Performance bounds of space-time block coding in Rician and log-normal fading channels

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Abstract: Analytical expressions concerning the capacity and bit error rate (BER) of multiple-input multiple-output systems with space-time block coding (STBC) are derived. Two fading environments are examined, log-normal and Rician channels. A tight closed-form upper bound is presented for the BER of systems operating in log-normal fading environments in addition to an upper bound for the capacity of this type of systems. The latter bound applies to systems that operate under Rician fading as well. The analytical results were validated against ample numerical simulations for three STBC schemes and three phase-shift-keying modulations. The proposed bounds proved to be a tractable way to evaluate the system performance when no closed-form expression for the probability density function or the moment generating function is known.

1 Introduction

The ever-increasing need for low-cost broadband communications has become the driving force behind the extensive research in the field of wireless communications. Wireless local area networks (WLANs) used for wideband transmission have attracted the interest of the scientific community with the bulk of studies focusing on the investigation of coding as well as modulation techniques. The need to examine the channel capacity and the bit error rate (BER) with mathematical analysis can become burdensome depending on the environment that is investigated. In this paper, two channel models are taken into account; the Rician and the log-normal channel models. Experimental results at several frequencies support the fact that the Rician model describes indoor (see Babich and Lombardi [1] and references therein) as well as outdoor environments, whereas, the log-normal distribution family is particularly true for indoor radio propagation environments, where terminals with low mobility have to rely on macroscopic diversity to overcome the shadowing from the indoor obstacles and moving human bodies. In slowly varying log-normal fading channels, the small- and large-scale effects tend to get mixed, and the log-normal statistics tend to dominate and to accurately describe the distribution of the channel path gain [2].

In most scattering environments, antenna diversity is a practical and convenient method aiming at ameliorating the detrimental effects of multipath fading. A simple transmit diversity scheme for two transmitting antennas was first introduced by Alamouti [3] and generalised to an arbitrary number of antennas as space–time block coding (STBC) by Tarokh *et al.* [4]. Considerable research efforts have been devoted in recent years for the average capacity and the BER performance, when applying multiple-input multiple-output (MIMO) diversity and STBC to fading channels [5–12].

The Shannon average capacity provides important information for the maximum transmission rate of wireless communications systems. On writing this paper, the capacity limits of wireless communications fading channels are of the utmost interest, because they represent an optimistic bound for practical communications systems. The Shannon capacity of a MIMO channel is not always easy to estimate, usually because of the difficulty that arises when it is necessary to find the distribution of the sum of the random variables (RVs) that represent the paths of the MIMO channel. To overcome this difficulty, some capacity bounds are proposed in the literature; Cui *et al.* [13] have suggested an upper and a lower bound for the capacity of MIMO correlated Rician fading channels, while Loyka and Kouki [14] have proposed an upper bound on the mean MIMO channel capacity. The MIMO capacity in fading environments has been shown to grow significantly if the number of antennas is increased both at the transmitter and at the receiver [8, 15]. As already known, the achieved information data rate of an STBC system is well below the theoretical capacity limit of the MIMO channel [9]. Further, the number of transmitting and receiving antennas, N_T and N_R, respectively, are combined to produce a diversity gain of order $N_T \times N_R$.

Regarding the BER performance of a STBC system in a Rice distribution environment, the BER can be easily evaluated. Nevertheless, when log-normal distribution is considered, there is difficulty in analytically evaluating the exact average BER arising from the fact that not closed-form expression for the moment generating function (MGF) is known; it can only be approximated as yet. Research has therefore concentrated on approximations for this unsolvable problem with several approximate methods so far suggested [16, 17]. In the work of Slimane [18], some performance bounds have been suggested for the distribution function and recently, Berggren and Slimane [19] have proposed a lower bound for the outage probability. In [20], closed-form expressions as well as bound approximations are investigated for the outage probability, the average allocated power, the achievable spectral efficiency and the BER over Nakagami-*m* fading channels in a single-input single-output (SISO) environment.

