Performance of Space Shift Keying Modulation over Generalized $\kappa - \mu$ Fading Channels

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Abstract: This paper analyzes the performance of space shift keying (SSK) modulation for a generic multiple-input multiple-output (MIMO) wireless system operating over generalized $\kappa - \mu$ fading channels. In particular, an expression of the pair wise error probability (PEP) is obtained. In addition, simple and general asymptotic expression for the PEP is given. The derived expression for the PEP is general, such that the PEP over various well-known fading channels can be derived as special cases, such as Nakagami-m and Nakagami-n (Rice) fading channels. Numerical results are provided, sustained by simulation results, which corroborate the exactness of the theoretical analysis.

Key–Words: Amplify-and-forward, Quadrature spatial modulation, Spectral efficiency, MIMO.

1 Introduction

In the past few years, the demand for a variety of wireless applications have seen tremendous growth. Data rate requirements of these application is growing exponentially as well. As such, several technologies are proposed to cope-up with these requirements. Multiple-input multiple-output (MIMO) is among the set of proposed technologies and considered one of the most important contributions to the progress in wireless communications in recent years. It is a key technology in many recent standards such as, 3rd Generation Partnership Project (3GPP) [1–5], Wireless World Initiative New Radio (WINNER) [6], and Long Term Evolution (LTE) [7].

MIMO techniques aim at improving power efficiency by maximizing spatial diversity (as in space-time coding (STC)) [8, 9], or at boosting the data rate by transmitting independent streams from each transmit antenna (as in V-BLAST (vertical Bell Labs layered space-time)) [10], or to achieve both of them at the same time at the expense of increasing complexity [11].

The use of multiple antennas at either transmitter/ receiver or at both of them can be utilized to achieve spatial diversity or multiplexing gains. Spatial diversity aims at improving power efficiency (as in space-time coding (STC)) [8,9]. Spatial multiplexing, on the other hand, boosts the data rate by transmitting independent streams from each transmit antenna (as in V-BLAST (vertical Bell Labs layered space-time)) [10]. Also, both gains can be achieved through pre-coding at the expense of increasing complexity [11].

However, practical deployment of multiple antennas at the transmitter and the receiver in a MIMO system may not be feasible in all applications due to size, cost, and hardware limitations [12]. Therefore, Many MIMO techniques were proposed to mitigate these hardware limitations [13–16].

Space shift keying (SSK) is a MIMO technique proposed to alleviate most of existing practical problems. In SSK system, a single transmit-antenna is activated during each time instant. The activated antenna index is utilized to implicitly convey information [16]. The fundamental idea of SSK is originally proposed in [17], which was further developed into spatial modulation in [18, 19]. Activating single transmit-antenna at a time eliminates inter-channel interference, relaxes inter-antenna synchronization requirements, reduces receiver complexity, and allows the use of a single RF chain at the transmitter. In addition, SSK is shown to enhance error performance with moderate number of transmit antennas as compared to other conventional MIMO techniques such as STC and V-BLAST. Hence, it has been investigated widely by several researchers and variant schemes based on its concept have been proposed [20–22, and references therein].

In all previous literature that consider SSK system and its performance analysis, Rayleigh, and Nakagami-m fading channels are only considered.

However, there exists a number of distributions that well describe the wireless channels, such as the $\kappa-\mu$ channel proposed in [23], where famous distributions such as Rayleigh, Nakagami-m, Hoyt (Nakagami-q) and Rice (Nakagami-n) can be derived as special cases from them [24]. Hence, it is the aim of this paper to study the performance of SSK system with $\kappa-\mu$ channel and study the effect of changing the values of μ and κ on the performance of the system. Similar works for other MIMO techniques proposed recently in literature. For instance, analytical expressions for the exact random coding exponent of MIMO systems employing STBC and operating over $\eta-\mu$ fading channels are derived in [25]. Vergara and Barbin derived an upper bound expression for the capacity of MIMO systems under the general $\eta-\mu$ fading model. They showed that the theoretical bound depends only on the first and the second moments of the random elements in the channel matrix [26].

With reference to current literature, the contributions in this paper are four folds: *i)* the performance of SSK system operating over generalized $\kappa-\mu$ fading channel is studied and a closed-form expressions for the pairwise error probability (PEP) is given. *ii)* An approximate expression, yet simple and accurate, for the PEP is also obtained to clearly analyze the impact of fading parameters on the system under study. *iii)* The derived PEP is used to derive an upper bound of the average bit error rate (BER), and *iv)* Well-known fading channels, such as Nakagami-m, one sided Gaussian, Nakagami-q and Rice are derived from the obtained results as special cases.

