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Performance Evaluation of Space–Time Block Codes Over Keyhole Weibull Fading Channels

Kostas Peppas · Andreas Maras

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Abstract It is well known that degenerate channel phenomena known as keyholes may significantly reduce the capacity of multiple-input and multiple-output (mimo) channels. Keyhole mimo channels were predicted theoretically and also observed experimentally. In this paper, a novel method of analyzing the performance of keyhole mimo channels is proposed. The proposed method is based on the assumption that the received signal at the keyhole encompasses an arbitrary number of multipath components and the propagation environment is such that the resulting signal is observed as a non-linear function of the modulus of the sum of these components. Based on this assumption, we initially introduce the double Weibull fading model, constructed by the product of two independent Weibull distributed fading envelopes. Closed-form expressions for its moments-generating function, probability density function, cumulative distribution function, and moments are also derived. Based on these formulas, we analytically evaluate the performance of a 2×2 mimo space–time block-coding (stbc) system, where performance metrics such as the average symbol error probability for several modulation schemes, outage probability, amount of fading and ergodic capacity are given in closed form. Various performance evaluation results are presented in order to verify the proposed analysis.

Keywords Space–time block codes · Weibull fading · Probability density function · Moment generating function · Ergodic capacity

1 Introduction

Multiple-input multiple-output (mimo) systems have recently drawn considerable attention in response to the increasing requirements on high data rate and reliability in radio links. It

K. Peppas (✉) · A. Maras
Department of Telecommunication Science and Technology, University of Peloponnese, Tripoli, Greece
e-mail: peppas@telecom.ntua.gr

A. Maras
e-mail: amaras@uop.gr

has also been shown that mimo communication systems significantly increase the channel capacity in rich scattering propagation environments [1,2]. However, in realistic propagation environments, the existence of degenerate channel matrix due to keyhole effects severely reduces the capacity of mimo channels [3–6]. The existence of rank-deficient (keyhole or pinhole) channels has been recently proposed for mimo channel modeling and demonstrated through physical examples that have a single or reduced degree of freedom. This rank deficiency was shown to reduce the achievable ergodic capacity (ec) and link quality of mimo systems.

Mimo space–time coding techniques can be effectively used in conjunction with well known modulation schemes to maximize the diversity gain [7–10]. Such a technique is space–time block coding (stbc) which is used to transmit multiple copies of a data stream across a number of antennas and to exploit the various received versions of the data to improve the reliability of data-transfer. It is also known that the use of stbc may provide a simple transmit diversity scheme with the same diversity order as maximal-ratio receiver combining, a fact which was originally discovered by Alamouti in his seminal work [8], where a simple and effective transmission paradigm for systems equipped with two transmit antennas was presented. The Alamouti scheme does not require channel knowledge at the transmitter, supports maximum likelihood detection and provides a full diversity gain over fading channels. As a result, it has been adopted as the open-loop transmit diversity scheme by current 3 GPP standards. Furthermore, using the theory of orthogonal designs, Tarokh et al. [7,10] were able to generalize the Alamouti scheme to an arbitrary number of antennas (mimo systems), thereby setting the basis for the so-called mimo stbc concept. Besides, the orthogonal space–time block encoding and decoding (signal combining) transforms a mimo fading channel into an equivalent single-input single-output (siso) channel with a path gain of the squared Frobenius norm of the channel matrix [11–13]. Finally, the orthogonal stbcs are optimal in terms of the signal-to-noise ratio (snr) [14].

From a literature review, there are different approaches to the performance evaluation of stbc in keyhole channels. For example, in [4,5], fading has been characterized by the so-called double Rayleigh fading model that is, each entry of the channel matrix has been assumed to be a product of two independent zero-mean Gaussian complex random variables (rv)s. Moreover, in [15,16], the exact average bit error probability (abep) of orthogonal stbc systems with M-ary-phase shift keying (M-psk) and M-ary-quadrature amplitude modulation (M-qam) constellations over keyhole Nakagami-m fading channels has been presented. Finally, in Gong and Letaief [17] a systematic analysis for orthogonal stbcs in keyhole channels is presented and closed form expressions for error rate of space–time block codes are derived. However, to the best of the authors' knowledge, mimo systems performance has not yet been addressed under the assumption that the resulting envelope at both sides of the keyhole may be characterized as a non-linear function of the modulus of the sum of the multipath components, thus resulting to the so-called Weibull fading model [18–23].