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In this paper, an invertible and closed-form upper bound for the average capacity in Rician or log-normal fading environments is derived using Jensen's inequality. This bound is then tested in two different STBC schemes, to corroborate the proposed mathematical analysis. An upper bound for the BER of a log-normal fading channel is proposed, based on the arithmetic-geometric mean inequality and on the capability of a MIMO channel that can be equal to a SISO one. This bound is tested in three different STBC schemes and in three different phase-shift-keying (PSK) modulations. Furthermore, we examine by analysis and simulation the exact BER performance of a Rician fading channel model, testing it in the same STBC schemes and PSK modulations as in the log-normal fading channel BER analysis.

2 System and channel model

We consider a STBC system with N_T transmitting and N_R receiving antennas, hereafter referred to as STBC $N_T \times N_R$, operating in a quasistatic flat fading channel, so that the path gains are constant over a frame period and vary independently from one frame to another. The system transmits a block of K symbols of energy E_s, produced from a complex or real signalling modulation, during a period of T timeslots. The symbols $\{x_k\}_{k=1}^{K}$ are encoded by a STBC, creating a $T \times N_T$ column orthogonal transmission matrix with linear combinations of $x_1, x_2, \ldots, x_K$ and their conjugates. The code rate R of STBC is determined by $R = K/T$. It should be mentioned that STBC achieves the maximum possible transmission rate for any number of transmitting antennas when using any arbitrary real constellation (e.g. M-PAM). On the other hand, for an arbitrary complex constellation (e.g. M-PSK and M-QAM), full-rate exists only for two transmitting antennas, while, for other cases, R is below unity (3/4 for three and for four transmitting antennas and 1/2 for all the other transmitting antenna schemes, i.e. $N_T \geq 5$) [4]. The channel gain from the ith ($i = 1, 2, \ldots, N_T$) transmitting to the jth ($j = 1, 2, \ldots, N_R$) receiving antenna is denoted as $h_{i,j}$ and is modelled as a complex RV with its phase uniformly distributed within $[0, 2\pi)$, whereas its envelope $c_{i,j} = |h_{i,j}|$ is distributed according to one of the well-known Rice or log-normal distribution families. The corresponding probability density functions (PDFs) are given by [21, eq. (2.16) and (2.53)]

$$p_\gamma(\gamma) = \frac{(1+K)\mathrm{e}^{-K}}{\bar{\gamma}} \exp\left[-\frac{(1+K)\gamma}{\bar{\gamma}}\right] \times I_0\left(2\sqrt{\frac{(1+K)K\gamma}{\bar{\gamma}}}\right), \quad \gamma \geq 0 \tag{1}$$

for the Rice distribution, where K is the Rician factor and $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind, and

$$p_\gamma(\gamma) = \frac{\xi}{\sqrt{2\pi}\sigma\gamma} \exp\left[-\frac{(10\log_{10}\gamma - \mu)^2}{2\sigma^2}\right] \tag{2}$$

for the log-normal distribution, where $\xi = 10/\ln\ 10 = 4.3429$, and μ (dB) and σ (dB) are the mean and the standard deviation of $10\log_{10}\gamma$, respectively.

Moreover, the instantaneous input signal-to-noise ratio (SNR) for the STBC system is defined as

$$\gamma_{i,j} = \frac{E_s}{N_0}|h_{i,j}|^2 \tag{3}$$

and the channel gain matrix $\boldsymbol{H}$ as

$$\boldsymbol{H} \triangleq \begin{bmatrix} h_{1,1} & h_{2,1} & \cdots & h_{N_T,1} \\ h_{1,2} & h_{2,2} & \cdots & h_{N_T,2} \\ \vdots & \vdots & \ddots & \vdots \\ h_{1,N_R} & h_{2,N_R} & \cdots & h_{N_T,N_R} \end{bmatrix} \tag{4}$$

The entries of $\boldsymbol{H}$ are assumed to be uncorrelated, but not necessarily identically distributed, with arbitrary values for the fading severity parameters. Furthermore, it should be noted that perfect knowledge of the channel matrix $\boldsymbol{H}$ is assumed at the receiver.