The rest of the paper is organized as follows: In Section 2, the system and channel models are introduced. In Section 3, the derivation of the PEP using two approaches, namely, the moment generation function (MGF) and power series approaches are presented. Some representative plots for the analytical results, along with their interpretations are illustrated in Section 4. Finally, Section 5 concludes this paper.

Mathematical Notations and Functions: matrices or vectors are shown with bold letters. $\mathbb{E}(\cdot)$ denotes expectation, $[\cdot]^T$ for transpose, $f_X(\cdot)$ represents the probability density function (pdf), $I_v(\cdot)$ denotes the v^{th}-order modified Bessel function of first kind, $\Gamma(\cdot)$ is the gamma function, $\text{PEP}_X(\cdot)$ and $\text{PEP}_X^{Asym}(\cdot)$ are the PEP and asymptotic PEP over X fading channel, $Q(\cdot)$ is the Q-function, $\mathcal{M}_X(\cdot)$ is the MGF, $F_1(\cdot)$ and $F(\cdot)$ represents the Appell's hypergeometric function and the Gaussian hypergeometric function, respectively, and $\Phi_1(\cdot)$ is the confluent hypergeometric function of two variables.

2 System and Channels Models

2.1 SSK System Model

A generic $N_t \times N_r$ SSK-MIMO system is considered, where N_t and N_r represent the number of transmit- and receive-antennas, respectively. In SSK-MIMO systems, the transmitter encodes a group of $m = \log_2(N_t)$ data bits into an index of a single transmit-antenna, which is also known as antenna index coded modulation. In other words, m bits are mapped to a symbol x_k, which is then transmitted by the k^{th}, $k \in \{1 : N_t\}$ antenna. The transmitted vector $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ specifies the activated antenna, during which all other antennas remain idle, which has the following form:

$$\mathbf{x}_k = [0 \ 0 \cdots \quad \overset{k^{th}\text{antenna position}}{\overset{\downarrow}{1}} \quad 0 \cdots 0]^T.$$

The signal vector $\mathbf{x}_k$ is then transmitted over the wireless channel $\mathbf{H} \in \mathbb{C}^{N_r \times N_t}$ and experiences an $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ complex additive white Gaussian (AWGN) noise vector with zero mean and variance N_0. The received signal vector $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is given by:

$$\mathbf{y} = \sqrt{\mathcal{E}}\mathbf{H}\mathbf{x}_k + \mathbf{n}, \tag{1}$$

where $\mathcal{E}$ denotes the transmitted energy and $\mathbf{H}$ models the $\eta-\mu$ or $\kappa-\mu$ fading channel. At the receiver, the optimal maximum likelihood (ML) detector is used to estimate the antenna index that is used during the transmission, and then de-maps the symbol to its components.

2.2 Channels Models

The $\kappa-\mu$ is a general fading distribution that represents the small-scale variation of the fading signal in a line-of-sight environment with the pdf of the instantaneous SNR given by [23]

$$f_{\kappa-\mu}(\gamma) = \frac{\mu(1+\kappa)^{\frac{\mu+1}{2}}\gamma^{\frac{\mu-1}{2}}}{\kappa^{\frac{\mu-1}{2}}\exp(\mu\kappa)\bar{\gamma}^{\frac{\mu+1}{2}}}\exp\left(-\frac{\mu(1+\kappa)\gamma}{\bar{\gamma}}\right) \times I_{\mu-1}\left(2\mu\sqrt{\frac{\kappa(1+\kappa)\gamma}{\bar{\gamma}}}\right), \tag{2}$$

where $\kappa > 0$ represents the ratio between the total power of the dominant components and the total power of the scattered waves and $\mu > 0$ describes the number of multi-path clusters.

Note that the $\kappa-\mu$ distribution includes the Nakagami-m ($\kappa \to 0, \mu = m$), the Rayleigh ($\kappa \to 0, \mu = 1$), the One-Sided Gaussian ($\kappa \to 0, \mu = 0.5$) and the Rice (Nakagami-n) ($\kappa = K, \mu = 0.5$), with K being the Rice K factor, as special cases.