In this paper, we study the effect of keyholes on the performance of the orthogonal 2×2 stbc with the assumption that the received signal at the keyhole encompasses an arbitrary number of multipath components and the propagation environment is such that the resulting signal is observed as a non-linear function of the modulus of the sum of these components [24]. In this case, the fading between each pair of the transmit and receive antennas in the presence of the keyhole is characterized by double Weibull fading, i.e., a product of two independent Weibull distributions. After first recalling same basic issues related to the keyhole channels, the statistical properties of the double Weibull fading model are studied in detail. Based on the derived formulas, the performance of a 2×2 mimo stbc system operating in keyhole Weibull fading is investigated, deriving closed-form expressions for the abep, outage probability (op), amount of fading (aof) and ec.

The paper is organized as follows: In Sect. 2, the system model is described in detail. In Sect. 3, the double Weibull fading model is introduced and its statistical properties are presented. In Sect. 4, the theoretical results are applied to analyze the performance of digital receivers, while the paper concludes with a summary given in Sect. 5.

Next, the following notations are used: $(\cdot)^T$ for the transpose, $\mathbb{E}\langle\cdot\rangle$ for the expectation operator and $\mathbb{L}^{-1}[\cdot;\cdot]$ for the inverse Laplace transform.

2 System Model

Let us consider a wireless mimo communication system with t transmit and r receive antennas. Let also $\mathbf{H}$ denote the $r \times t$ channel matrix, so the entry $[\mathbf{H}]_{ij}$ of $\mathbf{H}$ represents the channel gain linking the jth transmit antenna and ith receive antenna.

2.1 Preliminaries

We consider a non-line of sight, discrete-time baseband channel model and assume a narrow bandwidth system so that the channel can be considered as frequency non-selective. We also assume quasi-static fading, which implies that the channel characteristics remain constant at least for the period of transmission of an entire frame (T symbol durations). The channel may vary from frame to frame. In certain environments, the channel degeneracy may arise due to the keyhole or pinhole effect, thus the only way for the radio wave to propagate from the transmitter to the receiver is to pass through the keyhole. In this case, the mimo channel is given by

$$\mathbf{H} = \mathbf{b} \cdot \mathbf{a}^T = \begin{bmatrix} a_1 b_1 & a_2 b_1 & \cdots & a_t b_1 \\ a_1 b_2 & a_2 b_2 & \cdots & a_t b_2 \\ \cdots & \cdots & \ddots & \cdots \\ a_1 b_r & a_2 b_r & \cdots & a_t b_r \end{bmatrix} \tag{1}$$

where column vectors $\mathbf{a}$ and $\mathbf{b}$ describe the rich scattering at the transmit and receive antenna arrays, respectively and the keyhole is assumed to ideally reradiate the captured energy. In (1) the coefficients a_i and b_i are independent zero mean complex Gaussian distributed random variables, thus all entries of the channel matrix are uncorrelated. Furthermore, we assume that the keyhole ideally reradiates the captured energy, like the transmit and receive scatterers, and that each entry of the channel matrix has a unit power, i.e., $\mathbb{E}\langle |H_{ij}|^2 \rangle = 1$ for all $i = 1, 2, \ldots, r$ and $j = 1, 2, \ldots, t$. Finally, it is noted that although the entries of channel matrix are uncorrelated, the channel matrix has a single degree of freedom, i.e., $rank(\mathbf{H}) = 1$.