3 Upper bound for the average capacity

The evaluation of the average capacity, in a generalised fading environment, needs statistical averaging over the PDF of the instantaneous SNR. However, in many cases, this PDF is either unknown (e.g. at the output of equal-gain-combining (EGC) receivers), or is in such a complicated form (e.g. Rice fading) that it does not lend itself to this averaging. To overcome this difficulty, we present an invertible tight closed-form upper bound in terms of the average SNR.

For a signal's s transmission bandwidth BW and energy $E_s = \varepsilon\langle|s|^2\rangle$ (with $\varepsilon\langle\cdot\rangle$ denoting averaging) over the additive white Gaussian noise (AWGN) channel with a single-sided power spectral density (PSD) N_0, the Shannon capacity is given by

$$C_\gamma = BW\log_2(1+\gamma) \tag{5}$$

where γ indicates the constant received SNR per symbol.

When the same signal s is transmitted over a fading channel, it experiences multiplicative fading of the envelope of h. Hence, γ is a RV and is written as

$$\gamma = \frac{E_s}{N_0}|h|^2 \tag{6}$$

The Shannon capacity can also be considered as a RV, because C_γ is straightforwardly connected to γ in (5). The average channel capacity can be obtained by averaging C_γ over the PDF of γ at the output of the receiver [22], that is

$$\bar{C}_\gamma = BW\int_0^\infty \log_2(1+\gamma)f_\gamma(\gamma)\,\mathrm{d}\gamma \tag{7}$$

To overcome the already mentioned difficulties (nescience or complicated form of $f_\gamma(\cdot)$) of evaluating the average capacity in closed form, a tight bound for $\bar{C}_\gamma$ can be derived using Jensen's inequality, because $\log_2(1+x)$ is a concave function for $x \in [0, \infty)$

$$\varepsilon\langle\log_2(1+\gamma)\rangle \leq \log_2(1+\varepsilon\langle\gamma\rangle) \tag{8}$$

Hence, by applying (8) in (5), $\bar{C}_\gamma$ can be upper bounded as given by the following simple expression

$$\bar{C}_\gamma \leq BW\log_2(1+\bar{\gamma}) \tag{9}$$

where $\bar{\gamma}$ is the average SNR per symbol at the output of the receiver, $\bar{\gamma} = \Omega E_s/N_0$, with $\Omega = \varepsilon\langle|h|^2\rangle$ being the average fading power.

From (9), we observe that this upper bound is invertible, meaning that the average SNR can simply be expressed in terms of average capacity as

$$\bar{\gamma} \geq 2^{\bar{C}_\gamma/BW} - 1 \tag{10}$$

Also, comparing (9) with (5), we can see that the capacity of a fading channel is always less than the capacity of an AWGN channel with the same average power [23]. Hence, (9) provides an upper bound for the average channel capacity, requiring only knowledge of a closed-form expression for the received output SNR.

From this it can be concluded that, if we consider a regular adaptive transmission system, in which the users adapt their rates according to the instantaneous SNR, then the average capacity of these users will be a function of the average SNR that they are experiencing. In this case, the bound proposed in (9) gives an accurate evaluation of this average capacity as a function of the average SNR.