3 Performance Analysis

The average BER of an SSK system can be calculated using the union-bound technique [16,27–30] given by

$$P_{\text{ABER}} \leq \frac{1}{N_t - 1} \sum_{i_1=1}^{N_t} \sum_{i_2=i_1+1}^{N_t} \text{PEP}\left(t_{i_1} \to t_{i_2}\right), \tag{3}$$

where $\text{PEP}\left(t_{i_1} \to t_{i_2}\right)$ represents the pairwise error probability among the transmit-antenna t_{i_1} and t_{i_2}, with $i_1, i_2 = 1, 2, \cdots, N_t$. Furthermore, $\text{PEP}\left(t_{i_1} \to t_{i_2}\right)$ is the average BER of an equivalent $2 \times N_r$ MIMO SSK system where only first or second transmit antenna is activated for transmission. The $\text{PEP}\left(t_{i_1} \to t_{i_2}\right)$ is defined as [16, 31],

$$\text{PEP}_X\left(t_{i_1} \to t_{i_2} | \mathbf{H}\right) = Q\left(\sqrt{\sum_{\ell=1}^{N_r} \gamma_\ell}\right) \tag{4}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt$ and γ_ℓ being defined as

$$\gamma_\ell = \frac{\mathcal{E}}{2N_0} |h_{j,\ell} - h_{i,\ell}|^2, \tag{5}$$

with $h_{j,\ell}$ being the channel fading coefficient between the j^{th} transmit- and the ℓ^{th} receive-antennas. Note that γ_ℓ in (5) can be simplified to

$$\gamma_\ell = \begin{cases} \frac{\mathcal{E}}{2N_0} \left|h_{j,\ell}\right|^2 & \text{for } i = j \\ \frac{\mathcal{E}}{2N_0} \left|h_{j,\ell} - h_{i,\ell}\right|^2 & \text{for } i \neq j, \end{cases} \tag{6}$$

and the average SNR ($\bar{\gamma}$) is then give as

$$\bar{\gamma} = \begin{cases} \frac{\mathcal{E}\sigma_h^2}{2N_0} & \text{for } i = j \\ \frac{\mathcal{E}\sigma_h^2}{N_0} & \text{for } i \neq j. \end{cases} \tag{7}$$

The PEP in (4) can, then, be computed by

$$\text{PEP}_X\left(t_{i_1} \to t_{i_2}\right) = \int_0^\infty Q(\sqrt{\lambda}) f_\lambda(v) dv, \tag{8}$$

where $f_\lambda(v)$ is the pdf of $\lambda = \sum_{\ell=1}^{N_r} \gamma_\ell$.

3.1 SSK-MIMO Performance Analysis over $\kappa - \mu$ Fading Channels

Based on the MGF approach, the PEP for SSK-MIMO system over $\kappa - \mu$ fading channels can be derived using

$$\text{PEP}_{\kappa-\mu}\left(t_{i_1} \to t_{i_2}\right) = \frac{1}{\pi} \int_0^{\pi/2} \mathcal{M}_{\kappa-\mu}\left(\frac{1}{2\sin^2\theta}\right) d\theta. \tag{9}$$

where $\mathcal{M}_{\kappa-\mu}(\cdot)$ denotes the MGF of $f_{\kappa-\mu}(\gamma)$ and is given by

$$\mathcal{M}_X(s) \triangleq \int_0^\infty f_X(\gamma) \exp(-s\gamma) d\gamma. \tag{10}$$

Using the definition of λ above and with the help of [23], the pdf of $f_{\kappa-\mu}(\gamma)$ for an SSK-MIMO system can be written as:

$$f_{\kappa-\mu}(w) = \frac{\mu(1+\kappa)^{\frac{N_r\mu+1}{2}} w^{\frac{N_r\mu-1}{2}}}{(N_r\kappa)^{\frac{N_r\mu-1}{2}} \exp(N_r\mu\kappa) \bar{\gamma}^{\frac{N_r\mu+1}{2}}} \times \exp\left(\frac{-\mu(1+\kappa)w}{\bar{\gamma}}\right) \times I_{N_r\mu-1}\left(2\mu\sqrt{\frac{N_r\kappa(1+\kappa)w}{\bar{\gamma}}}\right). \tag{11}$$

An expression for the MGF of the instantaneous SNR in (9) is obtained, by substituting (11) into (10) and applying Laplace transform [32, eq. (3.15.2.8)], as

$$\mathcal{M}_{\kappa-\mu}(s) = \left(\frac{\mu(1+\kappa)}{\mu(1+\kappa) + \bar{\gamma}s}\right)^{Nr\mu} \exp\left(-\mu N_r \kappa\right) \times \exp\left(\frac{\mu^2 N_r \kappa(1+\kappa)}{\mu(1+\kappa) + \bar{\gamma}s}\right) \tag{12}$$

Substituting (12) into (9) and following a similar approach as in [33], a closed-form expression for the PEP is obtained in terms of confluent hypergeometric function of two variables as given in (13).