Transmit diversity over the wireless link using stbc is achieved by mapping each $R \le T$ complex input symbols with average power per symbol E_s, belonging to a given signal set S, into t orthogonal sequences of length T to be simultaneously transmitted through the t transmit antennas. Since R input symbols from the signal set S are transmitted within T symbol durations (a frame period), the information code-rate of the space–time block code is defined as $\mathcal{R} \triangleq R/T$. It is noted that space–time block codes codes are known in the literature only for $r = t = 2$ to achieve full rate and full diversity with all M-qam and M-ary-pulse amplitude modulation (M-pam) constellations [25]. Due to the decoupling of signals transmitted from different antennas, stbc converts the matrix channel into a scalar one [11,26]. The effective snr per symbol at the output of the stbc decoder is given by [15]

$$\gamma_{stbc} = \gamma_s \frac{\|\mathbf{H}\|_F^2}{t\mathcal{R}} \tag{2}$$

where $\gamma_s = E_s/N_o$ with N_o being the power spectral density (psd) of the additive white Gaussian noise (awgn) and $\|\mathbf{H}\|_F$ is the Frobenius norm of the matrix $\mathbf{H}$. Finally, the non-ergodic capacity of orthogonal stbc is given in [bits/s/Hz] by

$$C = \frac{1}{\ln 2}\mathcal{R}\ln(1+\gamma_{stbc}) \tag{3}$$

2.2 Distribution of the Output Snr

Using the definition of the matrix Frobenius norm, the effective output snr γ_{stbc} can be written as a sum of elementary snrs as follows:

$$\gamma_{stbc} = \frac{\gamma_s}{t\mathcal{R}} \sum_{i=1}^{r}\sum_{j=1}^{t} |a_i|^2 |b_j|^2 = \frac{\gamma_s}{t\mathcal{R}} R_1 R_2 \tag{4}$$

where $R_1 = \sum_{i=1}^{r} |a_i|^2$ and $R_2 = \sum_{j=1}^{t} |b_j|^2$. The resulting envelopes R_ℓ, where $\ell = 1, 2$ are expressed as the modulus of the sum of the multipath components they encompass, namely the elements of a and b respectively. Following the approach proposed in Yacoub [24], R_ℓs can be expressed as a non-linear function of the modulus of the sum of these components. Such a non-linearity is manifested in in the form of a power parameter $\beta_\ell > 0$ such that the resulting signal envelope is obtained not simply as the modulus of the sum of the multipath components but as this modulus to the power $2/\beta_\ell,\ \beta_\ell > 0$. Focusing our analysis on the Alamouti scheme, two transmit and two receive antennas are considered. In this case, the envelopes R_ℓ become $R_1 = (|a_1|^2 + |a_2|^2)^{2/\beta_1}$ and $R_2 = (|b_1|^2 + |b_2|^2)^{2/\beta_2}$. It is observed that since $|a_\ell|$ and $|b_\ell|$ are Rayleigh distributed, $|a_\ell|^2$ and $|b_\ell|^2$ are exponentially distributed. Also, due to the assumption that the coefficients a_ℓ and b_ℓ are independent random variables, the sums $|a_1|^2 + |a_2|^2$ and $|b_1|^2 + |b_2|^2$ follow a Gamma distribution. Finally, we observe that R_ℓ are Weibull distributed with parameters β_ℓ while γ_{stbc} follows the double Weibull model, described in detail in next sections.

3 The Double Weibull Model

Let $R_\ell(\ell = 1, 2)$ be a Weibull distributed fading envelope with probability density function (pdf) given by

$$f_{R_\ell}(r) = \frac{\beta_\ell}{2(\alpha_\ell\Omega_\ell)^{\beta_\ell/2}} r^{\beta_\ell/2-1} \exp\left[-\left(\frac{r_\ell}{\alpha_\ell\Omega_\ell}\right)^{\beta_\ell/2}\right] \tag{5}$$

where $\beta_\ell > 0$ is the fading parameter, $\Omega_\ell = \mathbb{E}\langle R_\ell^2\rangle$ and $\alpha_\ell = \Gamma(1 + 2/\beta_\ell)$ with $\Gamma(\cdot)$ being the Gamma function. The double Weibull model is defined as the product of R_1 and R_2, i.e:

$$Y \triangleq R_1 \cdot R_2 \tag{6}$$

Initially, a closed form of the moment generating function (mgf) of Y is derived. We prove the following theorem:

Theorem 1 (Moment Generating Function) *The mgf of Y is given by*

$$\mathcal{M}_Y(s) = V G^{\,n,p}_{\,p,n}\left[W s^n \left|\begin{smallmatrix}\Xi(n;0)\\ \Delta(n;0)\end{smallmatrix}\right.\right] \tag{7}$$

where $G[\cdot]$ is the Meijer G function [27, Eq. 9.301], $\Xi(n;x) = \Delta(2n/\beta_1\,;\,x),\ \Delta(2n/\beta_2\,;x)$ with $\Delta(k;\,x)$ defined as $\Delta(k;\,x) = x/k,\ (x+1)/k, \ldots, (x+k-1)/k$ (x an arbitrary real value and k a positive integer) and

$$V = \left(\sqrt{2\pi}\right)^{(3-n-p)} \sqrt{\frac{4n^3}{\beta_1\beta_2}}, \tag{8a}$$

$$W = \frac{1}{n^n}\prod_{i=1}^{2} \xi_i\,(\alpha_i\Omega_i)^n\,, \tag{8b}$$

$$\xi_\ell = (2n/\beta_\ell)^{(2n/\beta_\ell)}\,, \tag{8c}$$

$$n = k_1 k_2, \tag{8d}$$

$$p = 2n\,(1/\beta_1 + 1/\beta_2) \tag{8e}$$

By assuming that β_ℓ is rational, k_ℓ and l_ℓ are the two minimum positive integers such that $l_\ell = 2k_\ell/\beta_\ell$ holds. Depending upon the specific value of β, a set of minimum values of k_ℓ and l_ℓ can be properly chosen (e.g. for $\beta_\ell = 3.6,\ k_\ell = 9$ and $l_\ell = 5$).

Proof Using (5) and (6), the mgf of Y can be expressed as:

$$\begin{aligned}\mathcal{M}_Y(s) &= \mathbb{E}\left\langle \exp(-sY)\right\rangle = \int_0^\infty \exp(-sy) f_Y(y) dy \\ &= \frac{\beta_1\beta_2}{4(\alpha_1\Omega_1)^{\beta_1/2}(\alpha_2\Omega_2)^{\beta_2/2}} \cdot \int_0^\infty\int_0^\infty r_1^{\beta_1/2-1} r_2^{\beta_2/2-1} \\ &\quad \times \exp(-sr_1r_2)\exp\left[-\left(\frac{r_1}{\alpha_1\Omega_1}\right)^{\beta_1/2}\right]\exp\left[-\left(\frac{r_2}{\alpha_2\Omega_2}\right)^{\beta_2/2}\right] dr_1 dr_2\end{aligned} \tag{9}$$

The above two integrals are not included in tables of classical reference books such as [27], however by making the change of variables $z_\ell = r_\ell/(\alpha_\ell\Omega_\ell)$ and expressing the exponentials in terms of Meijer G functions [28, Eq. 11], $\mathcal{M}_Y(s)$ can be written as:

$$\begin{aligned}\mathcal{M}_Y(s) = &\int_0^\infty G^{\,1,0}_{\,0,1}\left[z_2 \left|\begin{smallmatrix}-\\0\end{smallmatrix}\right.\right] \int_0^\infty G^{\,1,0}_{\,0,1}\left[z_1 \left|\begin{smallmatrix}-\\0\end{smallmatrix}\right.\right] \\ &\times G^{\,1,0}_{\,0,1}\left[s\prod_{i=1}^{2}\alpha_i\Omega_i z_i^{2/\beta_i} \left|\begin{smallmatrix}-\\0\end{smallmatrix}\right.\right] dz_1 dz_2\end{aligned} \tag{10}$$

Using [28, Eq. 21] for the integral on z_1, $\mathcal{M}_Y(s)$ becomes:

$$\mathcal{M}_Y(s) = \frac{\sqrt{k_1 l_1}}{(\sqrt{2\pi})^{k_1+l_1-2}} \int_0^\infty G_{0,1}^{1,0}\left[z_2 \,\middle|\, {}^{-}_{0}\right] \times G_{l_1,k_1}^{k_1,l_1}\left[\frac{l_1^{l_1} z_2^{2k_1/\beta_2}}{(k_1/s)^{k_1}} \prod_{i=1}^{2} (\alpha_i \Omega_i)^{k_1} \,\middle|\, {}^{\Delta(l_1;0)}_{\Delta(k_1;0)}\right] dz_2 \tag{11}$$