The convenient general STBC capacity expression is given in matrix form by [7, 8]

$$C_{stbc} = BW\,R\,\log_2\left[\det\left(\boldsymbol{I}_{N_R} + \frac{E_s}{N_T R N_0}\boldsymbol{H}\boldsymbol{H}^{\dagger}\right)\right] \tag{11}$$

where $\boldsymbol{I}_{N_R}$ is an $N_R \times N_R$ identity matrix and $\boldsymbol{H}^{\dagger}$ denotes the transpose conjugate of the channel matrix $\boldsymbol{H}$. Following the analysis of [8, 9]

$$C_{stbc} = BW\ R\ \log_2\left(1 + \frac{E_s}{N_T\ R\ N_0}\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}|h_{i,j}|^2\right) \tag{12}$$

and based on the inequality (9), the bound for $\bar{C}_{stbc}$ measured at the output of STBC system can be expressed as a function of the channel components

$$\bar{C}_{stbc} \le BW\ R\ \log_2(1 + \bar{\gamma}_{stbc}) \tag{13}$$

where, based on [24]

$$\bar{\gamma}_{stbc} = \frac{E_s}{N_T R N_0}\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}\overline{|h_{i,j}|^2} \tag{14}$$

which corresponds to the equivalent Gaussian SISO model for the average output SNR [9].

4 Error-rate analysis

4.1 Rician fading

As far as the Rician channel is concerned, the BER performance is quite an easy task to compute, using the well-known formula for the MGF of the Rice fading model [21, equation (2.17)]

$$M_{\gamma}(s) = \frac{(1+K)}{(1+K) - s\bar{\gamma}}\mathrm{e}^{\left[Ks\bar{\gamma}/(1+K-s\bar{\gamma})\right]} \tag{15}$$

Thus, to evaluate the BER we need to find the distribution of a sum of Rician RVs. Regarding the instantaneous SNR and the MGF, we have

$$\gamma = \sum_{i=1}^{N_T N_R}\gamma_i \tag{16}$$

and

$$M_{\gamma}(s) = \prod_{i=1}^{N_T N_R} M_{\gamma_i}(s) \tag{17}$$

Knowing this MGF, the BER for M-PSK modulation is calculated using the integral [21, equation (5.78)]

$$P_e = \frac{1}{\pi}\int_0^{(M-1)\pi/M} M_{\gamma}\left(-\frac{a^2}{2\sin^2\theta}\right)\mathrm{d}\theta \tag{18}$$

where a^2 is a constant that depends on the specific modulation/detection combination and is equal to $a^2 = 2\sin^2(\pi/M)$.

4.2 Log-normal fading

When the fading channel is log-normal, as no closed-form expression is known, the MGF can only be approximated by [21, equation (2.54)]

$$M_{\gamma}(s) \simeq \frac{1}{\sqrt{\pi}}\sum_{n=1}^{N_p} H_{x_n}\exp\left[10^{(\sqrt{2}\sigma x_n+\mu)/10}s\right] \tag{19}$$

where x_n are the zeros of the N_p-order Hermite polynomial, H_{x_n} are the weight factors of the N_p-order Hermite polynomial, and μ (in dB) and σ (in dB) are the mean and the standard deviation of $10\log_{10}\gamma$, respectively, as in (2).

Based on the arithmetic-geometric mean inequality, which says that the geometric mean is less than or equal to the arithmetic mean

$$a_1 + a_2 + \cdots a_N \ge N(a_1 a_2 \cdots a_N)^{1/N} \tag{20}$$

and on the assumption that a log-normal distribution is generally produced by a normal one, i.e. if x is a normal variable, then e^x is a log-normal one, from (14) and (16) we obtain for the instantaneous SNR

$$\begin{aligned}\gamma_{stbc} &= \frac{E_s}{N_T R N_0}\sum_{l=1}^{N_T\times N_R}|h_l|^2 = \frac{E_s}{N_T R N_0}\sum_{l=1}^{N_T\times N_R}(\mathrm{e}^{x_l})^2\\ &\ge \frac{E_s}{N_T R N_0}(N_T N_R)\cdot\prod_{l=1}^{N_T\times N_R}\left[(\mathrm{e}^{x_l})^2\right]^{1/(N_T N_R)}\\ &= \frac{E_s N_R}{N_0 R}\exp\left[\left(\frac{2}{N_T N_R}\right)\sum_{l=1}^{N_T\times N_R}x_l\right]\end{aligned} \tag{21}$$

where x_l are normal variables with mean m and variance υ.