The derived close-form expression in (13) is a general expression for the PEP of SSK-MIMO systems operating over $\kappa - \mu$ fading channels. Therefore, the PEP for other well-known fading channels such as Nakagami-m and Nakagami-n can be obtained using (13) as special cases.

Special Case 1 (Nakagami-m fading channels). The PEP of SSK-MIMO systems that operate over Nakagami-m is obtained using (13) when $\kappa \to 0$ and $\mu = m$. Using the relation between the Appell's hypergeometric function and the confluent hypergeometric function of two variables and with the help of [34, eq. (22)], (13) reduces to (15).

Special Case 2 (Nakagami-n fading channels). When $\kappa = n^2$ and $\mu = 1$ in (13), the PEP of over Nakagami-n fading channels is obtained as in (16).

Special Case 3 (Rice fading channels). To obtain the desired result for the Rician fading channel, we substitute $n^2 = K$ in (16), which results in (17).

3.1.1 Asymptotic Analysis

In order to clearly show the system diversity gain and the effect of system parameters on the overall system

$$\mathrm{PEP}_{\kappa-\mu}\left(t_{i_1} \rightarrow t_{i_2}\right) = \frac{\Gamma(N_r\mu+\frac{1}{2})\exp\left(-\mu N_r\kappa\right)\left[2\mu(1+\kappa)\right]^{N_r\mu}\sqrt{\frac{\bar{\gamma}}{\pi}}}{2\Gamma(N_r\mu+1)\left[2\mu(1+\kappa)+\bar{\gamma}\right]^{N_r\mu+\frac{1}{2}}} \times\Phi_1\left(N_r\mu+\frac{1}{2},1,N_r\mu+1;\frac{2\mu(1+\kappa)}{\left[2\mu(1+\kappa)+\bar{\gamma}\right]},\frac{2\mu^2N_r\kappa(1+\kappa)}{\left[2\mu(1+\kappa)+\bar{\gamma}\right]}\right) \tag{13}$$

where

$$\Phi_1(a,b,c;x_1,x_2) \triangleq \sum_{k,l=0}^{\infty}\frac{(a)_{k+l}(b)_k}{(c)_{k+l}}\frac{x_1^kx_2^l}{k!l!} = \frac{1}{B(a,c-a)}\int_0^1 t^{a-1}(1-t)^{c-a-1}(1-x_1t)^{-b}\exp(tx_2)dt \quad |x_1|<1,\ \Re(c)>\Re(a)>0 \tag{14}$$

$$\mathrm{PEP}_{Nak-m}\left(t_{i_1} \rightarrow t_{i_2}\right) = \frac{\sqrt{\frac{\bar{\gamma}}{2m}}}{2\sqrt{\pi}\left(1+\frac{\bar{\gamma}}{2m}\right)^{N_rm+\frac{1}{2}}}\frac{\Gamma(N_rm+\frac{1}{2})}{\Gamma(N_rm+1)}F\left(1,N_rm+\frac{1}{2};N_rm+1;\frac{1}{1+\frac{\bar{\gamma}}{2m}}\right) \tag{15}$$

$$\mathrm{PEP}_{Nak-n}\left(t_{i_1} \rightarrow t_{i_2}\right) = \frac{\Gamma(N_r+\frac{1}{2})\exp\left(-N_rn^2\right)\left[2(1+n^2)\right]^{N_r}\sqrt{\frac{\bar{\gamma}}{\pi}}}{2\Gamma(N_r+1)\left[2(1+n^2)+\bar{\gamma}\right]^{N_r+\frac{1}{2}}} \times\Phi_1\left(N_r+\frac{1}{2},1,N_r+1;\frac{2(1+n^2)}{\left[2(1+n^2)+\bar{\gamma}\right]},\frac{2N_rn^2(1+n^2)}{\left[2(1+n^2)+\bar{\gamma}\right]}\right) \tag{16}$$

$$\mathrm{PEP}_{Rice}\left(t_{i_1} \rightarrow t_{i_2}\right) = \frac{\Gamma(N_r+\frac{1}{2})\exp\left(-N_rK\right)\left[2(1+K)\right]^{N_r}\sqrt{\frac{\bar{\gamma}}{\pi}}}{2\Gamma(N_r+1)\left[2(1+K)+\bar{\gamma}\right]^{N_r+\frac{1}{2}}} \times\Phi_1\left(N_r+\frac{1}{2},1,N_r+1;\frac{2(1+K)}{\left[2(1+K)+\bar{\gamma}\right]},\frac{2N_rK(1+K)}{\left[2(1+K)+\bar{\gamma}\right]}\right) \tag{17}$$