Using [28, Eq. 21] once again, (7) is obtained. □

Theorem 2 (Probability Density Function) *The pdf of Y is given by*

$$f_Y(y) = \frac{y^{-1} V \sqrt{n}}{(\sqrt{2\pi})^{1-n}} G_{p,0}^{0,p}\left[\frac{W n^n}{y^n} \,\middle|\, {}^{\Xi(n;0)}_{-}\right] \tag{12}$$

Proof By applying inverse Laplace $\mathbb{L}^{-1}[\cdot;\cdot]$ transform in (7), i.e. $\mathbb{L}^{-1}[\mathbb{M}_Y(s);\ y]$, expressing the exponentials in terms of G functions and using [28, Eq. 21], (12) is obtained.

It is observed that for identical fading parameters, i.e., $\beta_1 = \beta_2 = \beta$ $(\alpha_1 = \alpha_2 = \alpha)$, (12) can be simplified to

$$f_Y(y) = \frac{\beta y^{\beta/2-1}}{\alpha^2 \Omega_1 \Omega_2} K_0\left[2\left(\frac{y}{\alpha^2 \Omega_1 \Omega_2}\right)^{\beta/4}\right] \tag{13}$$

where $K_0(\cdot;\cdot)$ is the zero order modified Bessel function. Finally, we observe that for $\beta = 2$, (13) is further reduced to a known result [5, Eq. 5]. □

Theorem 3 (Cumulative Distribution Function) *The cumulative distribution function (cdf) of Y is given by*

$$F_Y(y) = \frac{V\sqrt{n}}{(\sqrt{2\pi})^{1-n}} G_{1,p+1}^{p,1}\left[\frac{y^n}{W n^n} \,\middle|\, {}^{1}_{\Xi(n;1)\ 0}\right] \tag{14}$$

Proof Starting with $F_Y(y) = \int_0^y f_Y(z) dz$ and using [28, Eq. 26], (14) is obtained. □

Theorem 4 (Moments) *The kth order moment of Y is given by*

$$\mathbb{E}\langle Y^k \rangle = \prod_{i=1}^{2} (\alpha_i \Omega_i)^k \,\Gamma\left(1 + \frac{2k}{\beta_i}\right) \tag{15}$$

Proof The kth order moment of Y is given by

$$\mathbb{E}\langle Y^k \rangle = \int_0^\infty y^k f_Y(y) dy = \int_0^\infty \int_0^\infty r_1^k r_2^k f_{R_1}(r_1) f_{R_2}(r_2) dr_1 dr_2 \tag{16}$$

Using (5) and the definition of the Gamma function, (15) is derived. □

4 Performance Evaluation of Mimo Stbc Systems

In this section, we evaluate the performance of a stbc mimo system with $t = 2$ transmitting and $r = 2$ receiving antennae, according to the Alamouti scheme. The performance metrics under consideration is the abep of the Alamouti space–time block codes used in conjunction with M-qam signal constellations with Gray encoding, the outage probability, the amount of fading and the ergodic capacity. Analytical expressions of the above considered metrics are derived, using the results of the previous section.

4.1 Average Bit Error Probability

According to the mgf-based approach to the performance analysis of digital communications systems over generalized fading channels, the mgf of γ_{stbc} can be efficiently used to evaluate the abep of M-ary modulations for several signaling constellations, namely M-psk and M-qam when used along with stbc [29]. Using (4) and (7) this mgf yields

$$\mathcal{M}_{\gamma_{stbc}}(s) = \mathcal{M}_Y\left(s\frac{\gamma_s}{2\mathcal{R}}\right) \tag{17}$$

As a typical example where full rate and full diversity can be achieved ($\mathcal{R} = 1$ symbol/timeslot), the abep of square M-qam with Gray encoding is plotted in Fig. 1 as a function of the bit energy to noise ratio, $\gamma_b = \gamma_s/\log_2(M)$, for $\beta_1 = \beta_2 = 2$ and 3.6 and for several values of M. As expected, the results show that the abep improves with an increase of β and/or a decrease of M. In order to verify these analytical results, equivalent computer simulations results (black squares) have been included in the same figure and an excellent match between them is observed.