The argument of the exponential factor is also equivalent to a normal variable, with mean

$$m_b = 2m \tag{22}$$

and standard deviation

$$\sigma_b = \left(\frac{2}{N_T N_R}\right)\sqrt{\upsilon(N_T N_R)} \tag{23}$$

Finally, from (18), (19), (21), (22) and (23), we obtain the upper bound for the BER of a log-normal fading channel when STBC is applied

$$\begin{aligned}\hat{P}_e &= \frac{1}{\pi}\int_0^{(M-1)\pi/M}\left\{\frac{1}{\sqrt{\pi}}\sum_{n=1}^{N_p}\right.\\ &\qquad\left.\left[H_{x_n}\exp\left(10^{(\sqrt{2}\sigma_b x_n+\mu_b)/10}\cdot\frac{E_s N_R}{N_0 R}\left(-\frac{a^2}{2\sin^2\theta}\right)\right)\right]\right\}\mathrm{d}\theta\\ &= \frac{1}{\pi^{3/2}}\sum_{n=1}^{N_p}H_{x_n}\int_0^{(M-1)\pi/M}\left[\exp\left(-10^{(\sqrt{2}\sigma_b x_n+\mu_b)/10}\right.\right.\\ &\qquad\left.\left.\times\frac{E_s N_R}{N_0 R}\cdot\frac{a^2}{2\sin^2\theta}\right)\right]\mathrm{d}\theta\end{aligned} \tag{24}$$

The integral in the last equation is easy to evaluate when applying binary-phase-shift-keying (BPSK) modulation

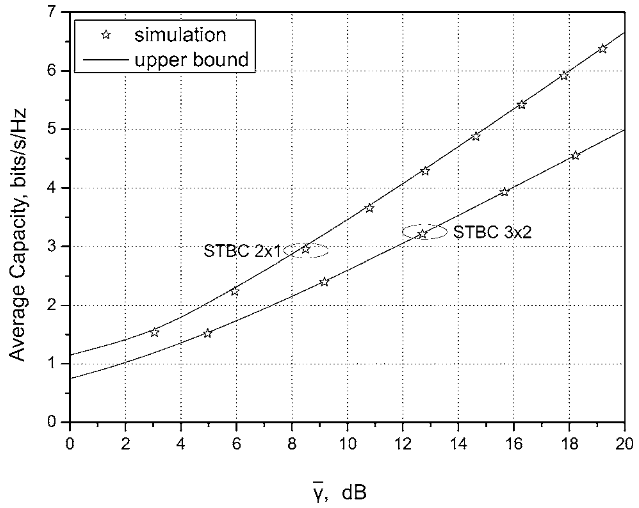

Fig. 1 *STBC capacity for Rician fading channel*

($M = 2$), so (24) reduces to

$$\hat{P}_e = \frac{1}{2\sqrt{\pi}} \sum_{n=1}^{N_p} H_{x_n} \times \left(1 - \operatorname{erf}\left(\sqrt{10^{(\sqrt{2}\sigma_b x_n + \mu_b)/10} \cdot \frac{E_s N_R}{N_0 R}}\right)\right) \quad (25)$$

However, in the case that quadrature phase-shift keying (QPSK) ($M = 4$) and 8-PSK ($M = 8$) modulations are applied, the integral in (24) can only be evaluated with numerical analysis methods. In our work, the integral is numerically evaluated with the help of Maple and Matlab and the results are presented in Section 5.