performance, an asymptotic expression for the PEP is obtained in what follows. According to [35], the asymptotic PEP can be derived based on the behavior of the PDF of the instantaneous SNR around the origin. As such and by using Taylor's series, the $f_{\kappa-\mu}(\gamma)$ given in (11) can be represented by

$$f_{\kappa-\mu}(\gamma) \approx= \frac{\mu^{N_r\mu}(1+\kappa)^{N_r\mu}}{\Gamma(N_r\mu)\exp(N_r\mu\kappa)\bar{\gamma}^{N_r\mu}}\gamma^{N_r\mu-1} + \mathcal{O}. \tag{18}$$

where $\mathcal{O}$ stands for higher order terms. Now plugging (18) into (8), the asymptotic PEP for SSK-MIMO systems in $\kappa-\mu$ fading channels can be given as

$$\mathrm{PEP}^{Asym}_{\kappa-\mu}(t_{i_1}\to t_{i_2}) = \frac{2^{N_r\mu-1}\Gamma(N_r\mu+\frac{1}{2})}{N_r\mu\sqrt{\pi}\Gamma(N_r\mu)\exp(N_r\mu\kappa)} \times\left(\frac{\mu(1+\kappa)}{\bar{\gamma}}\right)^{N_r\mu}, \tag{19}$$

where the system diversity is shown to equal $N_r\mu$.

It can be easily shown that the asymptotic PEP of Nakagami-m fading channels, using (19), can be reduced to

$$\mathrm{PEP}^{Asym}_{Nak-m}(t_{i_1}\to t_{i_2}) \approx \frac{2^{N_rm-1}\Gamma(N_rm+\frac{1}{2})}{\sqrt{\pi}\Gamma(N_rm+1)}\times\left(\frac{m}{\bar{\gamma}}\right)^{N_rm}. \tag{20}$$

The asymptotic PEP for Rayleigh fading channel can be readily obtained from (20) when $m=1$.

For Nakagami-n fading channels, the asymptotic PEP can be expressed as

$$\mathrm{PEP}^{Asym}_{Nak-n}(t_{i_1}\to t_{i_2}) = \frac{2^{N_r-1}\Gamma(N_r+\frac{1}{2})}{N_r!\sqrt{\pi}\exp(N_rn^2)} \times\left(\frac{(1+n^2)}{\bar{\gamma}}\right)^{N_r} \tag{21}$$

Similarly, substituting $n^2=K$ in (21), the asymptotic PEP in Rice fading channels is deduced as

$$\mathrm{PEP}^{Asym}_{Rice}(t_{i_1}\to t_{i_2}) = \frac{2^{N_r-1}\Gamma(N_r+\frac{1}{2})}{N_r!\sqrt{\pi}\exp(N_rK)} \times\left(\frac{(1+K)}{\bar{\gamma}}\right)^{N_r}. \tag{22}$$

Note that for Nakagami-n and Rice fading channels the diversity order equals N_r.

4 Numerical and Simulation Results

In this section, various numerical examples to study the impact of the fading parameters κ and μ on the system performance in terms of average bit error rate (P_{ABER}) are presented. Specifically, the P_{ABER} is portrayed as a function of SNR for different values of the fading parameters. Furthermore, the numerical results are accompanied with Monte-Carlo simulations to validate the accuracy of the conducted analysis.

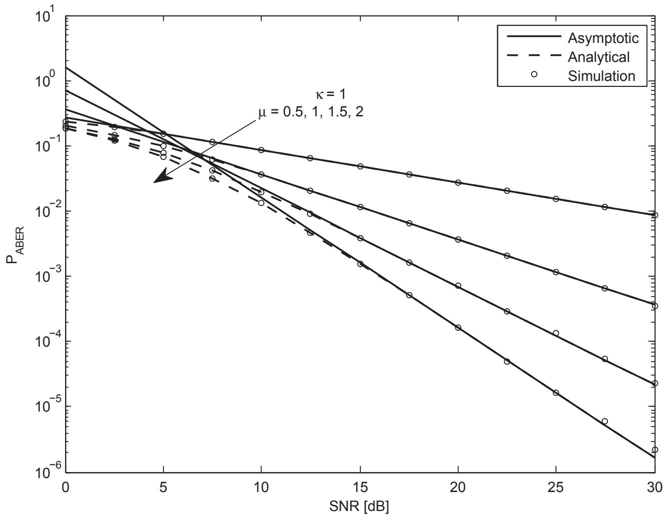

Figure 1: Impact of μ on the system performance: $\kappa=1$, $\mu=0.5,1,1.5,2$, $N_t=2$, and $N_r=1$.