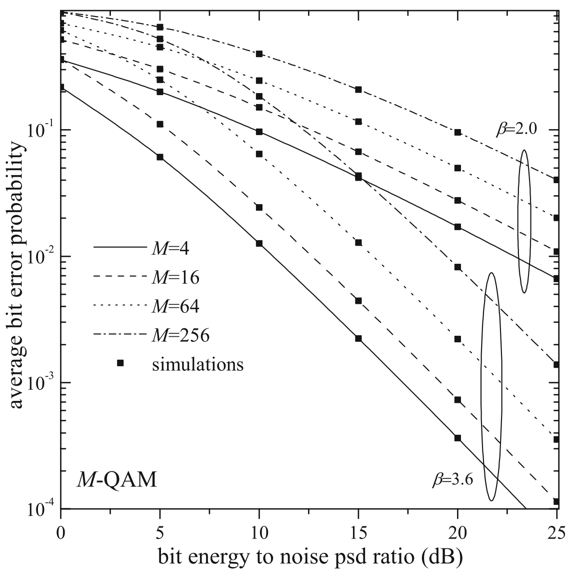
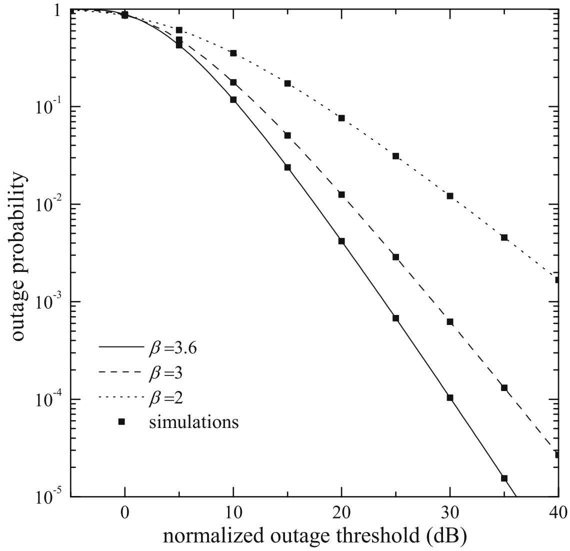


Fig. 1 abep of a 2 × 2 mimo system employing Gray-encoded square M-qam operating over keyhole Weibull channels

Fig. 2 Outage probability of a 2×2 mimo system operating over keyhole Weibull channels as a function of the normalized outage threshold



4.2 Outage Probability

An important measure of performance in fading channels is the outage probability, denoting the probability that the output snr, i.e., γ_{stbc}, falls below a predefined threshold level γ_{th}. The op of stbc fading can be easily determined using the expression for the cdf of γ_{stbc}. Using (4) and (14), the op can be expressed in closed form as:

$$F_{\gamma_{stbc}}(\gamma_{th}) = F_Y\left(2\mathcal{R}\frac{\gamma_{th}}{\gamma_s}\right) \tag{18}$$

In Fig. 2, the op of the considered stbc scheme is plotted as a function of the normalized outage threshold, γ_{th}/γ_s, for $\beta = 2$, 3, and 3.6. As expected, the op improves as γ_{th}/γ_s and/or β increases. Computer simulations results (black squares) have also been included in the same figure and an excellent match between them is observed.