5 Numerical evaluation and simulation results

The results of the upper bound for the normalised to BW average STBC capacity ($\bar{C}_{STBC}/BW$) and the BER performance are presented here. The results were obtained by running multiple simulations, to minimise the statistical errors and to assure the validity of the results. The simulation curves were created by evaluating a system, transmitting 2^{22} (4194304) data bits to achieve illustration of low BER. The STBC systems examined here are the STBC 2×1, STBC 3×1 and STBC 3×2, and are tested in the two aforementioned environments; the Rician and the log-normal fading channels. The STBC 2×1 is examined because it is the simplest STBC application. The STBC 3×1 and 3×2 are taken into consideration, to examine some other STBC schemes apart from Alamouti's proposal, with lower than unitary rate ($R = 3/4$). It should be mentioned here that full rate full diversity STBC exists for any number of transmit antennas when real orthogonal designs, like BPSK modulation, is considered. The STBC scheme of rate $R = 3/4$ considered for three transmit antennas is introduced in [4], thus we omit illustrating the transmission matrix. Furthermore, it should be mentioned that the modulation techniques taken into account are the BPSK, QPSK and 8-PSK.

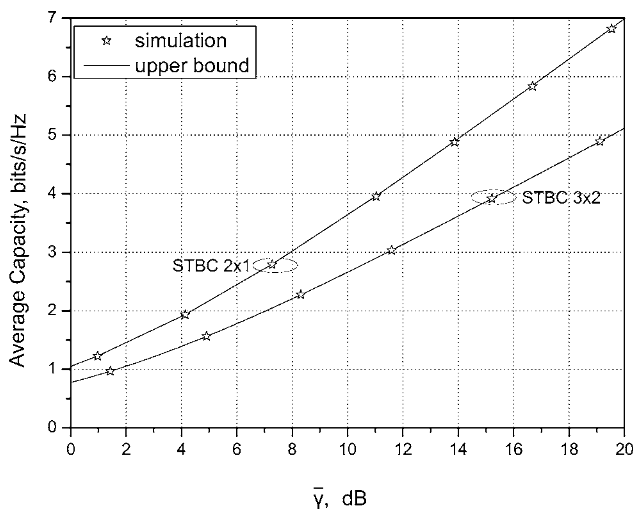

Fig. 2 *STBC capacity for log-normal fading channel*

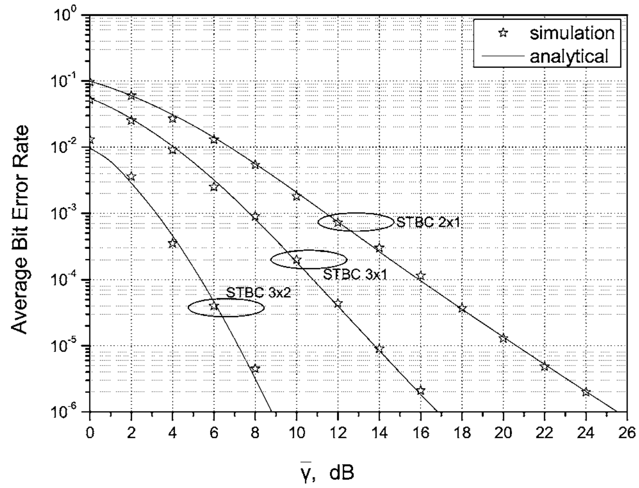

Fig. 3 *BER analysis for Rician fading channel with BPSK modulation*

5.1 Capacity

The parameters for the evaluated Rician channel are the Rician factor K, which is chosen to be 3 dB, and the variance, which is set to 0.1. On the other hand, for the normal sequence used to generate the log-normal channel, the mean and the standard deviation have been chosen to be 0 and 0.1, respectively.

Based on the mathematical analysis in Section 3, we obtain the results for the analytical bound and the simulation of two STBC schemes (STBC 2×1 and STBC 3×2) in