The impact of the fading parameters κ and μ, assuming $\kappa-\mu$ fading channels, on the system performance is illustrated in Figs. 1 and 2. Again, it is clear from Fig. 1 that as μ increases the system performance improves. The effect of κ on the P_{ABER} is depicted in Fig. 2. One can note that as κ increases the system performance slightly improves. This occurs because κ represents the ratio between the total power of the dominant components and the total power of the scattered waves. Thereby, higher κ indicates that one channel component dominates over the other and enhances the detection of the active antenna.

The effect of increasing the number of receive antennas on the system performance assuming $\kappa-\mu$ fading channels is shown in Figs. 3 and 4. As clearly shown and expected, increasing the number of receive antennas enhances the performance noticeably. Note that the diversity order of the $\kappa-\mu$ fading channels is $N_r\mu$.

5 Conclusion

This paper analyzes the performance of SSK-MIMO systems operating over i.i.d generalized $\eta-\mu$ and $\kappa-\mu$ fading channels. A closed-form expression for the PEP of SSK-MIMO systems is derived. Because the derived expression is general, it can readily allow derivation for various well-known fading channels such as Nakagami-m, Rayleigh, and Nakagami-n

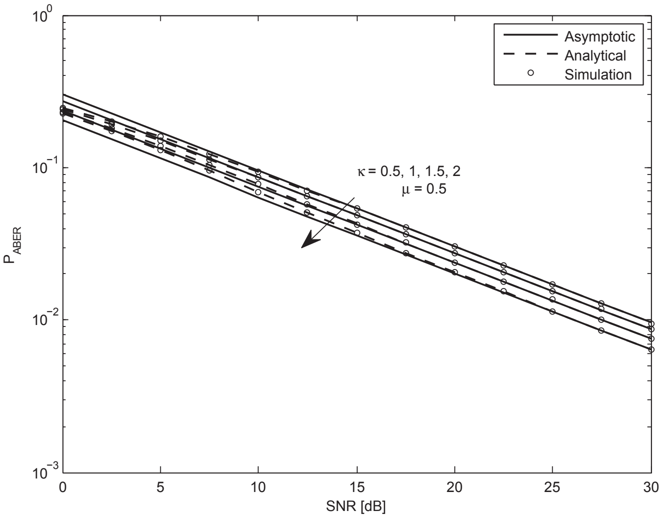

Figure 2: Impact of κ on the system performance: $\mu = 0.5$, $\kappa = 0.5, 1, 1.5, 2$. $N_t = 2$, $N_r = 1$.

(Rice) distributions. Besides, the effect of varying the fading parameters, κ and μ, on the overall system performance can be easily investigated. Results demonstrated that the fading parameter μ has a significant effect on the system performance as compared to κ. Conducted asymptotic analysis demonstrate a diversity gain of $N_r\mu$ for the system under study.

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References:

[1] P. Wang, Y. Li, L. Song, and B. Vucetic, "Multi-gigabit millimeter wave wireless communications for 5g: from fixed access to cellular networks," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 168–178, January 2015.

[2] A. Al-Dulaimi, S. Al-Rubaye, Q. Ni, and E. Sousa, "5g communications race: Pursuit of more capacity triggers lte in unlicensed band," *IEEE Vehicular Technology Magazine*, vol. 10, no. 1, pp. 43–51, March 2015.

[3] R. Mallik, S. Singh, R. Murch, and S. Mehra, "Signal design for multiple antenna systems with spatial multiplexing and noncoherent reception," *IEEE Transactions on Communications*, vol. 63, no. 4, pp. 1245–1258, April 2015.

[4] E. Larsson, O. Edfors, F. Tufvesson, and T. Marzetta, "Massive mimo for next generation wireless systems," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 186–195, February 2014.