4.3 Amount of Fading

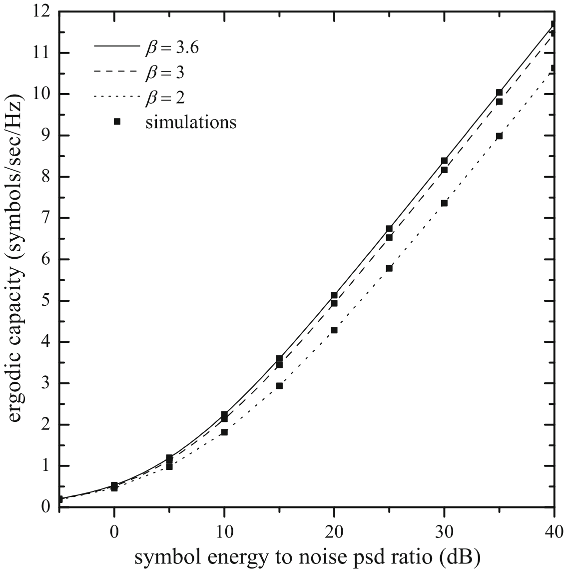
The amount of fading (aof) is a unified measure of the severity of the fading defined by the ratio of the variance of the received energy to the square of the average received energy. For a space–time block-coded mimo link, we have $A_F = \mathbb{E}\langle\gamma_{stbc}^2\rangle/(\mathbb{E}\langle\gamma_{stbc}\rangle)^2 - 1$. Using (15), aof can easily be expressed in closed form as follows:

$$A_F = -1 + \prod_{i=1}^{2} \frac{\Gamma\left(1 + 4/\beta_i\right)}{\Gamma\left(1 + 2/\beta_i\right)} \tag{19}$$

4.4 Ergodic Capacity

In this section, we derive a closed form expression for the ergodic capacity of a mimo keyhole fading channel using the Alamouti scheme, with channel knowledge at the receiver, as a

Fig. 3 Ergodic capacity of a 2×2 mimo system operating over keyhole Weibull channels as a function of the average input snr per symbol



function of the code rate $\mathcal{R}$ and the average snr per receive antenna γ_s. With perfect channel knowledge at the receiver, the ergodic capacity of the Alamouti scheme can be obtained by averaging the non-ergodic capacity expression given by (3) over the distribution of γ_{stbc} given by (12). By transforming the logarithm to Meijer G-functions [28, Eq. 11] and using [28, Eq. 21], the ec of the mimo channel yields in closed-form:

$$\mathbb{E}\langle C\rangle = \frac{V\sqrt{n}}{(\sqrt{2\pi})^{1-n}}\, G_{2n,p+2n}^{p+2n,n}\left[\left(\frac{2\mathcal{R}}{\gamma_s}\right)^n \middle|_{\Xi(n;1),\ \Delta(n;0),\ \Delta(n;1)}^{\Delta(n;0),\ \Delta(n;1)}\right] \tag{20}$$

while using (14), the outage ec can be also derived in a simple closed-form expression as $P_{out}(C) = F_{\gamma_{stbc}}(2^C - 1)$. In Fig. 3, the ec of a 2×2 mimo stbc is plotted as a function of γ_s for various values of β. As it is clear, the ec of the keyhole Weibull fading channel improves as γ_s and/or β increases. Computer simulations results (black squares) have also been included in the same figure and an excellent match between them is observed.

5 Conclusions

In this paper, the performance of stbc on keyhole Weibull channels was analyzed. The fading between each pair of the transmit and receive antennas for keyhole channels was assumed to be characterized by a double Weibull distribution. We derived the mgf of instantaneous snr after space–time block decoding via which the abep of the stbc with M-qam constellations over keyhole fading channels was derived. Closed form expressions for the outage probability, amount of fading and ergodic capacity were also derived. Finally, extensive numerical and computer simulated results were presented and compared, and a perfect match was observed.

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Author Biographies

Kostas Peppas was born in Athens in 1975. He obtained his diploma in Electrical and Computer Engineering from the National technical University of Athens in 1997 and the Ph.D. degree in telecommunications from the same department in 2004. His current research interests include wireless communications, smart antennas, digital signal processing and system level analysis and design. He is a member of IEEE and the National Technical Chamber of Greece.

Andreas Maras received the B.Sc. and Ph.D. degrees in Electrical and Electronic Engineering, and the M.Sc. in Applied Sciences, from the Department of Electrical and Electronic Engineering of the University of Newcastle Upon Tyne, England, in 1975, 1980 and 1977, respectively. He is currently a Professor with the Department of Communication Sciences, School of Applied Sciences, University of Pelloponnese.