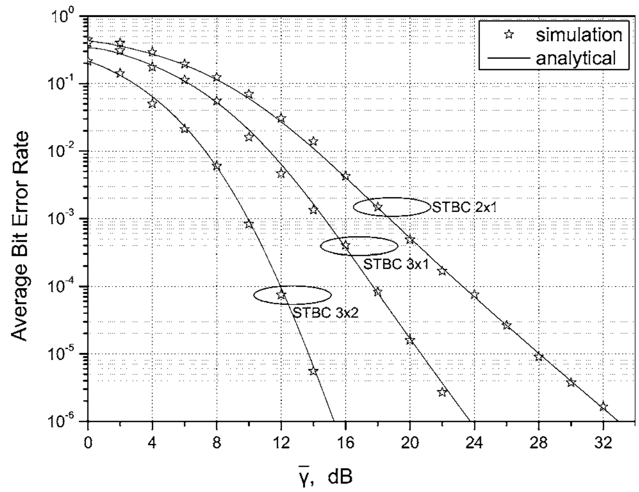

Fig. 4 *BER analysis for Rician fading channel with QPSK modulation*

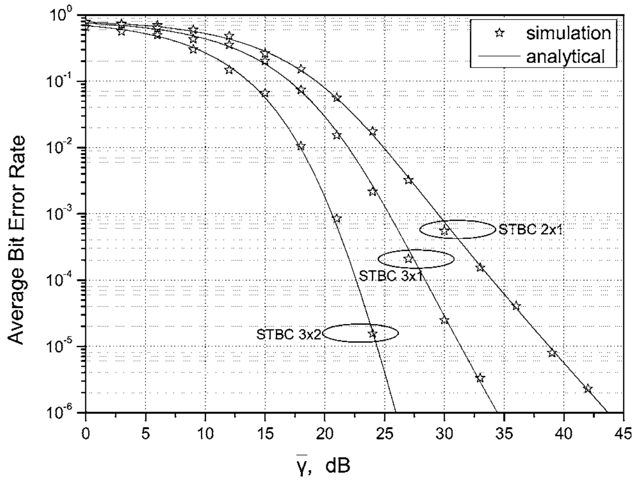

Fig. 5 *BER analysis for Rician fading channel with 8-PSK modulation*

each of Figs. 1 and 2 regarding Rician and log-normal fading channel, respectively. The symbols without line correspond to the capacity of the simulated system, while the solid line corresponds to the upper bound.

From the presented results, it can be seen that the proposed bound is very tight, regardless of the environment and the STBC scheme that is examined. Even though in both Figures the simulations' symbols are very close to the upper bound curves, they are always below the analytical curves in all the SNR range.

5.2 Bit error rate

The BER performance for the Rician channel is exhibited in Figs. 3–5, applying BPSK, QPSK and 8-PSK modulations, respectively. The solid line shows the analytical performance of the systems under study, stemming from the mathematical analysis given in Section 4, and the symbols without line show the simulations' results. The simulations' symbols have some fluctuations with respect to the analytical curves, because of the statistical errors generated from the noninfinite number of the simulated bits.

In Figs. 6–8, the credibility of the upper bound for the BER in a log-normal fading environment is examined, when applying BPSK, QPSK and 8-PSK modulations,