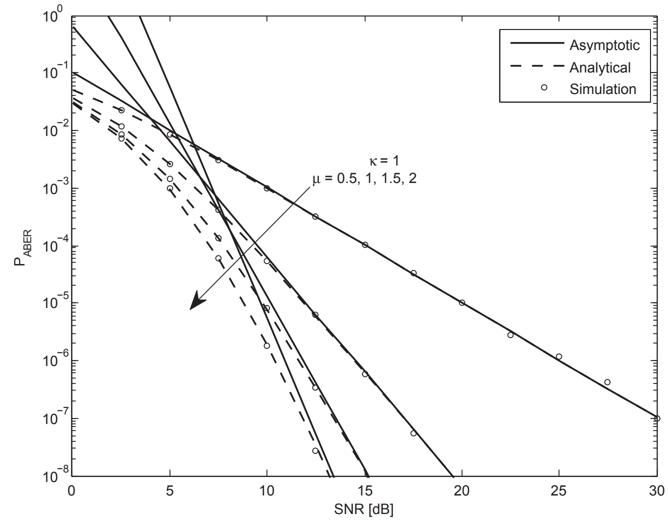

Figure 3: Impact of μ on the system performance where $\kappa = 1$, $\mu = 0.5, 1, 1.5, 2$, $N_t = 2$, and $N_r = 4$.

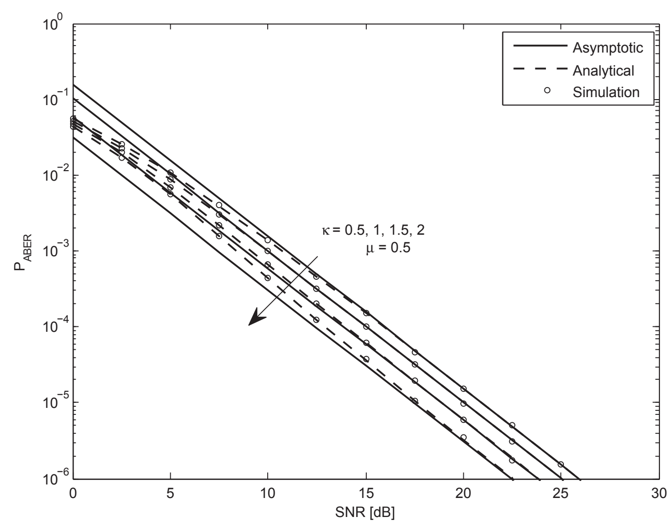

Figure 4: Impact of κ on the system performance where $\mu = 0.5$, $\kappa = 0.5, 1, 1.5, 2$, $N_t = 2$, and $N_r = 4$.

[5] 3rd Generation Partnership Project (3GPP), Technical Specification Group Radio Access Network, *Uplink Sounding for Obtaining MIMO Channel Information at NodeB in EUTRA*, 3GPP Std. R1-060 668, 2006.

[6] IST-4-027756 WINNER II, "D3.4.1, The WINNER II Air Interface: Refined Spatial Temporal Processing Solutions," Retrieved Mar. 08, 2010, from https://www.ist-winner.org/WINNER2-Deliverables/.

[7] Nokia, *E-UTRA Link adaption: consideration on MIMO*, 3GPP LTE Std. R1-051 415, 2005.

[8] S. M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[9] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-time Block Codes from Orthogonal Designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[10] P. Wolniansky, G. Foschini, G. Golden, and R. Valenzuela, "V-BLAST: an Architecture for Realizing very High Data Rates over the Rich-Scattering Wireless Channel," in *Unino Radio-Scientifique Internationale (URSI) Intern. Symp. on Signals, Systems, and Electronics (ISSSE)*, Sep. 29–Oct. 2, 1998, pp. 295–300.

[11] M. Sellathurai and S. Haykin, "Turbo-BLAST for Wireless Communications: Theory and Experiments," *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2538–2546, Oct. 2002.

[12] X. He, T. Luo, and G. Yue, "Optimized Distributed MIMO for Cooperative Relay Networks," *IEEE Commun. Lett.*, vol. 14, no. 1, pp. 9–11, Jan. 2010.

[13] S. Fang, L. Li, S. Hu, and G. Feng, "Layered space shift keying modulation over mimo channels," in *Communications (ICC), 2015 IEEE International Conference on*, June 2015, pp. 2148–2153.

[14] S.-T. Su, W.-H. Chung, and C.-F. Wu, "Exploiting entire gssk antenna combinations in mimo systems," *Communications Letters, IEEE*, vol. 19, no. 5, pp. 719–722, May 2015.

[15] R. Mesleh, H. Haas, C. W. Ahn, and S. Yun, "Spatial Modulation – A New Low Complexity Spectral Efficiency Enhancing Technique," in *IEEE International Conference on Communication and Networking in China (CHINACOM)*, Beijing, China, Oct. 25–27, 2006, pp. 1–5.

[16] J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, "Space Shift Keying Modulation for MIMO Channels," *IEEE Transaction on Wireless Communications*, vol. 8, no. 7, pp. 3692–3703, Jul. 2009.

