 2004, pp. 1-5.

[13] G. Femenias, "BER performance of linear STBC from orthogonal designs over MIMO correlated Nakagami-m fading channels", *IEEE Trans. Veh. Technol.*, vol. 53, no. 2, pp. 307-317, Mar. 2004.

[14] H. Zhang, and T. A. Gulliver, "Capacity and error probability analysis for orthogonal space-time block codes over fading channels", *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 808-819, Mar. 2005.

[15] S. Kaviani, and C. Tellambura, "Closed-form BER analysis for antenna selection using orthogonal space-time block codes", *IEEE Commun. Lett.*, vol. 10, no. 10, pp. 704-706, Oct. 2006.

[16] I.-M. Kim, "Exact BER analysis of OSTBCs in spatially correlated MIMO channels', *IEEE Trans. Commun.*, vol. 54, no. 8, pp. 1365-1373, Aug. 2006.

[17] N. H. Tran, H. H. Nguyen, and T. Le-Ngoc, "Symbol and bit error probabilities of orthogonal space-time block codes with antenna selection over keyhole fading channels", *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 4818-4824, Dec. 2008.

[18] M. R. Bhatnagar, A. Hjorungnes, and L. Song, "Precoded differential orthogonal space-time modulation over correlated Ricean MIMO channels", *IEEE J. Sel. Top. Signal Process.*, vol. 2, no. 2, pp. 124-134, Apr. 2008.

[19] G. A. Ropokis, A. A. Rontogiannis, P. T. Mathiopoulos, and K. Berberidis, "An exact performance analysis of MRC/OSTBC over generalized fading channels", *IEEE Trans. Commun.*, vol. 58, no. 9, pp. 2486-2492, Sep. 2010.

[20] P. Mary, M. Dohler, J. M. Gorce, and G. Villemaud, "Symbol error outage analysis of MIMO OSTBC systems over Rice fading channels in shadowing environments", *IEEE Trans. Wireless Commun.*, vol. 10, no. 4, pp. 1009-1014, Apr. 2011.

[21] K. Cho and D. Yoon, "On the general BER expression of one- and two-dimensional amplitude modulations", *IEEE Trans. Commun.*, vol. 50, no. 7, pp. 1074-1080, Jul. 2002.

[22] H. Exton, *Multiple Hypergeometric Functions and Applications* Johm Wiley & Sons, New York, 1976.