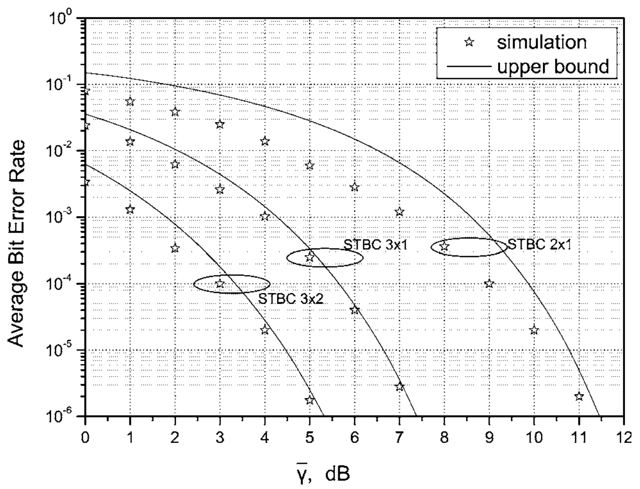

Fig. 6 *BER analysis for log-normal fading channel with BPSK modulation*

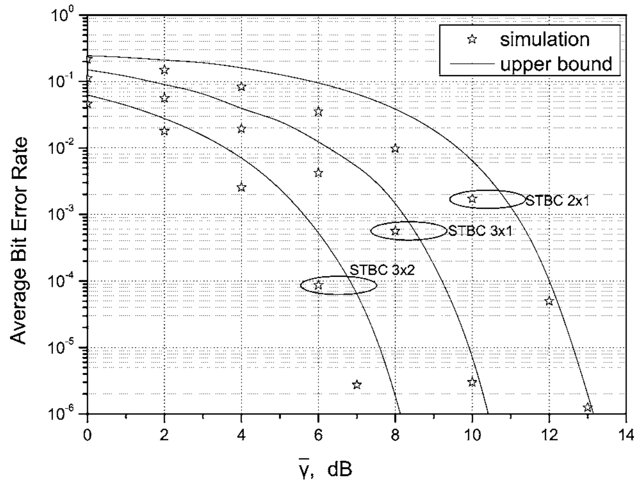

Fig. 7 *BER analysis for log-normal fading channel with QPSK modulation*

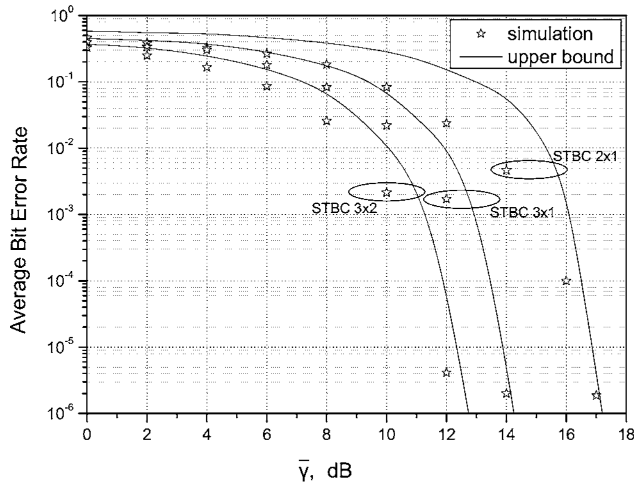

Fig. 8 *BER analysis for log-normal fading channel with 8-PSK modulation*

respectively. Again, with the solid line, we show the analytical results of the proposed upper bound and with the symbols without line we show the simulation results in each STBC scheme.

The parameters chosen for the BER analysis in both channel environments are the same with the ones taken into consideration in the capacity analysis. However, for the upper bound curves of the BER of the log-normal environment, equations (21)–(23) indicate the parameters for the log-normal distribution, which are for the STBC 2×1, the mean is equal to 0 and the standard deviation is equal to 0.1414; for the STBC 3×1, the mean is equal to 0 and the standard deviation is equal to 0.1155, and, for the STBC 3×2, the mean is equal to 0 and the standard deviation is equal to 0.0816. Finally, the abscissas and the weight factors for the N_p-order Hermite polynomial are taken from [25, Table 25.10], with the order of the polynomial chosen to be $N_p = 20$, so as to achieve better accuracy.

From all the presented Figures, comparing the performance evaluation results to accurate computer simulation ones, it is evident that the proposed bounds for both the average STBC capacity and the BER are very tight. Hence, the proposed formulations provide accurate expressions for evaluating these performance characteristics.

6 Conclusions

In this work, we examined the capacity and BER of STBC wireless communications systems. In particular, a closed-form upper bound for the capacity of wireless systems operating in either log-normal or Rician fading environments is derived. As far as the BER performance is concerned, albeit that it has been the subject of extensive research over the years, to the best of the authors' knowledge, there exists no study that grapples with this meaningful issue in log-normal fading environments to date. Toward this end, a tight upper bound for the BER has been presented. The validity of the proposed analysis was reinforced by numerical simulations for different STBC schemes and different PSK modulations. The analysis presented in this paper paves the way for an accurate evaluation of the performance of wireless systems in several fading environments.

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