[17] Y. A. Chau and S.-H. Yu, "Space Modulation on Wireless Fading Channels," in *Proc. IEEE VTC 2001 Fall Vehicular Technology Conference*, vol. 3, 7–11 Oct. 2001, pp. 1668–1671.

[18] R. Mesleh, H. Haas, S. Sinanović, C. W. Ahn, and S. Yun, "Spatial Modulation," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2228–2241, July 2008.

[19] J. Jeganathan, A. Ghrayeb, and L. Szczecinski, "Spatial Modulation: Optimal Detection and Performance Analysis," *IEEE Commun. Lett.*, vol. 12, no. 8, pp. 545–547, 2008.

[20] S. Sugiura, S. Chen, and L. Hanzo, "Coherent and differential space-time shift keying: A dispersion matrix approach," *IEEE Transaction on Communications*, vol. 58, no. 11, pp. 3219–3230, 2010.

[21] R. Mesleh, M. Di Renzo, H. Haas, and P. M. Grant, "Trellis Coded Spatial Modulation," *IEEE Trans. on Wireless Commun.*, vol. 9, no. 7, pp. 2349–2361, July 2010.

[22] M. Di Renzo and H. Haas, "Space Shift Keying (SSK) Modulation with Partial Channel State Information: Optimal Detector and Performance Analysis over Fading Channels," *IEEE Trans. on Commun.*, vol. 58, no. 11, pp. 3196 –3210, 2010.

[23] M. D. Yacoub, "The $\eta-\mu$ Distribution and the $\kappa-\mu$ Distribution," *IEEE Antennas Propag. Mag.*, vol. 49, no. 1, pp. 68–81, 2007.

[24] S. Kumar, G. Chandrasekaran, and S. Kalyani, "Analysis of outage probability and capacity for $\kappa-\mu$–$\eta-\mu$faded channel," *IEEE Commun. Lett.*, vol. 19, no. 2, pp. 211–214, Feb. 2014.

[25] J. Zhang, M. Matthaiou, G. Karagiannidis, H. Wang, and Z. Tan, "Gallager's exponent analysis of stbc mimo systems over $\eta-\mu$ and $\kappa-\mu$ fading channels," *IEEE Transactions on Communications,*, vol. 61, no. 3, pp. 1028–1039, 2013.

[26] V. Vergara and S. Barbin, "Mimo capacity upper bound for $\kappa-\mu$ and $\eta-\mu$ faded channels," in *2012 IEEE Radio and Wireless Symposium (RWS),*, Santa Clara, CA, 15–18 Jan. 2012, pp. 367–370.

[27] J. G. Proakis, *Digital Communications*. McGraw–Hill, 1995.

[28] M. K. Simon and M. Alouini, *Digital Communication over Fading Channels*, 2nd ed., ser. Wiley series in telecommunications and signal pro-

cessing. John Wiley & Sons, Inc., 2005, ISBN: 978-0-471-64953-3.

[29] M. Di Renzo and H. Haas, "Bit Error Probability of Space Modulation over Nakagami-m Fading: Asymptotic Analysis," *IEEE Communications Letters,*, vol. 15, no. 10, pp. 1026–1028, 2011.

[30] M. Di Renzo and H. Haas, "A General Framework for Performance Analysis of Space Shift Keying (SSK) Modulation for MISO Correlated Nakagami-m Fading Channels," *IEEE Trans. Commun.*, vol. 58, no. 9, pp. 2590 –2603, Sep. 2010.

[31] S. Ikki and R. Mesleh, "A General Framework for Performance Analysis of Space Shift Keying (SSK) Modulation in the Presence of Gaussian Imperfect Estimations," *IEEE Communications Letters*, vol. 16, no. 2, pp. 228–230, Feb. 2012.

[32] A. P. Prudnikov, Y. A. Brychkov, and O. I. Marcichev, *Integral and series*. Gordon and Breach Science Publisher, 1986, vol. 4.

[33] N. Ermolova, "Moment generating functions of the generalized η-μ; and $\kappa - \mu$ distributions and their applications to performance evaluations of communication systems," *IEEE Communications Letters*, vol. 12, no. 7, pp. 502–504, 2008.

[34] S. S. Miller and P. T. Mocanu, "Univalence of Gaussian and Confluent Hypergeometric Functions," *Proceedings of the American Mathematical Society*, vol. 110, no. 2, pp. 333–342, 1990.

[35] Z. Wang and G. B. Giannakis, "A Simple and General Parameterization Quantifying Performance in Fading Channels," *IEEE Transactions on Communication*, vol. 51, no. 8, pp. 1389–1398, aug 2003.